United States Department of Agriculture

U.S. AGRICULTURE AND FORESTRY

Greenhouse Gas Inventory

1990 - 2013

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Office of the Chief Economist | Climate Change Program Office

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U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990−2013

United States Department of Agriculture, Office of the Chief Economist, Climate Change Program Office.
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Abstract

The *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990–2013* was developed to update previous USDA greenhouse gas inventories and to revise estimates for previous years based on improved methodologies. This inventory provides a comprehensive assessment of the contribution of U.S. agriculture (i.e., livestock and crop production) and forestry to greenhouse gas (GHG) emissions. The document was prepared to support and expand on information provided in the official *Inventory of U.S. GHG Emissions and Sinks* (U.S. GHG Inventory), which is prepared annually by the U.S. Environmental Protection Agency. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) concentrations in the atmosphere have increased by approximately 43 percent, 152 percent, and 20 percent respectively since about 1750. In 2013, total U.S. GHG emissions were 6,673 million metric tons of carbon dioxide equivalents (MMT CO_2 eq.), rising 5.9 percent from 1990 estimates. Carbon sequestration in managed forests, urban trees, and harvested wood products (882 MMT CO_2 eq.) reduced these emissions to a net 5,791 MMT CO_2 eq. in the United States in 2013. Agriculture alone accounted for about 9 percent of total U.S. emissions (595 MMT CO_2 eq.). The primary GHG sources from agriculture are N_2O emissions from cropped and grazed soils (264 MMT CO_2 eq.), CH_4 emissions from ruminant livestock production (165 MMT CO_2 eq.) and rice cultivation (8 MMT CO_2 eq.), CH_4 and N_2O emissions from managed livestock waste (79 MMT CO_2 eq.), and CO_2 emissions from on-farm energy use (74 MMT CO_2 eq.). The largest managed carbon sink in the United States is managed forests, which sequester 705 MMT CO_2 eq. The U.S. agriculture and forestry sector in aggregate provided a net sink of 270 MMT CO_2 eq. in 2013 (including GHG sources from crop and livestock production, grasslands, energy use, and GHG sinks for forests and urban trees). This report serves to estimate U.S. GHG emissions for the agricultural sector, to quantify uncertainty in emission estimates, and to estimate the potential of agriculture to mitigate U.S. GHG emissions.

Keywords: climate change, greenhouse gas, land use, carbon stocks, carbon sequestration, enteric fermentation, livestock waste, nitrous oxide, methane, rice cultivation, energy consumption.

September 1, 2016

Dear Reader:

I am pleased to present The *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990–2013*. This report supersedes USDA Technical Bulletin 1930 (2011), which accounted for greenhouse gas emissions and sinks for the agricultural and forestry sectors through 2008.

This report is consistent with the U.S. Environmental Protection Agency's (EPA) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2013* (April, 2015). However, EPA's national-scale reporting here has been disaggregated by region or State when possible. Some categories are not directly comparable due to different greenhouse gas source grouping. We believe this format will serve as a useful resource to land managers, planners, and others with an interest in greenhouse gas dynamics and their relationships to land use and land use change.

As part of the USDA Building Blocks for Climate Smart Agriculture and Forestry, the Office of the Chief Economist is coordinating efforts to track greenhouse gas sources and sinks in agriculture. Over the next few years, we will be updating key agricultural management practice and technology data. We expect that these new data inputs will significantly refine estimates of soil carbon, methane emissions from manure management systems, and nitrous oxide emissions from fertilizers. We also anticipate future improvements due to the new U.S. Forest Carbon Accounting Framework.

Data collection and analysis, as well as coordination of this *Inventory*, could not have been accomplished without the contributions of Stephen Del Grosso, Melissa Reyes-Fox, and others within USDA's Agricultural Research Service. I would also like to thank Rich Birdsey, Linda Heath, Coeli Hoover, and James Smith of the USDA Forest Service; James Duffield of USDA's Office of Energy Policy and New Uses; Marlen Eve and Jerry Hatfield of USDA's Agricultural Research Service; Tom Capehart, Elizabeth Marshall, and Ken Matthews of USDA's Economic Research Service; Jan Lewandrowski of USDA's Office of the Chief Economist; Stephen Ogle at the Natural Resources Ecology Laboratory of Colorado State University; and Tom Wirth in EPA's Office of Atmospheric Programs for their data, analysis, and review. Their thoughtful and diligent efforts compose the foundation of this report.

Sincerely,

William Hohenstein
Director, USDA Climate Change Program Office

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U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990–2013

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The *U.S. Agriculture and Forestry Greenhouse Gas Inventory* (USDA GHG Inventory) is supplemental to the official *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (U.S. GHG Inventory) submitted by EPA to the United Nations Framework Convention on Climate Change each April. We thank the EPA for permission to reprint estimates and methodologies from the official U.S. GHG Inventory. We would like to acknowledge the contribution of Tom Wirth of EPA's Office of Atmospheric Programs, who provided detailed emissions data for livestock sources of methane and nitrous oxide reported in Chapter 2. We also acknowledge William Parton, Keith Paustian, Stephen Williams, Kendrick Killian, Mark Easter, Shannon Spencer and Ram Gurung of the Natural Resource Ecology Laboratory (NREL) of Colorado State University who helped generate the agricultural soil carbon and nitrous oxide estimates for Chapters 2 and 3.

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Glossary of Terms and Units

Chemical identities

C	Carbon
CO_2	Carbon dioxide
CO_2 eq.	Carbon dioxide equivalent
CH_4	Methane
N_2O	Nitrous oxide
NO_x	Nitrogen oxides

Metric units

MT	Metric ton (10^6 grams or 1,000 kilograms)
Mg	Megagram (10^6 grams)
Gg	Gigagram (10^9 grams)
Tg	Teragram (10^{12} grams)
MMT	Million metric tons (10^{12} grams)
ha	Hectares

Livestock specific

B_o	Maximum methane-producing capacity
CEFM	Cattle Enteric Fermentation Model
DE	Digestible energy
MCF	Methane conversion factor
Nex	Total Kjeldahl nitrogen excretion rate
TAM	Typical animal mass
VS	Volatile solids
WMS	Waste management system
Y_m	Fraction of gross energy converted to methane

Cropland specific

CRP	USDA Conservation Reserve Program
MLRA	Major Land Resource Area

Forestry specific

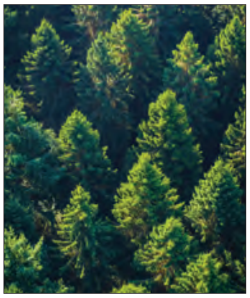
CRM	Component ratio method
dbh	Diameter breast height
FIA	USDA Forest Inventory and Analysis
FIADB	USDA Forest Inventory and Analysis Database
HWP	Harvested wood products
SOC	Soil organic carbon

Energy specific

BTU	British thermal unit
QBTU	Quadrillion British thermal units
EIA	Energy Information Administration
LP gas	Liquid petroleum gas

Other

EF	Emission factor
GHG	Greenhouse gas
GWP	Global warming potential
NRI	U.S. National Resources Inventory



Chapter 1

Download data: http://dx.doi.org/10.15482/USDA.ADC/1260729

Introduction

1.1 Global Change and Greenhouse Gas Emissions in Agriculture and Forestry

In 2013, total U.S. greenhouse gas emissions measured 6,673 million metric tons of carbon dioxide equivalents (MMT CO_2 eq.), rising 5.9 percent from 1990 estimates (EPA 2015). Global concentrations of the three most important long-lived greenhouse gases (GHG) in the atmosphere have increased measurably since the onset of the Industrial Revolution in 1750. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) concentrations in the atmosphere have increased by approximately 43 percent, 152 percent, and 20 percent respectively (EPA 2015, Keeling and Whorf 2005, Dlugokencky et al. 2005, Prinn et al. 2000). Agriculture and forestry practices may either contribute to or remove GHGs from the atmosphere. Agriculture and forestry have contributed to GHGs in the atmosphere through cultivation and fertilization of soils, production of ruminant livestock, management of livestock manure, land use conversions, and fuel consumption.

The primary GHG sources from agriculture are N_2O emissions from cropped and grazed soils, CH_4 emissions from ruminant livestock production and rice cultivation, CH_4 and N_2O emissions from managed livestock waste, and CO_2 emissions from on-farm energy use. The management of cropped, grazed, and forestland has helped offset GHG emissions by promoting the biological uptake of CO_2 through the incorporation of carbon into biomass, wood products, and soils, yielding a U.S. net emissions of 5,791 MMT CO_2 eq. in 2013. Net emissions equate to total greenhouse gas emissions minus CO_2 sequestration or removal of CO_2 from the atmosphere, including the net forest sink as well as the net soil sink from grazed lands and croplands. This report serves to estimate U.S. GHG emissions for the agricultural sector, to quantify uncertainty in emission estimates, and to estimate the potential of agriculture to mitigate U.S. GHG emissions.

Observed increases in atmospheric GHG concentrations are primarily a result of fossil fuel combustion for power generation, transportation, and construction. In the United States, agriculture accounted for approximately 9 percent of total GHG emissions in 2013 (EPA 2015). Greenhouse gas emission estimates reported here are in units of CO_2 equivalents. Box 1-1 describes this reporting convention, which normalizes all GHG emissions to CO_2 equivalents using Global Warming Potentials (GWP). Note that GWPs for CH_4 and N_2O have changed compared to the previous edition of this inventory.

Agriculture in the United States, including livestock, grasslands, crop production, and energy use, contributed a total of 595 MMT CO_2 eq. to the atmosphere in 2013 (Table 1-1). This total includes a relatively small soil CO_2 sink of 1.4 MMT CO_2 eq. in cropped soils (Table 1-2). In previous USDA Inventory reports, grazed lands were a relatively large sink for CO_2, but new simulations using more recent land cover data estimate that grazed lands are currently close to CO_2 neutral. Forests and urban trees in the United States contributed to a total reduction in atmospheric GHGs of approximately 865 MMT CO_2 eq. in 2013, which offset total U.S. GHG emissions by 13 percent. After accounting for GHG sources and C sequestration, agricultural and forested lands in the United States were estimated to be a net sink of 270 MMT CO_2 eq. (Table 1-1). The 95 percent confidence interval for this estimate ranges from a sink of 486 to 38 MMT CO_2 eq. (Table 1-1).

Table 1-1 Agriculture and Forestry Greenhouse Gas Emission Estimates and Uncertainty Intervals, 2013

	Estimate	Lower Bound	Upper Bound
Source		*MMT CO_2 eq.*	
Livestock	243	222	276
Crops[1]	175	129	249
Grassland[1]	102	32	190
Energy Use[2]	74		
Forestry	(776)	(973)	(576)
Urban Trees	(90)	(133)	(47)
Net Emissions	**(270)**	**(486)**	**(38)**

Note: Parentheses indicate a net sequestration. MMT CO_2 eq. is million metric tons carbon dioxide equivalent.

[1]Includes sequestration in agricultural soils.

[2]Confidence intervals were not available for this component.

Box 1-1

The USDA GHG Inventory report follows the international convention for reporting GHG emissions, as described in the introduction of the U.S. GHG Inventory (EPA 2015). Emissions of GHGs are expressed in equivalent terms, normalized to carbon dioxide (CO_2) using Global Warming Potentials (GWPs) published by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Table B1-1). GWPs, which are based on physical and chemical properties of gases, represent the effect of a given GHG on the climate, integrated over a given period of time, relative to CO_2 (IPCC 2006). Since the reference gas used is CO_2, GWP-weighted emissions are measured in million metric tons of CO_2 equivalent (MMT CO_2 eq.). GWP values allow for a comparison of the impacts of emissions and reductions of different gases. These values for methane (CH_4) and nitrous oxide (N_2O) are referenced to CO_2 and based on a 100-year time period (EPA 2015). These GWPs have been adjusted since the previous USDA Inventory Report was published.

Table B1-1 (reproduced from U.S. GHG Inventory Report (EPA 2015), Table 1-2)

Gas	**Atmospheric Lifetime**	**GWP**[c]
CO_2	[b]	1
CH_4[a]	12	25
N_2O	114	298

Source: (IPCC 2007)

[a] The GWP of CH_4 includes the direct effects and those indirect effects due to the production of tropospheric ozone and stratospheric water vapor. The indirect effect due to the production of CO_2 is not included.

[b] For a given amount of carbon dioxide emitted, some fraction of the atmospheric increase in concentration is quickly absorbed by the oceans and terrestrial vegetation, thus will continue to cycle through aquatic and terrestrial ecosystems as carbon. Some fraction of the atmospheric carbon dioxide will only slowly decrease over a number of years, and depending on the amount of carbon dioxide emitted, between 15% and 40% can remain in the atmosphere for up to 2000 years (IPCC 2013).

[c] 100-year time horizon.

The relationship between kilotons (kt) of a gas and MMT CO_2 eq. can be expressed as follows:

$$\text{MMT } CO_2 \text{ eq.} = (\text{kt of gas}) \times (\text{GWP}) \times (\text{MMT}/1000\text{kt})$$

where,

MMT CO_2 eq. = Million metric tons of CO_2 equivalent

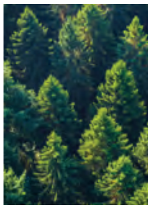
kt = Kilotons (equivalent to a thousand metric tons)

GWP = Global warming potential

MMT = Million metric tons

Close to half (45 percent) of agriculture's GHG emissions in 2013 were from soils (Figure 1-1). Most of the emissions from crop production were from non-rice soils, with residue burning and rice cropping accounting for about 1 percent of overall agricultural emissions (Figure 1-1). Enteric fermentation from livestock production was responsible for a large portion (28 percent) of the remaining agricultural emissions. Managed livestock waste and on-farm energy use each accounted for 13 percent of agricultural emissions. It should be noted that the estimates in Figure 1-1 are for emissions only, and do not account for C storage in agricultural soils and forests. Regarding sequestration, forests are by far the leading sink, followed by urban trees and harvested wood products (Figure 1-2).

Sources and sinks of emissions are conveniently partitioned in Figure 1-3 (sinks are values less than 0). Overall emissions profiles of agricultural sources, including energy use but excluding storage by soils and forestry, show that sources increased 13 percent between 1990 and 2013 (Table 1-2, Figure 1-3). The sink strength of the forests, harvested wood, and urban trees pool has increased 24 percent since 1990 (Table 1-2, Figure 1-3). However, the sink strength of agricultural soils has decreased by approximately 104 percent since 1990. In sum, emissions increased from 1990 to 2013, but C storage related to forestry increased to an even greater extent. Because C sequestration exceeds sources, net emissions are negative (GHG sink), and the amount of net sequestration increased by about 23 percent since 1990 (Table 1-2).



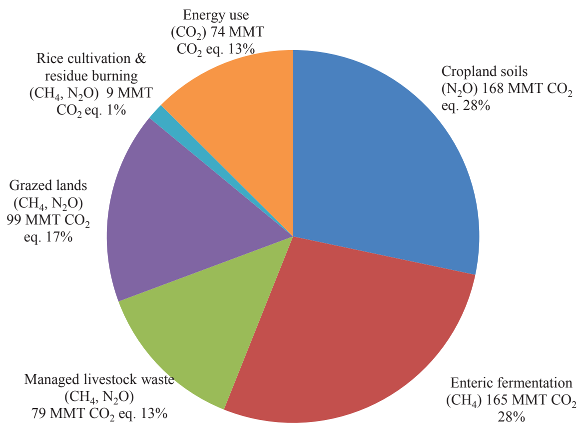


Figure 1-1 Agricultural Sources of Greenhouse Gas Emissions in 2013 *(CH_4 is methane; N_2O is nitrous oxide; CO_2 is carbon dioxide. MMT CO_2 eq. is million metric tons of carbon dioxide equivalent)*

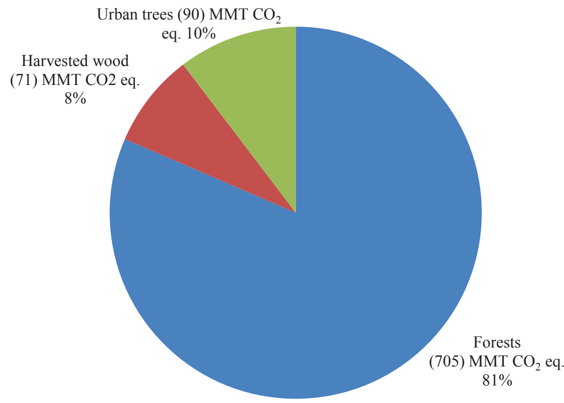


Figure 1-2 Agricultural and Forest Sinks of Carbon Dioxide in 2013 *(MMT CO_2 eq. is million metric tons of carbon dioxide equivalent)*

Table 1-2 Summary of Agriculture and Forestry Emissions and Offsets, 1990, 1995, 2000, 2005, 2010-2013

Source	GHG	1990	1995	2000	2005	2010	2011	2012	2013
		MMT CO_2 eq.							
Livestock		**215.1**	**236.9**	**236.9**	**241.6**	**249.1**	**247.4**	**247.4**	**243.2**
Enteric Fermentation	CH_4	164.2	178.7	170.6	168.9	171.1	168.7	166.3	164.5
Managed Waste	CH_4	37.2	43.3	50.0	56.3	60.9	61.4	63.7	61.4
Managed Waste	N_2O	13.8	15.0	16.3	16.4	17.1	17.3	17.3	17.3
Grassland		**73.9**	**93.6**	**33.0**	**82.9**	**101.5**	**101.4**	**100.7**	**102.0**
Grassland	CH_4	2.7	2.9	2.7	2.7	2.6	2.6	2.5	2.8
Grassland	N_2O	80.5	90.3	70.8	85.0	96.1	96.0	95.5	95.9
Grassland	CO_2	(9.3)	0.3	(40.5)	(4.8)	2.8	2.8	2.7	3.3
Crops		**117.0**	**161.5**	**133.1**	**164.0**	**174.7**	**173.0**	**177.1**	**175.1**
Cropland Soils[1]	N_2O	143.5	158.2	141.8	158.6	168.1	169.8	170.5	167.8
Cropland Soils[2]	CO_2	(36.0)	(6.9)	(18.8)	(3.9)	(4.9)	(5.7)	(3.1)	(1.4)
Rice Cultivation	CH_4	9.2	9.8	9.6	8.9	11.1	8.5	9.3	8.3
Residue Burning	CH_4	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3
Residue Burning	N_2O	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Energy Use[3]	CO_2	**73.9**	**73.9**	**73.9**	**69.9**	72.7	73.3	73.9	**74.4**
Forestry		**(699.8)**	**(728.0)**	**(563.2)**	**(887.6)**	**(851.5)**	**(856.1)**	**(860.7)**	**(865.2)**
Forests[4]	CO_2	(508)	(542)	(376)	(704)	(705)	(705)	(705)	(705)
Harvested Wood[4]	CO_2	(132)	(118)	(113)	(103)	(60.5)	(63.9)	(67.3)	(70.8)
Urban Trees[5]	CO_2	(60.4)	(67.1)	(73.8)	(80.5)	(86.1)	(87.3)	(88.4)	(89.5)
Net Emissions	***All GHGs***	**(219.8)**	**(162.0)**	**(86.2)**	**(329.2)**	**(253.5)**	**(261.1)**	**(261.6)**	**(270.4)**

Note: Parentheses indicate a net sequestration. MMT CO_2 eq. is million metric tons carbon dioxide equivalent. CH_4 is methane; N_2O is nitrous oxide; CO_2 is carbon dioxide.

[1]Includes emissions from managed manure during storage and transport before soil application.

[2]Agricultural soil C sequestration includes sequestration on land set aside under the USDA Conservation Reserve Program, in addition to cultivated mineral and organic soils.

[3]Data interpolated for all years except 2001, 2005, 2008, and 2013.

[4]Data were interpolated for years 2001-2004, 2006-2009, and 2011-2012.

[5]Data taken from EPA. Data were interpolated for years 1995 and 2000.

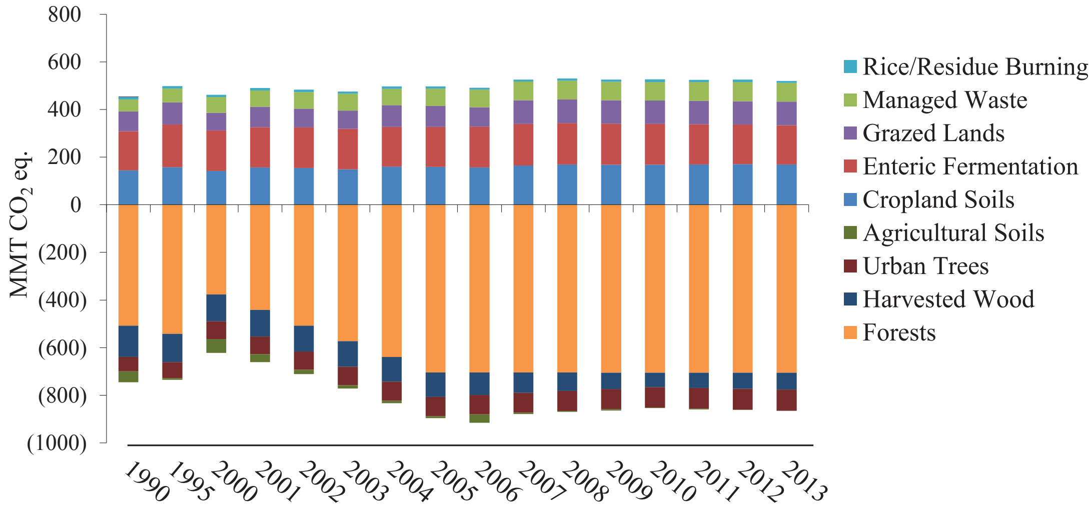


Figure 1-3 Agriculture and Forestry Emissions and Offsets for 1990, 1995, 2000-2013
(MMT CO_2 eq. is million metric tons of carbon dioxide equivalent)

Annual CO_2 emissions from on-farm energy use in agriculture are small relative to total energy use across all sectors in the United States. In 2013, fuel and electricity consumption associated with crop and livestock operations resulted in 74 MMT CO_2 (Table 1-1), which equals 1.4 percent of overall energy-related CO_2 emissions for 2013 (5332 MMT CO_2, EPA 2015). Diesel fuel use led to about 42 percent of CO_2 emissions from energy use in agriculture; electricity use led to about 37 percent; and gasoline, liquefied petroleum gas, and natural gas contributed 10 percent, 7 percent, and 4 percent, respectively, to total CO_2 emissions from energy use in agriculture.

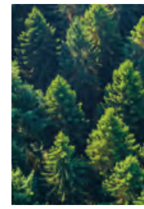
1.2 Sources and Mechanisms for Greenhouse Gas Emissions

One-half to two-thirds of global annual CH_4 emissions and roughly a third of global annual emissions of N_2O are believed to derive from human sources, mainly from agriculture (IPCC 2013). Agricultural activities contribute to these emissions in a number of ways. While losses of N_2O to the atmosphere occur naturally, the application of nitrogen to amend soil fertility increases the rate of emissions. The rate is amplified when more nitrogen is applied than can be used by the plants, either due to volume or timing. In agricultural practices, nitrogen is added to soils through the use of synthetic fertilizers, application of manure, cultivation of nitrogen-fixing crops/forages (e.g. legumes), and retention of crop residues. Rice cultivation involves periodic flooding of rice paddies, which promotes anaerobic decomposition of organic matter (rice residue and organic fertilizers) in the soil by soil microbes, resulting in methane emissions. Finally, burning of residues in agricultural fields produces CH_4 and N_2O as combustion byproducts.

Livestock grazing, production, and waste emit CH_4 and N_2O into the atmosphere. Ruminant livestock such as cattle, sheep, and goats emit CH_4 as a byproduct of their digestive processes (called enteric fermentation). Managed livestock waste can release CH_4 through the biological breakdown of organic compounds and N_2O through nitrification and denitrification of nitrogen contained in manure; the magnitude of emissions depends in large part on manure management practices and to some degree on the energy content of livestock feed. Grazed lands have enhanced N_2O emissions from nitrogen additions through manure and urine and from biological fixation of nitrogen by legumes, which are typically seeded in heavily grazed pastures. Some pastures are also amended with nitrogen fertilizers, managed manure, and sewage sludge, which also contribute to GHG emissions on those lands.

1.3 Strategies for Greenhouse Gas Mitigation

Agriculture and forest management can mitigate GHG emissions in two ways: sources can be reduced and emissions can be offset by increasing capacity for carbon uptake and storage in biomass, wood products, and soils. This process is referred to as carbon sequestration. The net flux of CO_2 between the land and the atmosphere is a balance between carbon losses from land use conversion and land management practices, and carbon gains from forest



growth and sequestration in soils (IPCC 2001). Improved forest regeneration and management practices such as density control, nutrient management, and genetic tree improvement promote tree growth and enhance carbon accumulation in biomass. In addition, wood products harvested from forests can serve as long-term carbon storage pools. The adoption of agroforestry practices like windbreaks and riparian forest buffers, which incorporate trees and shrubs into ongoing farm operations, represents a potentially large GHG sink nationally. While deforestation is a large global source of CO_2, within the United States, net forestland area has increased in recent decades (see Chapter 4). Avoidance of large-scale deforestation and adoption of the practices mentioned above have resulted in the forestry sector being a net GHG sink in the United States. This sink could be increased by increasing afforestation and implementing more intensive management to increase forest growth (McKinley et al. 2011).

Agricultural practices such as conservation tillage and grassland practices such as rotational grazing can also reduce carbon losses and promote carbon sequestration in agricultural soils. These practices offset CO_2 emissions caused by land use activities such as conventional tillage and cultivation of organic soils. However, strategies intended to sequester carbon in soils can also impact the fluxes of two important non-CO_2 GHGs, N_2O and CH_4. Consequently, the net impact of different management strategies on all three biogenic GHGs must be considered when comparing alternatives (Robertson et al. 2000, Del Grosso et al. 2005).

Innovative practices to reduce GHG emissions from livestock include modifying energy content of livestock feed, inoculating feed with agents that reduce CH_4 emissions from digestive processes, and managing manure in controlled systems that reduce or eliminate GHG emissions. For example, anaerobic digesters are a promising technology, whereby CH_4 emissions from livestock waste are captured and used as an alternative energy source. Nitrous oxide emissions from soils can be reduced by precision application of nitrogen fertilizers and use of nitrification inhibitors. A recent USDA report (Eve et al. 2014) discusses these and other mitigation options in detail and quantifies expected GHG reductions (or increases) for various land management practices.

1.4 Purpose of This Report

The *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990–2013* was developed to update the U.S. Agriculture and Forestry Greenhouse Gas Inventories: 1990-2001 (USDA 2004), 1990-2005 (USDA 2008) and 1990-2008 (USDA 2011) and to revise estimates for previous years based on improved methodologies. This inventory provides a comprehensive assessment of the contribution of U.S. agriculture (i.e., livestock and crop production) and forestry to greenhouse gas emissions. The document was prepared to support and expand on information provided in the official Inventory of U.S. GHG Emissions and Sinks (U.S. GHG Inventory), which is prepared annually by the U.S. Environmental Protection Agency to meet U.S. commitments under the United Nations Framework Convention on Climate Change (EPA 2015). This report, the U.S. Agriculture and Forestry GHG Inventory (USDA GHG Inventory), supplements the U.S. GHG Inventory, providing an in-depth look at agriculture and forestry emissions and sinks of GHG and presenting additional information on GHG emissions from fuel consumption on U.S. farms.

The U.S. GHG Inventory provides national-level estimates of emissions of the primary long-lived GHGs (carbon dioxide, methane, nitrous oxide, and fluorinated gases) across a broad range of sectors (energy, industrial processes, solvent use, agriculture, land use change and forestry, and waste). Due to the national-level scale of reporting in the U.S. GHG inventory, that report does not always provide regional or State GHG emissions data. However, in some cases Major Land Resource Area (MLRA), State, and regional emissions data are part of the inventory development process and can be used for more disaggregated analyses. For example, soil emissions are reported in this edition of the USDA Inventory disaggregated at the MLRA level.

Emissions reported here do not always exactly match the emissions reported in the U.S. GHG Inventory (EPA 2015) for some source categories. There are two main reasons for this; first the EPA (2015) report partitions emissions by IPCC (2006) categories, while the USDA report attempts to logically designate emissions due to agricultural production systems. For example, EPA (2015) includes CO_2 emissions from lime and urea fertilizer applied to cropped and grazed soils in the land Use, Land-Use Change, and Forestry category, whereas emissions from these sources are included in the agricultural soils category in this report. Second, in some tables and figures EPA (2015) reports CO_2 emissions from

energy (e.g., electric power generation) partitioned as its own category, whereas in other figures and tables, energy emissions are allocated to the end-use economic sector. In contrast, this report consistently accounts for CO_2 emissions from on-farm energy use in the agricultural sector. Note that this report does not account for CO_2 emissions from indirect energy, which is defined as energy used off the farm to manufacture farm inputs such as synthetic fertilizers.

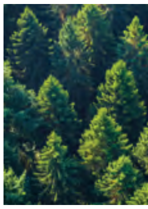
This report customizes the data from the U.S. GHG Inventory in a manner that is useful to agriculture and forestry producers and related industries, natural resource and agricultural professionals, as well as technical assistance providers, researchers, and policymakers. The information provided in this inventory will be useful in improving our understanding of the magnitude of GHG emissions by MLRA, State, region, and land use, and by crop, pasture, range, livestock, and forest management systems. The analyses presented in this report are the result of a collaborative process and direct contributions from EPA, USDA (Forest Service, Natural Resources Conservation Service, Agricultural Research Service, Office of Energy Policy and New Uses, and the Climate Change Program Office), and the Natural Resources Ecology Laboratory (NREL) of Colorado State University.

USDA administers a portfolio of conservation programs that have multiple environmental benefits including reductions in GHG emissions and increases in carbon sequestration. This and future USDA GHG Inventory reports will facilitate tracking of progress in promoting carbon sequestration and reducing GHG emissions through agriculture and forest management. The USDA GHG Inventory describes the role of agriculture and forestry in GHG emissions and sinks. Extensive and indepth emissions estimates are presented for all agricultural and forestry GHG sources and sinks for which internationally recognized methods are available. Where possible, emissions estimates are provided at MLRA, State and regional scales in addition to the national levels provided in the U.S. GHG Inventory. Emissions are categorized by additional information such as land ownership and management practices where possible. This report will help to:

- Quantify current levels of emissions and sinks at MLRA, State, regional, and national scales in agriculture and forestry,
- Identify activities that are driving GHG emissions and sinks and trends in these activities,
- Quantify the uncertainty associated with GHG emission and sink estimates.

1.5 Overview of the Report Structure

The report provides detailed trends in agriculture and forestry GHG emissions and sinks, with information by source and sink at MLRA, State and regional levels. The report is structured mainly from a land use perspective, addressing livestock operations, croplands, and forests separately; but, it also includes a chapter on energy use. The livestock chapter inventories GHG emissions from livestock and livestock waste from confined livestock operations as well as pasture and range operations. The cropland agriculture chapter addresses emissions from cropland soil amendments, rice production, and residue burning, as well as carbon sequestration in agricultural soils. The forest chapter details carbon sequestration in forest biomass and soils, urban trees, and wood products. Fluxes of CH_4 and N_2O in forestry are not addressed since little information is currently available to develop estimates for these sources for forests. Qualitatively, forest soils are net CH_4 sinks in the United States, and soil N_2O emissions are small because forests do not receive large N additions. The energy chapter provides information on CO_2 emissions from energy consumption on U.S. farms, covering GHG emissions from fuel use in livestock and



cropland agriculture. While the U.S. GHG Inventory provides estimates of GHG emissions from energy consumption in the production of fertilizer, this indirect source of agricultural GHG emissions is not covered in this report.

Chapters 2 through 5 present a summary of sources of GHG emissions and sinks in the land use or category of emissions covered by each chapter. A summary of GHG emissions at the national level is provided in each chapter, followed by more detailed descriptions of emissions by each source at national and sub-national scales where available. Methodologies used to estimate GHG emissions and quantify uncertainty are summarized. Changes from the previous edition of this inventory are indicated. Text describing the methods and uncertainty for some chapters is summarized from the U.S. GHG Inventory, with permission from the EPA.

1.6 Summary of Changes and Additions for the Fourth Edition of the Inventory

Compared to previous editions, more sophisticated methodologies were used in this report to estimate GHG fluxes from all the major categories. When adjustments are made to existing methodologies (e.g., using new data sources), recalculations are made for the entire time series of estimates to ensure consistency. In addition to updating GHG flux estimates for 1990-2008 (based on current methodologies), estimates for 2009-2013 are also included.

Major changes impacting livestock emissions involved revising animal population estimates or diet assumptions, refining the models used to calculate emissions, using updated activity data, applying animal-specific emissions factors, and accounting for sources previously neglected (see Chapter 2 for details). Methane conversion rates, digestible energy values for cattle, and feedlot diets were also updated. As a result of these changes, emissions from enteric fermentation increased by approximately 17 percent on average compared to the previous inventory (USDA 2011). The biggest changes for emissions from managed livestock also relate to updated livestock population data and refined methodologies. Consequently, emission estimates from manure management systems (see Chapter 2, Table 2-3 for full list of these systems) have increased by approximately 18 percent compared to the previous inventory. There were several changes in calculations of N_2O emissions from grazed soils which are generated primarily by DayCent model simulations.

The most important change was performing model simulations at National Resources Inventory (NRI) resolution (simulations were conducted at the county level for the previous inventory). In contrast to the previous edition which used model-generated estimates of N additions from grazing livestock waste, these were based on county-level animal population data to be consistent with activity data for emissions from enteric fermentation. Additional changes include using updated and refined model activity data, expanding the observational data sets used to quantify model uncertainty, and improving model algorithms to better represent the processes that control soil GHG fluxes. These changes resulted in an approximate 40-percent increase in grazed soil N_2O emissions. The biggest changes that impacted estimates of carbon dioxide fluxes for grazed lands also involved using annual survey data from the NRI and DayCent model improvements. These changes resulted in an average annual decrease in estimated soil C sequestration of approximately 69 percent compared to the previous inventory.

There were several changes in calculations of cropland emissions compared to the previous edition of the inventory, mainly relating to DayCent model simulations for soil N_2O and CO_2 emissions (see chapter 3 for details). The most important changes

were simulating more crops and using NRI for land cover information. In previous inventories, land cover was based on NASS statistics for areas of major crops (corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton) at the county level with region-specific assumptions regarding common cropping practices. In contrast, NRI data represent actual land use during any particular year. Another improvement relates to land area considered eligible to contribute to indirect N_2O from NO_3 leached or runoff from cropped fields. Instead of assuming that nitrate leaching and runoff can occur anywhere, a criterion was used to designate lands where nitrate is susceptible to be leached or runoff into waterways, as suggested by IPCC (2006). This is based on observations that in semi-arid and arid areas, nitrate can be leached below the rooting zone but does not enter waterways because water tables in dry areas are deep or non-existent. Other changes are related to improvements in the DayCent model and uncertainty estimation. These changes resulted in an increase in N_2O emissions of approximately 4 percent and a decline in estimated C sequestration in mineral soils of 14 percent, relative to the previous inventory.

The estimates of C storage in forests and wood products reflect a substantial number of incremental changes in methods and data between EPA (2010) and EPA (2015) in terms of net stock change since 1990 (see chapter 4 for details). New annual inventory data for most States and adjustments to the identification of land area classified as forests included in the inventories have affected stock totals and changes. In addition, major changes in carbon conversion factors as applied to live and standing dead trees as well as to down dead wood and litter pools affected estimates as each update was implemented. Overall, these changes decreased overall forest and wood product C stock estimates by 15 percent and C stock changes by 7 percent relative to the previous inventory.

Aggregating across all sources and sinks, net emissions are approximately a 30-percent smaller sink than reported in the previous inventory. Although some of the changes compared to the previous inventory may appear to be large, they are within the calculated uncertainty ranges. Because of the relatively large uncertainty associated with GHG fluxes for agricultural and forestry production systems, it is difficult to predict the magnitude of changes that will be reported in subsequent inventories. However, both the observational measurements that are used to test and constrain the methods and models used, and the estimates derived from the methods and models, should improve as more extensive observational data sets become available. Similarly, availability of more refined model input data sets should improve the estimates reported in future editions of this volume. The individual chapters provide details regarding expected improvements.

SUGGESTED CITATION

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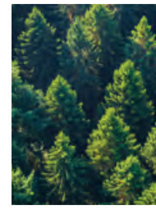

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Chapter 2

Download data: http://dx.doi.org/10.15482/USDA.ADC/1264149

Livestock and Grazed Land Emissions

2.1 Summary of U.S. Greenhouse Gas Emissions From Livestock

A total of 342 MMT CO_2 eq. of greenhouse gases (GHGs) were emitted from livestock, managed livestock waste, and grazed land in 2013 (Table 2-1, Figure 2-1). This represents about 66 percent of total emissions from the agricultural sector, which totaled 516 MMT CO_2 eq. (EPA 2015). Compared to the baseline year (1990), emissions from livestock sources were about 18 percent higher in 2013. There are three main reasons for this increase: methane (CH_4) emissions from managed livestock waste increased, nitrous oxide (N_2O) emissions from grazed lands increased, and the CO_2 sink strength of grazed lands decreased. The 95 percent confidence interval for 2013 was estimated to lie between 293 and 407 MMT CO_2 eq. (Table 2-1).

Table 2-1 Greenhouse Gas Emission Estimates and Uncertainty Intervals in 2013

Source	Estimate	Lower Bound	Upper Bound
		MMT CO_2 eq.	
CH_4 enteric fermentation	165	146	194
CH_4 managed waste + grazed land	61	50	74
N_2O managed waste	17	15	21
N_2O grazed land	96	72	138
CO_2 grazed land remaining grazed land	12	(24)	48
CO_2 land converted to grazed land	(9)	(18)	1
Total	**342**	**293**	**407**

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent.

Enteric fermentation contributed to a little less than half (165 MMT CO_2 eq.) of all emissions associated with livestock production, while soils from grazed lands (102 MMT CO_2 eq.) and managed waste (76 MMT CO_2 eq.) accounted for approximately 30 and 22 percent, respectively, of the total livestock emissions. All of the emissions from enteric fermentation and about 77 percent of emissions from managed livestock waste were in the form of CH_4. Of the emissions from grazed lands, 94 percent were in the form of N_2O from soils (Table 2-2). Soils in grazed lands do not often experience the anaerobic conditions required for CH_4 production to exceed CH_4 uptake. However, a small portion of manure from grazing animals is converted to CH_4 during the short period of time when paddies are drying. Although lands converted to grazing are estimated to be a C sink, this is balanced by long-term grazed lands being a C source in aggregate. Soils in grazed lands are estimated to be roughly CO_2 neutral, emitting an estimated net 3.3 MMT CO_2 eq. in 2013 (Table 2-2). Note that C storage in biomass is not accounted and the uncertainty ranges for both grazed land remaining grazed land and land converted to grazed land have lower bounds indicating sequestration and upper bounds indicating emissions (Table 2-1). Carbon (C) storage in grassland biomass is not accounted because biomass in these systems overturns quickly relative to soil C and does not contribute much to long term sequestration.

The largest total emissions associated with livestock production were from Texas and California (Map 2-1). Emissions were high in Texas primarily because of the large numbers of beef cattle, while dairy cattle emissions are responsible for most emissions in California. Emissions were also relatively high in Idaho, Montana, South Dakota, Nebraska, Colorado, Kansas, Oklahoma, Wisconsin, Iowa, and Missouri.

Beef cattle contributed the largest fraction (63 percent) of GHG emissions from livestock in 2013, with the majority of emissions in the form of CH_4

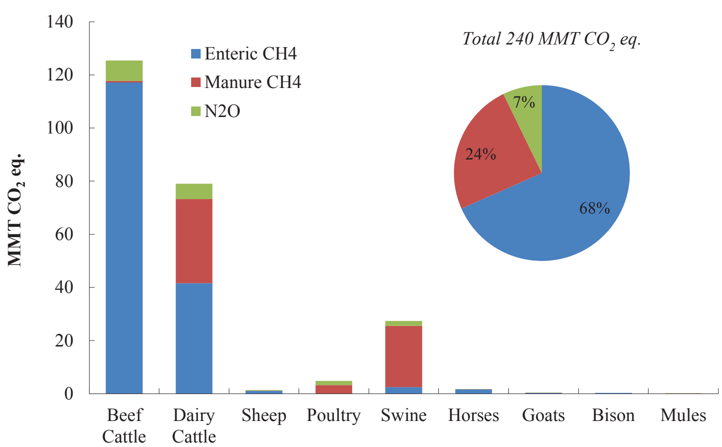
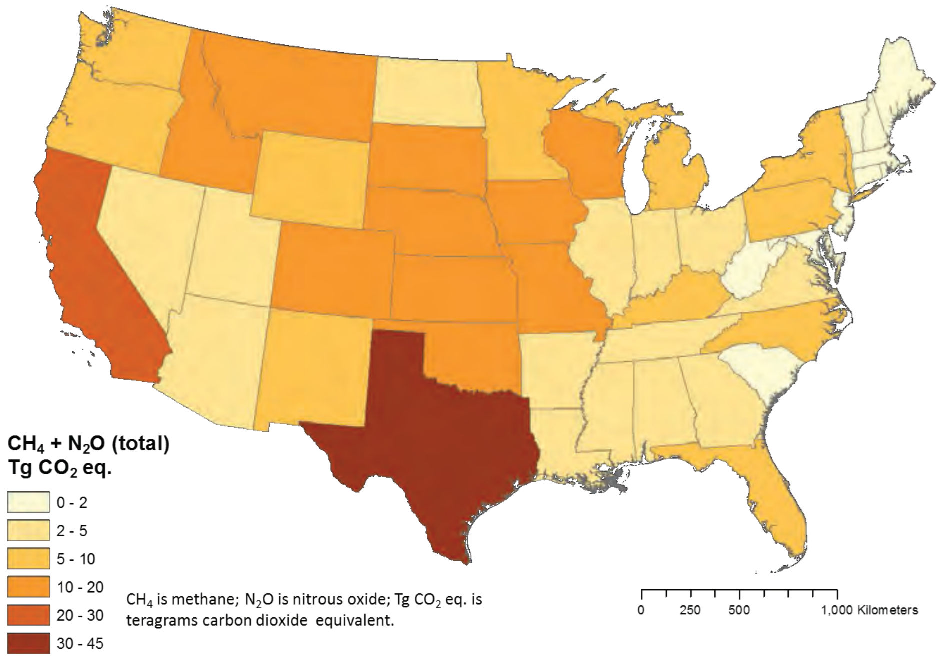


Figure 2-1 Greenhouse Gas Emissions from Livestock in 2013 *(CH_4 is methane; N_2O is nitrous oxide; CO_2 is carbon dioxide. MMT CO_2 eq. is million metric tons of carbon dioxide equivalent)*

Map 2-1 Greenhouse Gas Emissions from Livestock Production in 2013



from enteric fermentation and N_2O from grazed land soils (Figure 2-1, Table 2-2). Dairy cattle were the second-largest livestock source of GHG emissions (25 percent), primarily CH_4 from enteric fermentation and managed waste. The third-largest GHG source from livestock was swine (8 percent), nearly all of which was CH_4 from waste. Horses, mules, goats, sheep, and bison caused relatively small GHG emissions when compared to other animal groups, because populations of these types are relatively small. Poultry have relatively low emissions despite comprising the largest livestock group, because this group does not produce enteric waste.

Livestock contribute GHGs to the atmosphere both directly and indirectly. Livestock emit CH_4 directly as a byproduct of digestion through a process called enteric fermentation. In addition, livestock manure and urine (waste) cause CH_4 and N_2O emissions to the atmosphere through increased decomposition and nitrification/denitrification. Managed waste that is collected and stored emits CH_4 and N_2O throughout its lifecycle.

Table 2-2 Greenhouse Gas Emissions by Livestock Category and Source in 2013

	Enteric Fermentation	Managed Livestock Waste		Grazed Land			**Total**
	CH_4	CH_4	N_2O	N_2O[1]	CH_4	CO_2	
Animal Type			*MMT CO_2 eq.*				
Beef Cattle	117.10	0.62	7.65	85.16	2.38	2.95	**215.87**
Dairy Cattle	41.59	31.66	5.74	5.06	0.11	0.18	**84.34**
Swine	2.47	23.05	1.89	0.24	0.01	0.01	**27.66**
Horses	1.59	0.02	0.12	3.44	0.21	0.12	**5.49**
Poultry	NA	3.22	1.58	0.17	0.01	0.01	**4.98**
Sheep	1.07	0.03	0.31	0.80	0.04	0.03	**2.28**
Goats	0.31	0.00	0.02	0.64	0.02	0.02	**1.02**
American Bison	0.32	NA	NA	0.32	0.01	0.01	**0.66**
Mules and Asses	0.07	0.00	0.00	0.10	0.01	0.00	**0.19**
Total	**164.53**	**58.61**	**17.3**	**95.93**	**2.78**	**3.33**	342.49

Note: Methane emissions from manure deposited on grasslands is not partitioned by animal type. MMT CO_2 eq. is million metric tons carbon dioxide equivalent. CH_4 is methane; N_2O is nitrous oxide; CO_2 is carbon dioxide.
[1]Includes direct and indirect emissions.

Grazing animals influence soil processes (e.g., nitrification/denitrification) that result in N_2O emissions from the nitrogen (N) in their waste. Forage legumes on grazed lands also contribute to N_2O emissions because when legumes fix N from the atmosphere, that N can become mineralized in the soil and contribute to nitrification and denitrification. Grazed lands can also act as a source or sink for atmospheric carbon dioxide (CO_2), depending on whether C inputs to the soil—from plant residues and manure—exceed C losses from decomposition of soil organic matter. Soils that have been historically cropped using conventional tillage are often depleted of C because tillage disturbs soil aggregates and warms soil, which increases decomposition rates. Carbon-depleted soils can act as CO_2 sinks when converted to grazing land, because grazed soils are typically not plowed. Factors such as grazing intensity and weather patterns also influence net CO_2 fluxes, so a particular parcel of grazed land may be a net source or sink of C during any given year.

This chapter provides national and State-level data on CH_4 emissions from enteric fermentation, CH_4 and N_2O emissions from managed livestock waste, and CO_2, N_2O, and CH_4 fluxes for grazed lands. Emissions associated with waste applied to grazed land are included in this chapter, while N_2O

emissions from managed livestock waste applied to cropped soils are included in the Cropland Agriculture chapter (Chapter 3). State-level livestock population data also are presented in this chapter because GHG emissions from livestock are related to livestock population sizes.

2.2 Sources of Greenhouse Gas Emissions From Livestock

The mechanisms and important factors that generate GHG fluxes from livestock, waste management, and grazed lands are detailed below.

2.2.1 Enteric Fermentation

Enteric fermentation is a normal digestive process in animals where anaerobic microbial populations in the digestive tract ferment food and produce CH_4 gas as a byproduct. Methane is then emitted from the animal to the atmosphere through exhaling or eructation. Ruminant livestock—including cattle, sheep, and goats—have greater rates of enteric fermentation because of their unique digestive system, which includes a large rumen or fore-stomach where enteric fermentation takes place. Non-ruminant livestock such as swine, horses, and mules produce less CH_4 because enteric fermentation takes place in the large intestine, which has a smaller capacity to produce CH_4 than the rumen. The energy content and quantity of animal feed also affect the amount of CH_4 produced in enteric fermentation, with lower quality and higher quantities of feed causing greater emissions. Low quality feeds, such as dormant grasses and crop residues, are relatively low in protein and high in fiber which reduces digestibility and enhances CH_4 production.

2.2.2 Managed Livestock Waste

Livestock waste can be managed in storage and treatment systems or spread on fields in lieu of long-term storage. Alternatively, livestock waste is termed unmanaged when it is deposited directly on grazed lands and not transported. Many livestock producers in the United States manage livestock waste in systems such as solid storage, dry lots, liquid/slurry storage, deep pit storage, and anaerobic lagoons. Table 2-3 (adapted from EPA 2015) provides descriptions of managed and unmanaged pathways for livestock waste, indicating the relative impacts of different pathways on GHG emissions. Sometimes livestock waste that is stored and treated is subsequently applied as a nutrient amendment to agricultural soils. Greenhouse gas emissions from treated waste applied to cropped soils as a nutrient amendment are discussed in the next chapter along with GHG emissions from other nutrient amendments for crop production.

The magnitude of CH_4 and N_2O emissions from managed livestock waste depends in large part on storage system and environmental conditions. Methane is emitted under anaerobic conditions, when oxygen is not available to the bacteria that decompose waste. Storage in ponds, tanks, or pits such as those that are coupled with liquid/slurry flushing systems often promote anaerobic conditions (i.e., where oxygen is not available and CH_4 is produced), whereas solid waste stored in stacks or shallow dry pits tends to provide aerobic conditions (i.e., where oxygen is available and little or no CH_4 is produced). However, moist conditions (which are a function of rainfall and humidity) can promote CH_4 production in non-liquid-based manure systems. High temperatures generally accelerate the rate of decomposition of organic compounds in waste, increasing CH_4 emissions under anaerobic conditions. In addition, longer residency time in a storage system can increase CH_4 production, and added moisture, particularly in solid storage systems that normally experience aerobic conditions, can amplify CH_4 emissions.

While storage system and environmental conditions are important factors affecting CH_4 emissions from the management of livestock waste, diet and feed characteristics are also influential. Livestock feed refers to the mixture of grains, hay, and byproducts from processed foods that is fed to animals at feedlots and as supplemental feed for grazing animals, while diet includes the mixture of plants that animals graze. Livestock feed, diet, and growth rates affect both the amount and quality of manure. Not only do greater amounts of manure lead to higher CH_4 production, but higher energy feed also produces manure with more volatile solids, increasing the substrate from which CH_4 is produced. However, this impact is somewhat offset because some higher energy feeds are more digestible than lower quality forages, and thus less waste is excreted.

The production of N_2O from managed livestock waste depends on the composition of the waste, the type of bacteria involved, and the conditions following excretion. For N_2O emissions to occur, the waste must first be handled aerobically where ammonia (NH_3) or organic N is converted to nitrates (NO_3) and nitrites (NO_2) (nitrification), and if conditions become sufficiently anaerobic, NO_3 and NO_2 can be denitrified, i.e., reduced to nitrogen oxides and nitrogen gas (N_2) (Groffman et al. 2000; Archibeque et al. 2012). Nitrous oxide is produced

Table 2-3 Descriptions of Livestock Waste Deposition and Storage Pathways

Manure Management System	Description
Pasture/Range/Paddock	Manure and urine from pasture and range grazing animals are deposited directly onto the soil (unmanaged).
Daily Spread	Manure and urine are routinely collected and spread on fields within 24 hours of excretion; there is little or no storage of the manure/urine before it is applied to soils. Nitrous oxide emissions are assumed to be zero during the transport/storage phase but not after the waste has been applied to soils.
Solid Storage	Manure and urine (with or without litter) are collected by some means and placed under long-term bulk storage.
Dry Lot	Manure and urine are deposited directly onto a paved or unpaved open containment area where the manure is allowed to dry and it is periodically removed (after removal, it is sometime spread onto fields).
Liquid/Slurry	Manure is stored as excreted or with some minimal addition of water to facilitate handling and is stored in either tanks or earthen ponds, usually for periods less than 1 year.
Anaerobic Lagoon	Uncovered anaerobic lagoons are designed and operated to combine waste stabilization and storage. Lagoon supernatant is usually used to remove manure from the associated confinement facilities to the lagoon. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors, and must be cleaned out every 5-15 years.
Anaerobic Digester	Animal excrement with or without straw is collected and anaerobically digested in a large containment vessel (complete mix or plug flow digester) or covered lagoon. Digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CO_2 and CH_4, which are captured and flared or used as a fuel.
Deep Pit	Combined storage of manure and urine in pits (up to one year) below livestock confinements. Little to no water added to manure.
Poultry With Litter	Enclosed poultry houses use bedding derived from wood shavings, chopped straw, or other products depending on availability. The bedding absorbs moisture and dilutes manure. Litter is cleaned out once a year. This system is used for breeder flocks and meat chickens (broilers) and other fowl.
Poultry Without Litter	In high-rise cages or scrape-out/belt systems, manure is excreted onto the floor below with no bedding to absorb moisture. The ventilation system dries the manure as it is stored. This high rise system is a form of passive windrow composting.

Adapted from IPCC 2006.

as an intermediate product of both nitrification and denitrification and can be directly emitted from soil as a result of both of these processes. These emissions are most likely to occur in dry-waste handling systems that have aerobic conditions but that also contain pockets of anaerobic conditions due to high water content and high oxygen gas (O_2) demand from decomposition. For example, waste in dry lots is deposited on soil, oxidized to NO_2 and NO_3, and encounters anaerobic conditions following precipitation events that increase water content, enhance decomposition, and deplete the supply of O_2.

Managed livestock waste can also contribute to indirect N_2O emissions. Indirect emissions result from N that was volatilized or leached/runoff from the manure management system in a form other than N_2O, and was then converted to N_2O offsite. These sources of indirect N_2O emission from animal waste are from NH_3 volatilization and NO_3 runoff into ground or surface waters. The gaseous losses of NH_3 to the atmosphere can then be deposited to the soil and converted to N_2O by nitrification. The NO_3 runoff into waterways can be converted to N_2O by aquatic denitrification. Note that in addition to

NH_3 losses, nitrogen oxides (NO_x) can contribute to volatilization but because there are no quantified estimates available, losses due to volatilization are based solely on NH_3 loss factors. Similarly, leached NO_3 can contribute to indirect N_2O, but because little is known about leaching from manure management systems, only emissions associated with runoff are calculated.

2.2.3 Grazed Lands

Nitrous oxide from soils is the primary GHG associated with grazed lands. Grazed lands contribute to N_2O emissions by adding N to soils from animal wastes, forage legumes, and fertilizer additions. Legumes fix atmospheric N_2 into forms that can be used by plants and by soil microbes. Nitrogen from manure, legumes, and fertilizers is cycled into the soil and can provide substrates for nitrification and denitrification. Nitrous oxide is a byproduct of this cycle; thus, more N added to soils yields more N_2O released to the atmosphere. A portion of the N cycled within the plant-animal-soil system volatilizes to the atmosphere in various gaseous forms and is eventually re-deposited onto the soils where it can contribute to indirect N_2O emissions. Some N in the form of NO_3 can leach into groundwater and surface runoff, undergo denitrification, and contribute to indirect N_2O emissions. In addition to N additions, weather, soil type, grazing intensity, and other factors influence emissions from grazed lands.

Manure deposited on grazed lands also produces CH_4 emissions. Methane emissions from this source are relatively small, less than 5 percent of total grazed land GHG emissions, because of the predominately aerobic conditions that exist on most pastures and ranges.

Grazed lands can be emission sources or net sinks for CO_2. Typically, cropland that has recently been converted to grazed land stores CO_2 from the atmosphere in the form of soil organic carbon. But after sufficient time, soil organic C reaches a steady state, given consistent weather patterns. Long-term soil C levels are sensitive to climate change, and soils that were previously sinks can revert to being sources of CO_2. Note that current methodology does not include CO_2 fluxes resulting from growing (or senescing) biomass nor CO_2 emissions from grassland fires.

2.3 U.S. Livestock Populations

Greenhouse gas emissions from livestock are related to population size. Livestock population data are collected annually by USDA's National Agricultural Statistics Service (NASS). Those data are an input into the GHG estimates from livestock in the U.S. GHG Inventory.

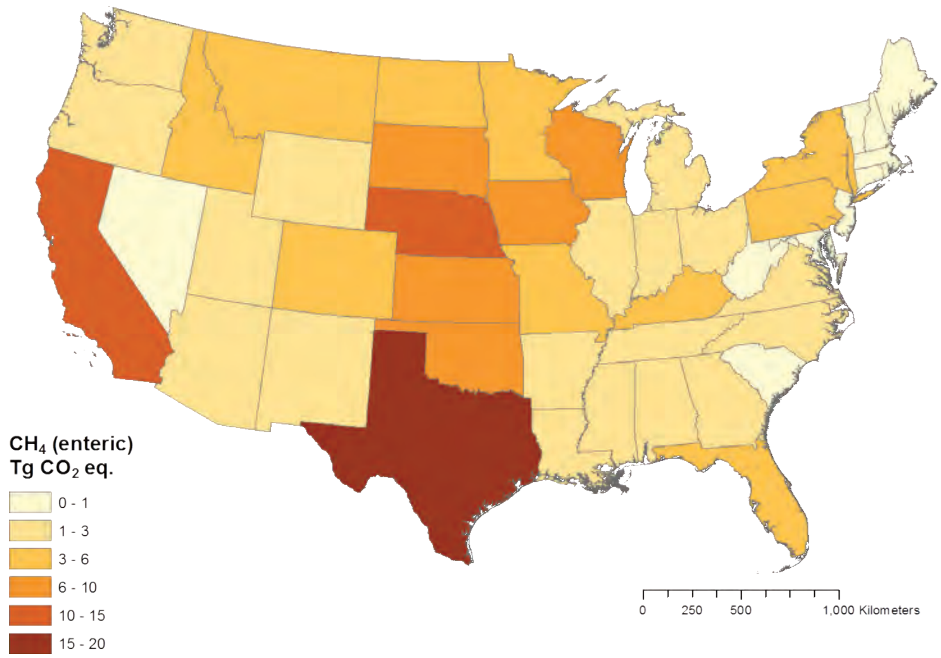
Beef and dairy cattle, swine, sheep, goats, poultry, and horses are raised throughout the United States. Detailed livestock population numbers for each State in 2013 are provided in Appendix Table A-1. Appendix Table A-2 shows total national livestock population sizes from 1990 to 2013 by livestock categories. Trends for beef cattle, dairy cattle, and swine are described in more detail below because of their relatively high population numbers and consequently high contributions to GHG emissions.

Texas raised by far the most beef cattle, at over 11 million head in 2013 (Appendix Table A-1). Kansas, Nebraska, and Oklahoma each raised from 4 to 7 million head of beef cattle, while several other States raised ~2 million head. Fewer dairy cattle than beef cattle are raised currently in the United States. Dairy cattle populations were highest in California and Wisconsin (3.4 million and 2.6 million, respectively) (Appendix Table A-1). New York, Idaho, Pennsylvania, and Minnesota had the next largest populations of dairy cattle, ranging from 982,000 to 1.2 million head in each State. Most States had fewer than 100,000 head of dairy cattle. Iowa was the largest swine producer, with 20 million head in 2013 (Appendix Table A-1). North Carolina housed the second-largest swine population at nearly 9 million head. Minnesota, Illinois, and Indiana also have sizeable swine populations.

2.4 Enteric Fermentation

Just less than half (48 percent) of emissions associated with livestock production were from CH_4 produced by enteric fermentation. Cattle were responsible for the majority of enteric CH_4 emissions (71 percent) in 2013 (Table 2-2). Texas (19.3 MMT CO_2 eq.) and California (11.3 MMT CO_2 eq.) had the largest CH_4 emissions from enteric fermentation for beef cattle and dairy cows in 2013 (Map 2-2, Appendix Table A-3). These emissions were largely tied to the sizable populations of cattle in both States. However, enteric fermentation emissions in Texas were mostly from beef cattle, whereas in California they were derived mostly from dairy cattle (Appendix Table A-3). State-level data for non-cattle

Map 2-2 Methane Emissions from Enteric Fermentation in 2013
(CH_4 is methane. Tg CO_2 eq. is teragrams of carbon dioxide equivalent)



livestock (i.e., swine, sheep, goats, mules, bison, and horses) were not generated due to the relatively low contributions of these animals to total enteric emissions. Central, Northern Plains, and some Great Lakes States also had relatively high CH_4 emissions from enteric fermentation, ranging between 3 and 10 MMT CO_2 eq. per State in 2013 (Appendix Table A-3). Emissions tended to be lower from some States in the northeast, southeast, and the desert southwest, mainly because cattle populations are low in these States.

Annual emissions of CH_4 from enteric fermentation fluctuated by approximately 14 MMT CO_2 eq. between 1990 and 2013 (Table 2-4). Emissions peaked in 1995, then decreased by about 10 MMT CO_2 eq. by 2005, then rose slightly by 2010. In recent years, CH_4 emissions from enteric fermentation have declined. Overall, by 2013, CH_4 emissions from enteric fermentation increased by over 0.2 percent compared to 1990 levels. Emissions increased slightly even though animal numbers of beef cattle (the major contributor) decreased (Appendix Table A-2) because the amount of feed consumed per animal increased. State-level emissions for 1990, 1995, 2000 and 2005-2013 are presented in Appendix Table A-4.

Table 2-4 U.S. Methane Emissions from Enteric Fermentation in 1990, 1995, 2000, 2005, 2010-2013

Animal Type	*MMT CO_2 eq.*							
	1990	1995	2000	2005	2010	2011	2012	2013
Beef Cattle	119.1	135.5	126.7	125.2	124.4	121.7	118.7	117.1
Dairy Cattle	39.4	37.5	38.0	37.6	40.7	41.1	41.7	41.6
Sheep	2.3	1.8	1.4	1.2	1.1	1.1	1.1	1.1
Horses	1.0	1.2	1.5	1.7	1.7	1.7	1.6	1.6
Swine	2.0	2.2	2.2	2.3	2.4	2.5	2.5	2.5
Goats	0.3	0.3	0.3	0.4	0.4	0.3	0.3	0.3
American Bison	0.1	0.2	0.4	0.4	0.4	0.3	0.3	0.3
Mules and Asses	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
Total	**164.2**	**178.7**	**170.6**	**168.9**	**171.1**	**168.7**	**166.3**	**164.5**

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent.

2.4.1 Methods for Estimating Methane Emissions From Enteric Fermentation

The official U.S. GHG Inventory estimates for enteric fermentation (as well as those for managed waste and grazed soils) are calculated according to the methodological framework provided by the Intergovernmental Panel on Climate Change (IPCC) for preparing national GHG inventories. The IPCC guidance is organized into a hierarchical, tiered analytical structure, in which higher tiers correspond to more complex and detailed methodologies. The methods detailed below correspond to both Tier 1 and Tier 2 approaches. With the permission of EPA, Annex 3.10 from the official U.S. GHG Inventory is summarized below. Methane emissions from enteric fermentation were estimated for seven livestock categories: cattle, horses, sheep, swine, goats, American bison, and mules. Emissions from cattle represent the majority of U.S. emissions; consequently, the more detailed IPCC Tier 2 methodology was used to estimate emissions from cattle and the IPCC Tier 1 methodology was used to estimate emissions from the other types of livestock.

2.4.1.1 Estimating Methane Emissions From Cattle

This section describes the process used to estimate enteric fermentation emissions of CH_4 from cattle on a regional basis. A Cattle Enteric Fermentation Model (CEFM) based on recommendations provided in IPCC (2006, 1997) was developed that uses information on population, energy requirements, digestible energy, and the fraction of energy converted to methane to estimate CH_4 emissions. The emission estimation methodology consists of the following three steps: (1) characterize the cattle population to account for cattle population categories with different emissions profiles; (2) characterize cattle diets to generate information needed to estimate emissions factors; and (3) estimate emissions using these data and the IPCC Tier 2 equations.

Step 1: Characterize U.S. Cattle Population

Calf birth rates, population statistics, feedlot placement information, and slaughter weight data were used to create a transition matrix that models cohorts of individual animal types and their specific emission profiles. This level of detail accounts for the variability in CH_4 emissions associated with each life stage. Given that the time in which cattle can be in a stage can be less than 1 year (e.g., beef calves are weaned at 4 to 6 months or later), the stages are modeled on a per-month basis. The type of cattle use also impacts CH_4 emissions (e.g., beef versus dairy). Consequently, cattle life stages were modeled for several categories of dairy and beef cattle. These categories are listed in Appendix Table A-5. The key variables tracked for each of these cattle population categories[1] includes calving rates, pregnancy and lactation (Appendix Table A-6), average weights and weight gains (Appendix Table A-7), feedlot placements (Appendix Table A-8), death rates, number of animals per category each month, and animal characteristics (i.e., age, gender, etc.) data.

Cattle population data were taken from USDA NASS (National Agricultural Statistics Service) (Appendix Table A-2). USDA NASS publishes monthly, annual, and multi-year livestock population and production estimates. Multi-year reports include revisions to earlier published data. Cattle and calf populations, feedlot placement statistics (e.g., number of animals placed in feedlots by weight class), slaughter numbers, beef calf birth percentages, and lactation data were obtained from NASS QuickStats database (USDA 2013a).

[1] Except bulls. Only end-of-year census population statistics and a national emission factor are used to estimate CH4 emissions from the bull population.

Step 2: Characterize U.S. Cattle Diets

Data were collected on diets considered representative of different regions to support development of digestible energy (DE), the percent of gross energy intake digestible to the animal, and CH_4 conversion rate (Y_m), the fraction of gross energy converted to CH_4, values for each of the cattle population categories. For both grazing animals and animals being fed mixed rations, representative regional diets were estimated using information collected from State livestock specialists and from USDA APHIS VS (USDA 2010). The data for each of the diets (e.g., proportions of different feed constituents, such as hay or grains) were used to determine chemical composition for use in estimating DE and Y_m for each animal type. Region- and cattle-type-specific estimates for DE and Y_m were developed for the United States (Appendix Tables A-9 and A-10). Regions in the enteric fermentation model are defined in Appendix Table A-11, A-12. Additional detail on the regional diet characterization is provided in EPA (2015).

Step 3: Estimate Methane Emissions From Cattle

Emissions were estimated in three steps: (a) determine gross energy intake using the IPCC (2006) Tier 2 equations, (b) determine an emissions factor using the gross energy values and other factors, and (c) sum the daily emissions for each animal type. The necessary data values include:

- Body weight (kg)
- Weight gain (kg/day)
- Net energy for activity (Mj/day)
- Standard reference weight (dairy = 1,324 lbs; beef = 1,195 lbs)
- Milk production (kg/day)
- Milk fat (% of fat in milk = 4)
- Pregnancy (% of population that is pregnant)
- DE (% of gross energy intake digestible)
- Y_m (the fraction of gross energy converted to CH_4)
- Population

This process was repeated for each month, and the totals for each subcategory were summed to achieve an emissions estimate for the entire year. The estimates for each of the 12 subcategories of cattle are listed in Appendix Table A-13. The CH_4 emissions for each subcategory were then summed to estimate total emissions from beef cattle and dairy cattle for the entire year. The cattle emissions calculation model estimates emissions on a regional scale. Individual State-level estimates were developed from these regional estimates using the proportion of each cattle population subcategory in the State relative to the population in the region.

2.4.1.2 Emission Estimates From Other Livestock

Emissions other (non-cattle) livestock used the default Tier 1 emission factor recommended by IPCC (2006). Other livestock population data (sheep, goats, swine, horses, mules, poultry, and American bison) were taken from USDA NASS (2014) or earlier census data. Appendix Table A-2 shows the population data for all livestock that were used for estimating all livestock-related emissions. For each animal category, the USDA publishes monthly, annual, and multi-year livestock population and production estimates. Multi-year reports include revisions to earlier published data. Recent reports were obtained from the USDA Economics and Statistics System, while historical data were downloaded from USDA NASS. National-level emission calculations for other livestock were developed from national population totals. Appendix Table A-14 shows the emission factors used for these other livestock types.

2.4.2 Uncertainty in Estimating Methane Emissions From Enteric Fermentation

The following discussion of uncertainty in the enteric fermentation estimates is from the U.S. GHG Inventory (EPA 2015) and reproduced here with permission from EPA.

Uncertainty is estimated using an IPCC-recommended Tier 2 method based on the Monte Carlo Stochastic Simulation technique. Emission factors and animal population data are the primary sources of uncertainty in estimating CH_4 emissions from enteric fermentation. A total of 185 input variables were identified as key input variables for uncertainty analysis (e.g., estimates of births by month, weight gain of animals by age class, and placement of animals into feedlots based on placement statistics and slaughter weight data). The uncertainty associated with these input variables is ±10 percent or lower. However, the uncertainty for many of the emission factors is over ± 20 percent. The overall 95-percent confidence interval around the estimate of 165 MMT CO_2 eq. ranges from 146 to 194 MMT CO_2 eq. (Table 2-1).

2.4.3 Changes Compared to the 3rd edition of the USDA GHG Report

There were several modifications made to the emissions estimates for this edition of the USDA GHG report relative to the previous inventory (USDA 2011). Most of the changes involved revising estimates of animal populations, average weights, and diet assumptions, or refining the models used to calculate emissions. American bison, which were previously excluded, are now included in the inventory. Enteric fermentation emissions from bull populations are now calculated with a Tier 2, instead of Tier 1, methodology. As a result of the changes outlined above, the amount of emissions estimated for enteric fermentation increased by approximately 17 percent on average compared to the previous inventory (USDA 2011).

2.5 Managed Livestock Waste

Greenhouse gas emissions from managed livestock waste are composed of CH_4 and N_2O from livestock waste storage, transport, and treatment and CH_4 emissions from the daily spread of livestock waste. Emissions from these sources are discussed below, with estimates disaggregated spatially and by livestock category where possible. Methane was the predominant GHG emitted from managed livestock waste in 2013, accounting for 78 percent of 78 MMT CO_2 eq. total emissions from this source (Table 2-5). The remaining 22 percent of GHG emissions from managed livestock waste was N_2O. Dairy cattle and swine were responsible for 37 and 25 percent of total managed waste emissions, respectively (Figure 2-2). Poultry (5 percent) and beef cattle (8 percent) were also important sources in 2013. For beef cattle, N_2O was the predominate form (93 percent) of waste emissions. Over time, emissions from managed waste increased by 14 percent from 1990 to 2013 (Figure 2-3). Most of the increase was from higher CH_4 emissions due to the trend of storing more waste in liquid systems and anaerobic lagoons which facilitate CH_4 production.

While beef cattle contribute the largest overall emissions from all livestock (Table 2-2, Figure 2-1), emissions from beef-cattle managed waste are relatively small (Figure 2-2) because most waste generated by beef cattle is unmanaged. Emissions from beef-cattle managed manure changed little between 1990 and 2013. Managed manure emissions from horses, sheep, and goats are small due to the relatively small population of these animals (Appendix Table A-2), and most of the manure

Table 2-5 Greenhouse Gas Emissions from Managed Livestock Waste in 1990, 1995, 2000, 2005, 2010-2013

GHG Type	1990	1995	2000	2005	2010	2011	2012	2013
	MMT CO_2 eq.							
Nitrous Oxide[1]	13.8	15.0	16.3	16.4	17.1	17.3	17.3	17.3
Methane[2]	37.2	43.3	50.0	56.3	60.9	61.4	63.7	61.4
Total	**51.0**	**58.2**	**66.4**	**72.8**	**78.0**	**78.7**	**81.0**	**78.7**

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent.

[1] Does not include emissions from managed manure applied to cropped soils.

[2] Includes CH_4 from managed sources and from grazed grasslands. Manure deposited on grasslands produces little CH_4 due to predominantly aerobic conditions.

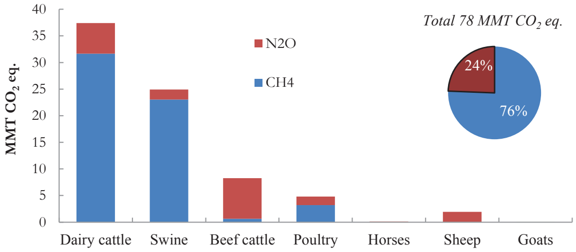


Figure 2-2 Greenhouse Gas Emissions from Managed Livestock Waste by Livestock Type in 2013
(CH_4 is methane; N_2O is nitrous oxide; CO_2 is carbon dioxide. MMT CO_2 eq. is million metric tons of carbon dioxide equivalent)

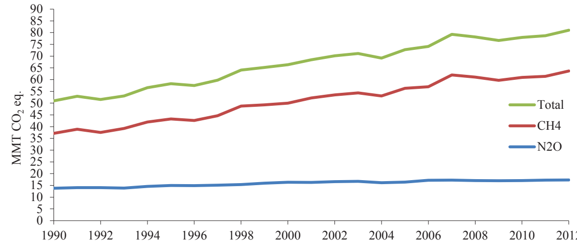


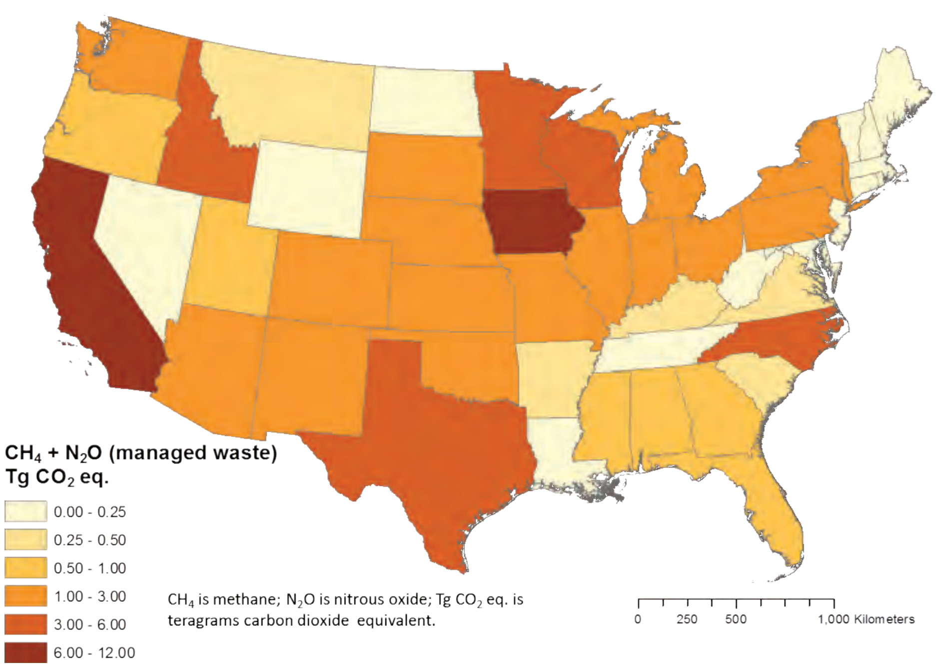
Figure 2-3 Greenhouse Gas Emissions from Managed Livestock Waste, 1990-2013
(CH_4 is methane; N_2O is nitrous oxide; CO_2 is carbon dioxide. MMT CO_2 eq. is million metric tons of carbon dioxide equivalent)

is unmanaged or managed in dry systems (EPA 2015). State-level GHG emissions from managed livestock waste varied across States in 2013, with a small number of States responsible for the larger contributions to national GHG emissions. California and Iowa had the largest GHG emissions from managed livestock waste, 11.7 and 10.5 MMT CO_2 eq., respectively (Appendix Table A-15). In California, emissions were primarily from dairy cattle. In Iowa most emissions were from swine (Appendix Table A-16, A-17).

2.5.1 Methods for Estimating Methane and Nitrous Oxide Emissions From Managed Livestock Waste

This section summarizes how CH_4 and N_2O emissions from livestock waste were calculated in the U.S. GHG Inventory (EPA 2015) as well as for this inventory report. Animal population data were used to estimate CH_4 production potential and N in waste, and these were multiplied by a methane conversion factor (MCF) and direct and indirect N_2O emission factors. Methane conversion factors are used to determine the amount of CH_4 emissions that are potentially produced by each unit of livestock waste. Methane conversion factors vary by livestock type, manure storage system, and the waste storage temperature. The IPCC (2006) default direct N_2O emission factor was used, while indirect N_2O emission factors varied by region and waste management system. The EPA provides the USDA with State and national estimates of GHG emissions from managed livestock waste. The estimates of GHG emissions from managed livestock waste were prepared following a methodology developed by EPA, consistent with international guidance, and are described in detail in Annex 3.11 of the U.S. GHG Inventory (EPA 2015).

Map 2-3 Greenhouse Gas Emissions from Managed Livestock Waste in 2013



Data required to calculate CH_4 emissions from livestock waste:

- Animal population data (by animal type and State);
- Typical Animal Mass (TAM) data (by animal type);
- Portion of manure managed in each Waste Management System (WMS), by State and animal type;
- Volatile solids (VS) production rate (by animal type and State or national);
- CH_4 producing potential (Bo) of the volatile solids (by animal type);
- Methane Conversion Factors (MCF), the extent to which the CH_4 producing potential is realized for each type of WMS (by State and manure management system, including the impacts of any biogas collection efforts).

Eight livestock types are considered for this particular emissions category: dairy cattle, beef cattle, swine, sheep, goats, poultry, horses, and mules/asses. For swine and dairy cattle, manure management system usage is determined for different farm-size categories using data from the USDA (Ott 2000; USDA 1996a, 1998, 2009) and EPA (EPA 2002a, 2002b, ERG 2000). For beef cattle and poultry, manure management system usage is not tied to farm size and is based on other sources (ERG 2000, UEP 1999, USDA 2000a). For other animal types, manure management system usage is based on previous estimates (EPA 1992).

Appendix Table A-18 presents a summary of the waste characteristics used in the emissions estimates. The method for calculating volatile solids production from beef and dairy cows, heifers, and steers is based on the relationship between animal diet and energy utilization, which is modeled in the enteric fermentation portion of the inventory. Volatile solids content of manure equals the fraction of the diet consumed by cattle that is not digested and thus excreted as fecal material which, when combined with urinary excretions, constitutes manure. Estimations of gross energy intake and digestible energy were used to calculate the indigestible energy per animal unit as gross energy minus digestible energy plus an additional 2 percent of gross energy for urinary energy excretion per animal unit. This was then converted to volatile solids production per animal unit using the typical conversion of dietary gross energy to dry organic matter of 20.1 MJ/kg (Garrett & Johnson 1983). Appendix Table A-19 shows volatile solid production rates by State and livestock category.

MCFs for liquid-slurry, anaerobic-lagoon, and deep-pit systems were calculated based on the forecast performance of biological systems relative to temperature changes. These calculations account for the following: average monthly ambient temperature, minimum system temperature, the carryover of volatile solids from month to month, and a factor to account for management and design practices that result in loss of volatile solids form lagoon systems. State-level MCFs for liquid-slurry, deep-pit, and anaerobic-lagoon systems are shown in Appendix Table A-20. Appendix Table A-21 has national-scale maximum methane-generation potential (B0) by animal type, and Appendix Table A-22 has methane conversion factors for dry waste management systems equal to the default IPCC (2006) factors for temperate climates. For each animal type, the base emission factors were weighted to incorporate the distribution of waste management systems within each State to get a State level weighted MCF (Appendix Table A-23).

Methane emissions were estimated by multiplying regional or national animal type-specific volatile solid production by the animal type-specific maximum CH_4 production capacity of the waste and the State-specific MCF.

The following inputs were used in the calculation of direct and indirect N_2O emissions:

- 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 N_2O emission factor (EFWMS);
- Indirect N_2O emission factor for volatilization (EFvolitalization);
- Indirect N_2O emission factor for runoff and leaching (EFrunoff/leach);
- Fraction of N loss from volatilization of NH_3 and nitrogen oxides (NO_x) (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, typical animal mass (TAM), WMS usage, and waste characteristics. Nitrous oxide emissions factors for all manure-management systems were set equal to the default IPCC (2006) factors for temperate climates (Appendix A-24). Nitrogen excretion rates for all cattle except for bull and calves were calculated for each State and animal type in the Cattle Enteric Fermentation Model (CEFM), which is described in section 6.1, Enteric Fermentation and in more detail in Annex 3.9, Methodology for Estimating CH_4 Emissions from Enteric Fermentation. Nitrogen excretion rates for all other animals were determined using data from USDA's Agricultural Waste Management Field Handbook (USDA 1996b, 2008; ERG 2010a, 2010b) and data from the American Society of Agricultural Engineers, Standard D384.1 (ASAE 2003). All N_2O emissions factors (direct and indirect) were taken from IPCC (IPCC 2006). Country-specific estimates were developed for the fraction of N loss from volatilization (Fracgas) and runoff and leaching (Fracrunoff/leach). Fracgas values were based on WMS-specific volatilization values as estimated from U.S. EPA's *National Emission Inventory - Ammonia Emissions from Animal Agriculture Operations* (EPA 2005). Fracrunoff/leaching values were based on regional cattle runoff data from EPA's Office of Water (EPA 2002b; see Table A-9 in Annex 3.1).

To estimate N_2O emissions, first, the amount of N excreted (kg per year) in manure in each WMS for each animal type, State, and year was calculated. The population (head) for each State and animal was multiplied by TAM (kg animal mass per head) divided by 1,000, the N excretion rate (Nex, in kg N per 1,000 kg animal mass per day), WMS distribution (percent), and the number of days per year.

Direct N_2O emissions were calculated by multiplying the amount of Nex (kg per year) in each WMS by the N_2O direct emission factor for that WMS (EFWMS, in kg N_2O-N per kg N, Appendix A-21) and the conversion factor of N_2O-N to N_2O. These emissions were summed over State, animal, and WMS to determine the total direct N_2O emissions (kg of N_2O per year).

Then, indirect N_2O emissions from volatilization (kg N_2O per year) were 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, and the emission factor for volatilization (EFvolatilization in kg N_2O per kg N), and the conversion factor of N_2O-N to N_2O. Next, indirect N_2O emissions from runoff and leaching (kg N_2O per year) were 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 N_2O per kg N), and the conversion factor of N_2O-N to N_2O. The indirect N_2O emissions from volatilization and runoff and leaching were summed to determine the total indirect N_2O emissions.

2.5.2 Uncertainty in Estimating Methane and Nitrous Oxide Emissions From Managed Livestock Waste

The following discussion of uncertainty in estimating GHG emissions from livestock waste is modified from information provided in the U.S. GHG Inventory (EPA 2015). The information is reproduced here with permission from EPA.

Uncertainty is estimated using an IPCC-recommended Tier 2 method developed by EPA (2003) based on the Monte Carlo Stochastic Simulation technique. A normal probability distribution was assumed for each source data category. The series of equations used were condensed into a single equation for each animal type and State. The results of the uncertainty analysis showed that the manure management CH_4 inventory has a 95-percent confidence interval from 50 to 74 MMT CO_2 eq. around the inventory value of 61 MMT CO_2 eq., and the manure management N_2O inventory has a 95-percent confidence interval from 15 to 21 MMT CO_2 eq. around the inventory value of 17 MMT CO_2 eq. (Table 2-1).

2.5.3 Changes Compared to the 3rd edition of the USDA GHG Report

In addition to updating livestock population data, the total VS and Nex estimates from the CEFM were used in the manure management calculations for cattle in the current inventory. An error in the crude protein calculation in the CEFM was corrected. The VS and Nex for other animal types were updated using data from USDA's updated Agricultural Waste Management Field Handbook (USDA 2010). For the current Inventory, USDA population data were used that included updated market swine categories. Data from the 2007 USDA Census of Agriculture were used to update goat populations and the WMS distributions for dairy and swine. Temperature data, which are used to estimate MCFs for liquid systems, were updated. Anaerobic digester data were updated using the AgSTAR database. In aggregate, these changes resulted in increased average emissions of 13 percent for CH_4 and 3 percent for N_2O.

2.6 Grazed Lands

Grazed-land soils emit N_2O due to enhanced N cycling as well as a relatively small amount of CH_4 emissions from manure deposits. Manure deposited on grazed land (i.e., unmanaged manure) produces little CH_4 due to predominant aerobic conditions. Nitrous oxide sources include direct and indirect emissions of N_2O associated with increased N from synthetic fertilizer and managed manure application, forage legumes cultivation, and unmanaged waste from grazing animals. Grazed lands can be either a source or a sink of CO_2, depending on the level of soil disturbance, soil type, previous land use, and grazing intensity. In general, grazed mineral soils that were previously cropped with annuals and then tilled sequester C upon conversion to perennial vegetation cover. However, drained organic soils (histosols) used for grazing are typically a CO_2 source because draining enhances decomposition of soil organic matter.

Table 2-6 Greenhouse Gas Emissions from Grazed Lands in 1990, 1995, 2000, 2005, 2010-2013

	1990	1995	2000	2005	2010	2011	2012	2013
GHG Type				*MMT CO_2 eq.*				
Nitrous Oxide[1]	**80.5**	**90.3**	**70.8**	**85.0**	**96.1**	**96.0**	**95.5**	**95.9**
Direct	73.7	83.4	64.8	78.1	89.2	89.1	88.5	89.0
Indirect Volatilization	4.2	4.3	4.0	4.5	4.5	4.5	4.5	4.4
Indirect Leaching & Runoff	2.7	2.6	2.0	2.4	2.5	2.5	2.5	2.5
Methane[2]	**2.7**	**2.9**	**2.7**	**2.7**	**2.6**	**2.6**	**2.5**	**2.8**
Carbon Dioxide	**(9.3)**	**0.3**	**(40.5)**	**(4.8)**	**2.8**	**2.8**	**2.7**	**3.3**
Grazed Lands Remaining Grazed	(1.9)	8.1	(30.1)	4.2	11.7	11.7	11.5	12.1
Land Converted to Grazed Land	(7.4)	(7.7)	(10.4)	(9.0)	(8.9)	(8.9)	(8.8)	(8.8)
Total	**73.9**	**93.6**	**33.0**	**82.9**	**101.5**	**101.4**	**100.7**	**102.0**

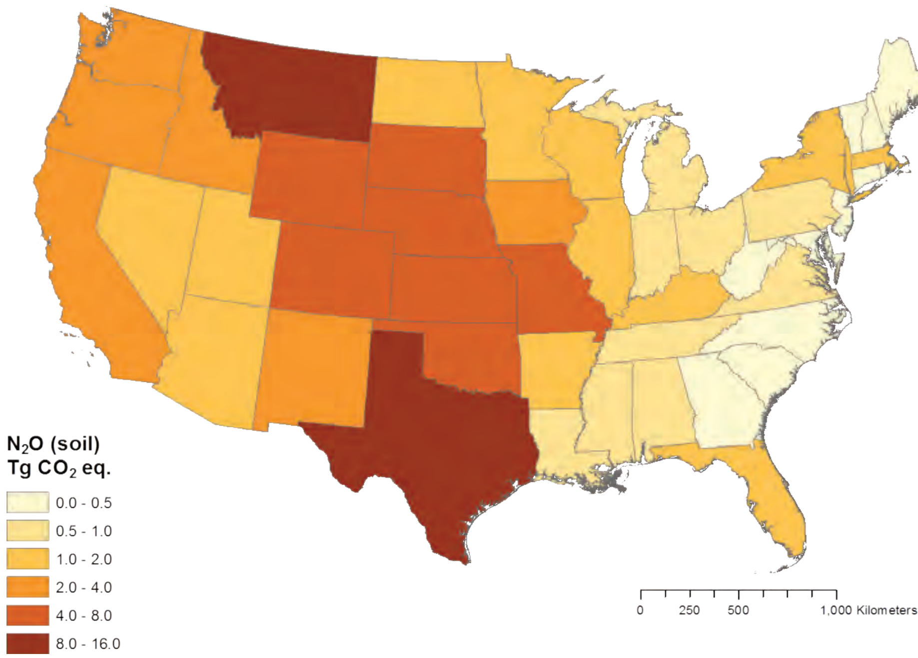
Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent.
[1] Does not include emissions from managed manure applied to cropped soils.

Nitrous oxide was the predominant GHG emitted from grazed land soils in 2013, accounting for 94 percent of all emissions from this source (Table 2-6). The remaining 6 percent of GHG emissions from grazed lands was divided roughly equally between CH_4 and CO_2. Grazed lands were sources of CO_2 in 2013, contributing 3 percent of emissions. Nitrous oxide emissions from grazed land totaled 10[2] MMT CO_2 eq. in 2013 (Table 2-6), including direct and indirect sources. Beef cattle are responsible for the highest proportion of direct N_2O emissions from grazed lands because the vast majority of grazed lands in the United States are used for beef production. Texas and Montana had the largest emissions from grazed lands due to the large amounts of rangeland in these States (Map-2-4). Emissions tended to be high in most Great Plains States, again due to large areas of rangeland. In aggregate, emissions from managed grazed land were greater than those of managed manure in 2013 and for most years since 1990, when national emissions from this source were first estimated (Tables 2-5, 2-6). This is due to large numbers of beef cattle on grazing land (about 80 percent of all cattle) compared to feedlots, which are a source of managed waste. In addition to Map 2-4, direct and indirect N_2O emisisons for non-Federal are reported in Gg CO_2 eq.'s at the more resolved Major Land Resource Area (MLRA) level in Appendix Table A-25. Similarly, MLRA level soil C stock changes for non-Federal grasslands are reported in Appendix Table A-26.

2.6.1 Methods for Estimating Nitrous Oxide Emissions From Grazed Lands

Estimates of N_2O emissions from this component were based on DayCent model simulations of non-Federal grazed lands (IPCC Tier 3 approach), estimates of animal waste production and application on to grazed lands (Appendix Table A-27), estimates of synthetic N fertilizer applied to grazed lands, and IPCC (2006) methodology for emissions from Federal grazed lands, grazed organic soils, and sewage sludge N additions (EPA 2015). Both managed manure applications and unmanaged manure are considered here. Managed manure is defined as manure that was transported and temporarily stored in a management system before soil application. Unmanaged manure remains on soils after being deposited by grazing animals in pastures, rangelands, and paddocks. The livestock included in this component were dairy cattle, beef cattle, swine, sheep, goats, poultry, and horses.

Map 2-4 Nitrous Oxide Emissions from Grazed Soils in 2013
(N_2O is nitrous oxide. Tg CO_2 eq. is teragrams of carbon dioxide equivalent)



The DayCent ecosystem model simulated non-Federal pastures and rangelands at National Resources Inventory (NRI) survey (USDA 2013b) resolution. The NRI is a statistically based sample of all non-Federal land, and includes over 500,000 points in agricultural land for the conterminous United States and Hawaii (note that not all of these points were simulated using the Tier 3 method). Data have been reported every 5 years starting in 1982, with 2007 being the most recent year. Each point is associated with an "expansion factor" that allows scaling of N_2O emissions from NRI points to the entire country (i.e., each expansion factor represents the amount of area with similar land-use/management history as the sample point). Land-use and some management information (e.g., vegetation type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. However, the NRI program began collecting annual data in 1998, and data are currently available through 2007. For subsequent years (2008-2013), raw model outputs for 2007 were repeated, but emissions were not identical because some expansion factors changed.

Pastures are defined as grazing lands that are relatively intensively managed and may have been seeded with legumes and/or amended with organic N (e.g., managed manure) or synthetic fertilizer N and/or irrigated. Rangelands are typically extensive areas of native grasslands that are not intensively managed. Grazing intensity on pastures was assumed to be moderate to heavy while intensity on rangelands was assumed to be light to moderate. Key model inputs are daily weather, soil texture class, vegetation mix, animal waste N inputs, and grazing intensity. The model simulates soil water and temperature flows, plant growth and senescence, decomposition of dead plant material and soil organic matter, mineralization of nutrients, and trace gas fluxes. Nitrous oxide emissions, NO_3 leaching and N (NO_x, NH_3) volatilization were simulated on a per unit area basis, and multiplied by the estimated expansion factor for each NRI point. Outputs for each NRI point were then aggregated to the State and national levels. The DayCent simulations are described in more detail in Chapter 3 of this report and in EPA (2015) and Del Grosso et al. (2010).

Manure N deposition from grazing animals (i.e., PRP manure) on non-Federal grasslands was an input to the DayCent model (see Annex 3.12 EPA 2015), and included approximately 92 percent of total PRP manure. The remainder of the PRP manure N excretions in each county was assumed to be excreted on Federal grasslands, and the N_2O emissions were estimated using the IPCC (2006) Tier 1 method with IPCC default emission factors. Waste N deposited on grazed lands not accounted for by the DayCent simulations and sewage sludge N additions were multiplied by the default IPCC (2006) emission factor of 0.02 kg N_20-N/kg N to estimate direct N_2O-N emissions, as opposed to the 0.01 kg N_2O-N/kg N used to estimate N additions from

managed soils (including mineral fertilizers, organic amendments, crop residues, and N mineralization from soil C losses). Data available at the time the IPCC (2006) guidelines were developed suggested that the default emission factor should be greater for waste N deposited by grazing animals compared to other N sources, but more recent observations suggest that this factor should be close to the 0.01 kg N_2O-N/kg N factor use for the other sources (van der Weerden 2011).

The amounts of PRP manure N applied on non-Federal grasslands in each NRI point were based on the proportion of non-Federal grassland area compared to total grassland area according to data from the NRI (USDA 2009, relative to the area of Federal grasslands from the U.S. Geological Survey (USGS) National Land Cover Dataset (Forest Inventory and Analysis Data, <http://fia.fs.us/tools-data/data>). Managed manure N amendments to grasslands were estimated from Edmonds et al. (2003) and adjusted for annual variation using data on the availability of managed manure N for application to soils. All managed manure applied to grasslands was assumed to be applied to non-Federal grasslands. Sewage sludge was assumed to be applied on grasslands instead of cropped land because of the heavy metal content and other pollutants in human waste that limit its use as an amendment to croplands. Sewage sludge application was estimated from data compiled by EPA (1993), NEBRA (2007), and AAPFCO (1995-2014).

Indirect N_2O emissions due to volatilization of applied N and indirect N_2O emissions due to leaching were calculated using DayCent and IPCC (2006) estimates of volatilization and NO_3 leaching and IPCC estimates of the portion of volatilized or leached/runoff N that is converted to N_2O. Nitrogen volatilized, leached, or runoff N are all outputs for the grazed lands simulated by DayCent. For animal waste not accounted for by the DayCent simulations, 10 percent of animal waste N was assumed to volatilize and 30 percent of animal waste N was assumed to be leached or runoff. The total volatilized N was multiplied by the IPCC default emission factor of 0.01 kg N_20- N/kg N (IPCC 2006). The total N leached or runoff was multiplied by the IPCC (2006) default emission factor of 0.0075 kg N_20-N/kg N.

Total grazed land N_2O emissions were partitioned among different animal types by assuming that emissions are linearly proportional to waste N production.

2.6.2 Uncertainty in Nitrous Oxide Emissions From Grazed Lands

Uncertainty due to model inputs and model structure were quantified. Model inputs used to represent N inputs from livestock waste and synthetic fertilizer are not known precisely, and each of these has an associated range of uncertainty represented by a probability density function. Model structural uncertainty refers to the errors inherent in the model. That is, the model is not expected to yield perfect results even if model inputs were precisely known. To address uncertainty in model inputs, a series of 100 Monte Carlo simulations were performed for each NRI point. To address model structural uncertainty, DayCent-simulated N_2O emissions were compared with measured emissions from over 15 grassland experiments. IPCC (2006) methodology was used to estimate uncertainties for Federal grazed lands not accounted for by the DayCent simulations. Uncertainty from the DayCent-simulated grazed land was combined with uncertainty for remaining grazed lands calculated using IPCC (2006) methodology based on simple error propagation. The calculated 95-percent confidence interval around the estimate of 96 MMT CO_2 eq. for grazed-soil N_2O emissions was 72 to 138 MMT CO_2 eq. (Table 2-1). Uncertainty calculations are described in detail in Chapter 3 of this report.

2.6.3 Methodology To Estimate Methane Emissions From Grazed Lands

Methane emissions were estimated by multiplying regional or national animal-type-specific volatile solid production by the animal-type-specific maximum CH_4 production capacity of the waste and the national MCF for manure deposited on grazed lands. As noted previously, these emissions are very small because of predominately aerobic conditions in deposited manure.

2.6.4 Changes Compared to the 3rd Edition of the USDA GHG Report

There were several changes compared to the previous inventory. The most important change was performing DayCent model simulations at NRI resolution (simulations were conducted at the county level for the previous inventory). Simulations also incorporated MODIS Enhanced Vegetation Index to reduce uncertainties in the estimation of crop production, and instead of using model-generated N and C deposited from animal waste, these were based on county-level animal population data to be consistent with activity data for emissions from enteric fermentation and livestock waste. Additional changes include using updated and refined model activity data, better representing land use change and tillage practices, expanding the observational data sets used to quantify model uncertainty, and improving model algorithms to better represent the processes that control soil GHG fluxes. In aggregate, these changes resulted in an approximate 40-percent increase in N_2O emissions from grazed lands on average.

2.6.5 Methods for Estimating Carbon Dioxide Fluxes for Grazed Lands

As with N_2O emissions, carbon dioxide (CO_2) fluxes for non-Federal grasslands were estimated using results from the DayCent ecosystem model and IPCC (2006) methodology. See section 2.6.1 for details on model simulations. Although model simulations for N_2O and CO_2 fluxes were identical, model outputs for CO_2 are portioned by land use (grassland remaining grassland versus land converted to grassland) whereas N_2O emissions from grazed lands are not partitioned by land use. DayCent has been parameterized to simulate continuous grasslands and croplands converted to grasslands but not other land uses converted to grasslands. Consequently, IPCC (2006) methodology was used to estimate CO_2 fluxes for land converted from non-agricultural uses to grazed land. Also, DayCent has not been well tested with organic soils, so IPCC (2006) methodology was also used for grazed organic soils.

Both DayCent and IPCC (2006) methodologies rely on land use classifications and land use histories. The National Resources Inventory (USDA 2009) was used to identify grassland remaining grassland and land converted to grassland. Grassland includes pasture and rangeland where the primary land use is livestock grazing. According to NRI data, ~17 million ha of grassland (out of a total ~261 million ha reported in 2007) were converted to grassland between 1997 and 2007. An example of land converted to grassland is land that was cropped historically but then converted to pasture use. Carbon dioxide fluxes for grazed lands were calculated using estimates of changes in soil organic C stocks and molecular stoichiometry.

Mineral soil C stocks and stock changes for NRI points classified as grasslands remaining grasslands and cropland converted to grassland were estimated using the DayCent model. In addition to accounting for weather and soil texture, these simulations also included estimates of managed manure additions to grasslands. DayCent estimates carbon-stock changes by accounting for C inputs from plant material and manure and C outputs from grazing and decomposition. For details on sources of the input data required to run DayCent and how the simulations were conducted, see Chapter 3 of this report and Chapter 7 and Annex 3.12 of the U.S. GHG Inventory (EPA 2015).

Mineral soil C stocks and stock changes for NRI points classified as land other than cropland converted to grassland and all grasslands growing on organic soils were estimated using IPCC (2006, 1997) methodology. U.S.-specific stock change factors based on field data were developed for land converted to grassland and for drained histosols used for grazing. As with grazed-land N_2O emissions, CO_2 fluxes were partitioned among different animal types by assuming that fluxes are linearly proportional to waste N production.

2.6.6 Uncertainty in Carbon Dioxide Fluxes for Grazed Lands

Uncertainty for the estimates of CO_2 fluxes from mineral soil grassland remaining grassland and cropland converted to grassland provided by DayCent model simulations used a Monte Carlo approach, which addresses uncertainties in model inputs, uncertainty in model structure, and uncertainties from scaling NRI points to cover all grasslands remaining grassland in the United States. Uncertainty for estimates from other land uses converted to grassland and all organic soil grasslands provided by IPCC (2006, 1997) methodology used a Monte Carlo approach that addressed uncertainties in carbon-stock change factors and in land use data. To assess structural uncertainty, DayCent simulated

soil C-stock changes were compared with measured values from over 25 grassland experiments in North America. Uncertainties were combined using simple error propagation. The results yielded an uncertainty of (24) to 48 around the estimate of 12 MMT CO_2 eq. in 2013 for land remaining grazed land and (18) to 1 around the estimate of (9) MMT CO_2 eq. for land converted to grazed land in 2013, where parentheses indicate a net sequestration of CO_2 (Table 2-1). Uncertainty calculations are described in detail in Chapter 3 of this report.

2.6.7 Changes Compared to the 3rd edition of the USDA GHG Report

As with N_2O, the major change compared to the previous inventory was performing DayCent model simulations at NRI resolution (see section 2.6.4 for details). The implemented changes resulted in a decrease in estimated soil C sequestration of approximately 30 MMT CO_2 eq. on average (69 percent decrease), compared to the previous inventory.

2.7 Mitigating Greenhouse Gas Emissions From Livestock

In addition to the mitigation strategies discussed below that are based primarily on implementation of improved technologies designed to decrease emissions from enteric fermentation, livestock waste management, and grazed lands, there are also mitigation options related to human behavior. Specifically, recent research suggests that consuming less animal products is likely to reduce GHG emissions and have co-benefits such as improved human health and increased biodiversity (Del Grosso and Cavigelli 2012, Smith et al. 2013, Eshel et al. 2014, Machovina et al. 2015).

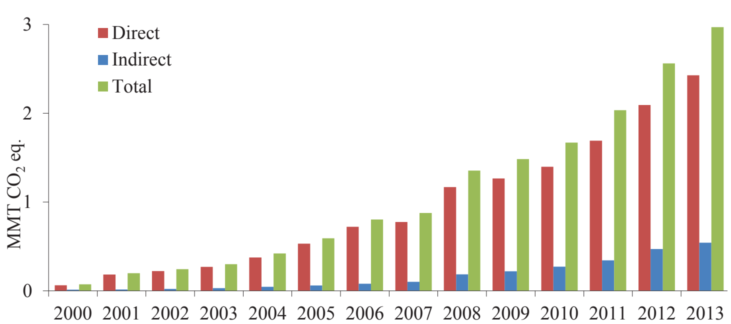


Figure 2-4 Estimated Reductions in Methane Emissions from Anaerobic Digesters, 2000-2013

2.7.1 Enteric Fermentation

Emissions of CH_4 from enteric fermentation in ruminant and non-ruminant animals are dependent on the animal's digestive system and the amount and type of feed consumed. On average, beef and dairy cattle convert 6 percent of gross energy intake from feed into CH_4 through enteric fermentation, constituting a loss of energy from the perspective of the animal (Johnson & Johnson 1995). Research on animal nutrition has focused on reducing this energy loss, which consequently reduces CH_4 emissions and increases nutritional efficiency. Through such research, a number of potential strategies have been identified to reduce CH_4 emissions from enteric fermentation, including (Mosier et al. 1998):

- Increasing the digestibility of forages and feeds;
- Providing feed additives which may tie up hydrogen in the rumen;
- Inhibiting the formation of CH_4 by rumen bacteria;
- Increasing acetic acid in the rumen;
- Improving production efficiency; and
- Modifying bacteria in the rumen.

Currently, Government research programs indirectly address mitigation of CH_4 emissions through improved livestock production. Ongoing research development and deployment efforts related to mitigating CH_4 emissions include:

- Decreasing feed digestion time by improving grazing management to increase the digestibility of forages, increasing the digestibility of feed grains, and increasing the feeding of concentrated supplements;
- Adding edible oils in feed to sequester hydrogen, making it unavailable for methanogens;
- Using feed additives, ionophores, which inhibit the formation of CH_4 by rumen bacteria;
- Improving livestock production efficiency by feed additives such as hormones to increase milk production and growth regulators for beef production or by improved diet or genetics;
- Enhancing rumen microbes to produce usable products rather than CH_4.

Although many of the mitigation options mentioned above have been extensively studied (Hristov et al. 2013), reliable quantitative estimates of these potentials remain elusive. Reasons for lack of reliable quantitative estimates include variability in observations and complex interactions with other GHG sources (e.g., emissions from livestock waste) that compromise the efficacy of general

recommendations. Agro-ecosystem models have potential to account for these interactions, but empirical models are limited by simplistic assumptions that lead to large errors, and complex models are limited by difficulty in acquiring required input data (Kebreab et al. 2016).

2.7.2 Livestock Waste

Livestock and poultry waste from production facilities has the potential to produce significant quantities of CH_4 and N_2O, depending on the waste management practices used. In the United States, livestock and poultry manure is managed in a myriad of ways, suggesting there are multiple options for reducing CH_4 and N_2O emissions. When manure is stored or treated in systems that promote anaerobic conditions, such as lagoons and tanks, the decomposition of the biodegradable fraction of the waste tends to produce CH_4. When manure is handled as a solid, such as in stacks or deposits on pastures, the biodegradable fraction tends to decompose aerobically and produce little or no CH_4, although it produces N_2O.

A relatively large portion of CH_4 is emitted from livestock and poultry waste in anaerobic lagoons. Current, commercially available technologies that have been the most successful in reducing CH_4 emissions from manure management are anaerobic digestion systems. Unlike conventional lagoons, digestion technologies keep waste treatment and storage functions separate and allow for gas recovery and combustion, pathogen and organic stabilization, odor and other air-quality pollution control, and flexible approaches to nutrient management.

The EPA tracks installation and usage of anaerobic digesters under voluntary programs such as AgStar (http://www.epa.gov/agstar/) and uses this data to estimate how much anaerobic digesters have reduced overall CH_4 emissions from livestock waste over the last 12 years. Figure 2-4 shows an increasing trend in emissions reductions annually from the use of anaerobic digesters, reflecting increasing numbers of digester systems being installed each year.

Other emission reduction processes can include separation, aeration, or shifts to solid handling or storage management systems. These strategies, however, could be limited by other farm or environmental constraints and costs.

2.7.3 Grazed Lands

Nitrous oxide is by far the largest source of emissions from grazed lands, so it also provides the largest mitigation potential (Table 2-6). However, because most grazed lands are not highly managed, particularly the large expanses of rangeland in the Western United States, mitigation options are limited. One strategy that may be feasible for more intensely managed pastures in the Eastern United States is nitrification inhibitors. Although synthetic N fertilizer inputs are low, grazing lands usually have large N inputs from biological N fixation because they are seeded with legumes. Equations to estimate the mitigation potential of fertilizers formulated with nitrification inhibitors are included in a recent USDA report (Ogle et al. 2014).

2.8 Planned Improvements

There are a few areas where changes could be made to improve upon the existing inventory. Regarding enteric CH_4 emissions, changes involve updating and refining input values such as cattle births, DE, animal weight gains, emissions factors, and updating the uncertainty methodology. For managed manure emissions, the uncertainty analysis will be updated to more accurately assess uncertainty of emission calculations due to extensive changes in emission calculation methodology and the use of new calculations and variables for indirect N_2O emissions. The 2012 Agricultural Census data will be used to update county-level animal population and WMS estimates. For grazing emission from soils, major improvements include refining the DayCent model and using more recent NRI data. Future inventories will attempt to quantify mitigation potentials from all sources related to livestock production.

SUGGESTED CITATION

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2.10 Appendix A

A-1 Population of Animals by State in 2013

A-2 U.S. Livestock Population, 1990, 1995, 2000, 2005-2013

A-3 State-Level Methane Emissions From Enteric Fermentation by Livestock Category in 2013

A-4 State-Level Methane Emissions From Enteric Fermentation in 1990, 1995, 2000, 2005-2013

A-5 Cattle Population Categories Used for Estimating Methane Emissions

A-6 Dairy Lactation by Region

A-7 Typical Livestock Weights

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A-27 MLRA-Level Estimates of Mean Annual Direct and Indirect N_2O Emissions From Non-Federal Grasslands, 2003-2007

Appendix Table A-1 Population of Animals by State in 2013

	Beef Cattle	Dairy Cattle	Swine	Sheep	Goat	Horse	Poultry
State				*Head*			
Alabama	1,164,323	17,605	85,000	12,083	47,212	59,026	206,577,762
Alaska	11,681	805	1,000	12,083	626	1,443	1,212,966
Arizona	716,787	360,285	175,000	140,000	77,557	97,124	1,212,966
Arkansas	1,529,163	20,585	115,000	12,083	39,816	57,514	211,111,970
California	1,948,078	3,470,786	95,000	570,000	141,886	134,921	35,115,697
Colorado	2,905,849	288,910	705,000	435,000	31,913	108,624	6,310,216
Connecticut	12,609	36,203	3,500	7,333	4,356	18,607	3,292,216
Delaware	8,354	9,796	6,000	12,083	1,704	6,596	40,412,966
Florida	1,544,585	219,544	15,000	12,083	50,923	121,118	22,346,307
Georgia	864,002	148,980	141,000	12,083	69,256	68,492	270,221,762
Hawaii	123,956	5,168	11,500	12,083	13,761	4,827	1,212,966
Idaho	1,368,084	1,186,413	38,200	235,000	18,208	58,921	1,212,966
Illinois	928,878	196,112	4,625,000	53,000	31,120	59,361	15,352,580
Indiana	505,098	319,163	3,625,000	55,000	36,940	100,629	51,466,697
Iowa	3,739,688	429,699	20,375,000	175,000	56,297	60,248	76,182,580
Kansas	6,075,096	299,269	1,812,500	65,000	40,878	71,868	1,212,966
Kentucky	1,946,299	158,722	315,000	43,000	57,308	135,110	63,290,034
Louisiana	800,046	29,200	8,000	12,083	18,220	59,645	13,121,580
Maine	24,191	63,864	4,500	7,333	6,558	11,953	3,912,216
Maryland	94,328	106,053	22,000	12,083	9,516	28,245	59,341,125
Massachusetts	14,149	24,893	8,500	7,333	8,674	20,288	442,216
Michigan	461,980	726,955	1,045,000	82,000	26,903	85,370	26,567,580
Minnesota	1,292,988	982,438	7,787,500	135,000	33,107	61,633	37,940,121
Mississippi	879,933	28,158	500,000	12,083	23,304	57,371	143,196,762
Missouri	3,298,804	180,591	2,800,000	75,000	105,113	110,921	150,681,212
Montana	2,958,072	29,151	166,000	235,000	9,937	96,457	896,216
Nebraska	7,339,137	103,169	3,037,500	80,000	24,087	64,066	21,772,580
Nevada	435,537	52,863	2,000	73,000	23,287	23,278	1,212,966
New Hampshire	7,792	26,904	3,800	7,333	5,072	8,936	1,212,966
New Jersey	17,937	14,576	9,000	12,083	7,785	27,161	1,212,966
New Mexico	789,115	608,835	1,200	100,000	30,044	50,144	1,212,966
New York	250,477	1,241,783	66,000	70,000	35,745	91,189	16,162,580
North Carolina	673,494	92,519	8,900,000	26,000	59,969	64,569	175,307,515
North Dakota	1,885,554	40,177	135,000	74,000	4,830	45,375	1,212,966
Ohio	780,309	533,110	2,140,000	121,000	47,969	113,113	51,455,788
Oklahoma	3,942,639	89,538	2,187,500	75,000	81,811	157,591	42,041,125
Oregon	1,109,398	253,845	8,500	210,000	32,249	66,628	12,974,580
Pennsylvania	488,239	1,118,260	1,127,500	86,000	48,366	120,614	63,279,242
Rhode Island	2,916	1,860	1,900	7,333	923	2,203	1,212,966
South Carolina	318,626	31,187	245,000	12,083	37,761	54,217	50,900,818
South Dakota	3,809,849	193,980	1,162,500	275,000	17,706	68,665	4,586,333
Tennessee	1,655,886	97,535	175,000	33,000	83,866	87,449	34,381,398
Texas	11,475,115	857,519	632,500	700,000	826,704	387,214	136,119,489
Utah	639,196	185,983	730,000	295,000	14,210	58,818	6,021,333
Vermont	30,796	261,563	3,200	7,333	11,388	11,342	459,216
Virginia	1,329,691	177,138	255,000	87,000	48,379	86,135	54,576,485
Washington	780,991	508,126	38,200	54,000	25,906	59,591	18,362,580
West Virginia	383,913	20,113	5,000	30,000	17,001	24,215	20,672,333
Wisconsin	908,325	2,618,905	305,000	84,000	62,145	100,168	16,784,762
Wyoming	1,428,100	13,061	90,000	375,000	9,416	70,858	329,216
Total	**75,700,053**	**18,481,893**	**65,746,500**	**5,335,000**	**2,517,711**	**3,539,852**	**2,177,309,818**

Source: EPA 2015

Appendix Table A-2 U.S. Livestock Population, 1990, 1995, 2000, 2005-2013

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013
Animal Type						*1 million head*						
Dairy Cattle[1]	**14**	**14**	**13**	**13**	**13**	**13**	**14**	**14**	**14**	**14**	**14**	**14**
Dairy Cows	10	9	9	9	9	9	9	9	9	9	9	9
Dairy Heifers	4	4	4	4	4	4	4	4	5	5	5	5
Swine	**54**	**59**	**59**	**61**	**62**	**65**	**67**	**66**	**65**	**66**	**66**	**66**
Market <60 lbs.	18	20	20	20	21	22	20	19	19	19	19	19
Market 60-119 lbs.	12	13	13	14	14	15	17	17	17	17	17	17
Market 120-179 lbs.	9	11	11	11	11	12	13	13	12	12	13	13
Market >180 lbs.	8	9	9	10	10	11	11	11	11	11	11	11
Breeding Swine	7	7	6	6	6	6	6	6	6	6	6	6
Beef cattle	**82**	**90**	**85**	**82**	**83**	**83**	**82**	**81**	**80**	**79**	**77**	**76**
Feedlot Steers	17	18	17	17	17	17	16	16	16	16	15	15
Feedlot Heifers	6	7	8	8	9	9	8	8	9	9	8	8
Bulls NOF[2]	2	2	2	2	2	2	2	2	2	2	2	2
Calves NOF	32	35	34	33	33	33	32	32	31	31	30	29
Heifers NOF	10	12	9	8	8	8	8	9	8	8	7	8
Steers NOF	3	4	5	5	5	5	5	5	5	5	5	5
Cows NOF	10	12	10	10	10	10	9	9	9	9	9	9
Sheep	**11**	**9**	**7**	**6**	**6**	**6**	**6**	**6**	**6**	**5**	**5**	**5**
Goats	**3**	**2**	**2**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**	**3**
Poultry	**1,537**	**1,827**	**2,033**	**2,150**	**2,154**	**2,167**	**2,176**	**2,089**	**2,104**	**2,096**	**2,169**	**2,177**
Hens >1 yr.	273	299	334	348	350	347	340	341	342	339	347	353
Pullets	73	81	95	97	97	104	99	102	106	102	104	105
Chickens	7	8	8	8	8	8	8	8	7	7	7	7
Broilers	1,066	1,332	1,506	1,613	1,612	1,619	1,638	1,555	1,568	1,565	1,626	1,633
Turkeys	118	107	90	84	87	89	91	82	81	83	84	80
Horses	**2**	**3**	**3**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**4**

Source: EPA 2015

Note: Totals may not sum due to independent rounding.

[1]Dairy cattle does not include dairy calves.

[2](NOF) Not on feed.

Appendix Table A-3 State-Level Methane Emissions from Enteric Fermentation by Livestock Category in 2013

	Beef cattle	Dairy cattle	Swine	Horses	Total*
State			*MMT CO_2 eq.*		
Alabama	1.94	0.05	0.00	0.03	1.99
Alaska	0.02	0.00	0.00	0.00	0.02
Arizona	1.07	0.86	0.01	0.04	1.93
Arkansas	2.55	0.04	0.00	0.03	2.59
California	3.08	8.22	0.00	0.06	11.30
Colorado	4.30	0.60	0.03	0.05	4.91
Connecticut	0.02	0.09	0.00	0.01	0.11
Delaware	0.01	0.02	0.00	0.00	0.04
Florida	2.58	0.56	0.00	0.06	3.13
Georgia	1.43	0.38	0.01	0.03	1.81
Hawaii	0.22	0.01	0.00	0.00	0.23
Idaho	2.24	2.73	0.00	0.03	4.98
Illinois	1.40	0.40	0.17	0.03	1.80
Indiana	0.76	0.72	0.14	0.05	1.48
Iowa	5.23	0.96	0.76	0.03	6.19
Kansas	8.36	0.56	0.07	0.03	8.92
Kentucky	3.22	0.36	0.01	0.06	3.58
Louisiana	1.34	0.07	0.00	0.03	1.40
Maine	0.04	0.14	0.00	0.01	0.18
Maryland	0.15	0.24	0.00	0.01	0.39
Massachusetts	0.02	0.05	0.00	0.01	0.08
Michigan	0.66	1.62	0.04	0.04	2.27
Minnesota	1.89	1.97	0.29	0.03	3.86
Mississippi	1.47	0.06	0.02	0.03	1.53
Missouri	5.31	0.33	0.11	0.05	5.64
Montana	5.23	0.06	0.01	0.04	5.29
Nebraska	10.22	0.22	0.11	0.03	10.44
Nevada	0.77	0.13	0.00	0.01	0.89
New Hampshire	0.01	0.06	0.00	0.00	0.08
New Jersey	0.03	0.03	0.00	0.01	0.06
New Mexico	1.39	1.54	0.00	0.02	2.93
New York	0.41	2.93	0.00	0.04	3.34
North Carolina	1.13	0.23	0.33	0.03	1.36
North Dakota	3.01	0.07	0.01	0.02	3.09
Ohio	1.16	1.09	0.08	0.05	2.25
Oklahoma	6.27	0.22	0.08	0.07	6.49
Oregon	1.92	0.56	0.00	0.03	2.48
Pennsylvania	0.76	2.53	0.04	0.05	3.29
Rhode Island	0.00	0.00	0.00	0.00	0.01
South Carolina	0.53	0.07	0.01	0.02	0.61
South Dakota	5.93	0.37	0.04	0.03	6.29
Tennessee	2.76	0.24	0.01	0.04	3.00
Texas	17.20	2.11	0.02	0.17	19.31
Utah	1.11	0.42	0.03	0.03	1.53
Vermont	0.05	0.58	0.00	0.01	0.63
Virginia	2.18	0.45	0.01	0.04	2.64
Washington	1.20	1.22	0.00	0.03	2.42
West Virginia	0.64	0.04	0.00	0.01	0.68
Wisconsin	1.32	5.47	0.01	0.05	6.79
Wyoming	2.48	0.03	0.00	0.03	2.50
Total	117.0	41.7	2.5	1.6	158.8

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent.
Source: EPA 2015
*State totals include all livestock categories

Appendix Table A-4 State-Level Methane Emissions from Enteric Fermentation in 1990, 1995, 2000, 2005-2013

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013
State						*MMT CO_2 eq.*						
Alabama	2.53	2.82	2.37	2.16	2.08	2.08	2.00	2.02	2.05	2.00	1.97	1.98
Alaska	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.02
Arizona	1.55	1.62	1.61	1.86	1.95	2.03	2.07	2.14	1.97	1.88	1.96	1.95
Arkansas	2.82	3.17	2.91	3.01	2.82	2.82	2.90	2.85	2.96	2.80	2.72	2.58
California	8.69	9.05	9.92	10.69	10.80	11.50	11.47	11.26	11.06	11.04	11.34	11.20
Colorado	4.34	4.96	5.08	4.27	4.50	5.02	5.08	4.93	4.92	5.04	5.24	5.05
Connecticut	0.17	0.16	0.15	0.12	0.11	0.11	0.11	0.11	0.10	0.10	0.10	0.10
Delaware	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Florida	3.58	3.87	3.43	3.26	3.21	3.30	3.23	3.24	3.25	3.15	3.23	3.15
Georgia	2.25	2.49	2.18	2.10	2.07	2.04	1.96	1.91	1.88	1.82	1.86	1.82
Hawaii	0.32	0.30	0.29	0.28	0.29	0.28	0.27	0.27	0.26	0.26	0.25	0.23
Idaho	2.87	3.34	3.74	4.16	4.28	4.50	4.58	4.56	4.58	4.76	4.81	5.01
Illinois	2.71	2.67	2.38	2.17	2.17	2.12	2.03	1.98	1.91	1.78	1.72	1.81
Indiana	1.95	1.87	1.55	1.50	1.51	1.57	1.56	1.51	1.58	1.55	1.51	1.47
Iowa	6.49	6.44	5.96	5.76	6.05	6.26	6.31	6.35	6.29	6.19	6.14	6.24
Kansas	7.79	9.46	9.48	9.74	9.98	9.88	10.06	9.89	9.56	9.73	9.45	9.17
Kentucky	3.92	4.31	3.63	3.80	3.87	4.11	3.98	3.81	3.70	3.53	3.42	3.58
Louisiana	1.85	1.74	1.62	1.57	1.51	1.55	1.60	1.60	1.53	1.43	1.40	1.39
Maine	0.23	0.22	0.21	0.19	0.18	0.18	0.19	0.19	0.19	0.19	0.18	0.18
Maryland	0.61	0.61	0.51	0.44	0.45	0.43	0.40	0.39	0.40	0.39	0.40	0.39
Massachusetts	0.16	0.14	0.12	0.10	0.10	0.09	0.09	0.09	0.08	0.08	0.08	0.08
Michigan	2.08	2.11	1.87	1.92	1.99	2.09	2.12	2.14	2.21	2.21	2.27	2.32
Minnesota	4.35	4.40	4.11	3.77	3.75	3.85	3.86	3.89	3.89	3.84	3.82	3.88
Mississippi	2.12	2.18	1.81	1.79	1.61	1.58	1.59	1.58	1.62	1.55	1.55	1.53
Missouri	6.63	7.34	6.76	6.84	7.14	6.84	6.63	6.52	6.35	5.97	5.88	5.64
Montana	4.00	4.98	4.88	4.47	4.58	4.98	5.34	5.26	5.13	5.13	5.09	5.30
Nebraska	8.88	9.90	10.64	10.34	10.69	11.07	10.77	10.76	10.62	10.41	10.77	10.66
Nevada	0.90	0.92	0.92	0.91	0.92	0.90	0.88	0.89	0.90	0.91	0.91	0.89
New Hampshire	0.10	0.10	0.10	0.09	0.09	0.08	0.09	0.09	0.08	0.08	0.08	0.08
New Jersey	0.14	0.13	0.10	0.08	0.08	0.07	0.07	0.08	0.07	0.06	0.06	0.06
New Mexico	2.37	2.83	3.06	3.11	3.28	3.30	3.44	3.44	3.31	3.25	3.06	2.88
New York	3.44	3.26	3.34	3.16	3.19	3.32	3.38	3.28	3.30	3.31	3.35	3.36
North Carolina	1.51	1.81	1.59	1.47	1.42	1.43	1.37	1.40	1.35	1.33	1.35	1.36
North Dakota	2.83	3.44	3.23	3.10	3.09	3.20	3.09	3.08	3.00	2.99	2.91	3.10
Ohio	2.55	2.45	2.15	2.28	2.29	2.24	2.27	2.37	2.35	2.27	2.31	2.28
Oklahoma	7.24	8.08	7.39	7.69	7.97	7.76	7.78	7.86	8.01	7.53	6.70	6.50
Oregon	2.46	2.82	2.65	2.73	2.68	2.52	2.65	2.42	2.47	2.54	2.53	2.47
Pennsylvania	3.64	3.46	3.40	3.19	3.17	3.24	3.24	3.22	3.27	3.25	3.26	3.28
Rhode Island	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
South Carolina	0.91	0.87	0.78	0.74	0.70	0.69	0.67	0.65	0.65	0.65	0.64	0.61
South Dakota	5.35	6.44	6.28	6.26	6.32	6.27	6.17	6.23	6.32	6.16	6.08	6.35
Tennessee	3.61	4.02	3.42	3.52	3.60	3.71	3.51	3.21	3.31	3.25	3.16	2.98
Texas	20.76	24.75	22.55	22.48	23.16	22.83	22.63	23.08	22.73	22.42	20.74	19.55
Utah	1.44	1.63	1.65	1.61	1.53	1.60	1.67	1.60	1.58	1.55	1.57	1.53
Vermont	0.71	0.68	0.70	0.64	0.64	0.65	0.65	0.64	0.62	0.64	0.63	0.65
Virginia	2.73	2.83	2.58	2.67	2.73	2.66	2.62	2.47	2.57	2.53	2.50	2.63
Washington	2.57	2.61	2.52	2.23	2.31	2.39	2.34	2.34	2.24	2.35	2.38	2.42
West Virginia	0.76	0.82	0.69	0.67	0.69	0.72	0.69	0.70	0.65	0.66	0.66	0.68
Wisconsin	7.42	6.62	6.37	6.17	6.23	6.47	6.52	6.59	6.68	6.75	6.79	6.86
Wyoming	2.05	2.57	2.69	2.31	2.44	2.69	2.55	2.57	2.51	2.49	2.57	2.51
Total	**158.44**	**173.40**	**165.42**	**163.51**	**166.29**	**169.12**	**168.55**	**167.53**	**166.13**	**163.87**	**161.49**	**159.82**

Note: State level emissions do not include data for non-cattle. MMT CO_2 eq. is million metric tons carbon dioxide equivalent.
Source: EPA 2015

Appendix Table A-5 Cattle Population Categories Used for Estimating Methane Emissions

Dairy Cattle	***Beef Cattle***
Calves (4-6 mo)	Calves (4-6 mo)
Heifer Replacements	Heifer Replacements
Cows	Heifer and Steer Stockers
	Animals in Feedlots (Heifers and Steers)
	Cows
	Bulls[1]

Source: EPA 2015

[1] Bulls (beef and dairy) are accounted for in a single category.

Appendix Table A-6 Dairy Lactation by Region[1]

	California	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Year				*(lbs * year)/cow*			
1990	18,456	146,737	94,384	50,123	170,274	115,308	116,277
1991	18,534	149,227	95,175	49,752	174,570	117,551	117,666
1992	18,722	155,838	98,240	51,413	180,353	121,223	121,419
1993	18,852	155,984	98,723	52,135	179,289	121,622	124,859
1994	20,203	160,840	101,511	52,944	180,102	122,992	127,801
1995	19,573	159,752	102,563	52,913	184,544	125,823	129,453
1996	19,161	162,417	104,164	52,860	185,547	124,764	128,195
1997	19,829	164,233	105,060	52,846	191,086	128,219	130,930
1998	19,451	166,106	108,478	53,279	195,078	131,930	130,626
1999	20,781	166,741	111,222	53,903	197,570	133,766	134,263
2000	21,130	169,877	116,222	55,413	199,323	138,105	137,216
2001	20,904	168,163	116,523	55,120	204,650	136,009	139,062
2002	21,277	172,668	121,146	56,623	208,267	139,990	140,620
2003	20,993	171,078	122,244	57,926	205,592	145,306	136,904
2004	21,139	170,757	122,811	61,092	207,408	147,148	140,976
2005	21,404	174,066	127,412	62,071	209,638	151,582	143,500
2006	21,815	175,077	131,933	61,406	213,221	152,633	145,258
2007	22,440	178,152	132,981	60,537	213,130	152,983	149,937
2008	22,344	176,679	136,074	61,381	217,190	151,903	148,871
2009	22,000	179,386	139,674	62,443	217,153	154,529	152,199
2010	23,025	184,540	143,910	63,000	220,024	157,303	150,623
2011	23,438	187,898	144,853	64,369	221,859	157,887	151,149
2012	23,457	190,031	149,516	66,056	227,856	162,671	152,473
2013	23,178	184,682	150,877	64,082	231,351	163,624	151,718

Source: EPA 2015

[1] Beef lactation data developed using methodology described in EPA 2015.

Appendix Table A-7 Typical Livestock Weights for 2013

Cattle Type	*lbs*
Calves	270
Dairy Cows	1,500
Dairy Replacements	899
Beef Cows	1,348
Bulls	2,022
Beef Replacements	893
Steer Stockers	721
Heifer Stockers	711
Steer Feedlot	1,017
Heifer Feedlot	959

Source: Feedstuffs (1998), Western Dairyman (1998), Enns (2008), Johnson (2010), NRC (1999), Holstein Association 2010, USDA (2013b,) EPA (2015).

Appendix Table A-8 U.S. Feedlot Placements for 2013

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	*Total*
Weight Place	*Number of animals placed, 1,000 head*												
< 600 lbs.	460	400	380	445	415	460	620	715	685	840	750	550	**6,720**
600 - 700 lbs.	475	365	360	310	355	380	400	365	415	590	500	385	**4,900**
700 - 800 lbs.	544	492	589	485	480	420	495	476	504	487	377	360	**5,709**
> 800 lbs.	410	410	585	545	560	435	620	690	865	575	410	378	**6,483**
Total	**1,889**	**1,667**	**1,914**	**1,785**	**1,810**	**1,695**	**2,135**	**2,246**	**2,469**	**2,492**	**2,037**	**1,673**	**23,812**

Source: USDA (2002f, 2001f, 2000f, 1999a, 1995a), EPA 2015.
Note: Totals may not sum due to independent rounding.

Appendix Table A-9 Regional Estimates of Digestible Energy and Methane Conversion Rates for Foraging Animals 2007-2013

Animal Type	Data	West	Central	Northeast	Southeast
Beef Repl. Heif.	DE [1]	61.9	65.6	64.5	64.6
	Ym [2]	6.5%	6.5%	6.5%	6.5%
Steer Stockers	DE	61.9	65.6	64.5	64.6
	Ym	6.5%	6.5%	6.5%	6.5%
Heifer Stockers	DE	61.9	65.6	64.5	64.6
	Ym	6.5%	6.5%	6.5%	6.5%
Beef Cows	DE	59.9	63.6	62.5	62.6
	Ym	6.5%	6.5%	6.5%	6.5%
Beef Calves (4-6 mo)	DE	61.9	65.6	64.5	64.6
	Ym	6.5%	6.5%	6.5%	6.5%
Bulls	DE	59.9	63.6	62.5	62.6
	Ym	6.5%	6.5%	6.5%	6.5%

Source: EPA 2015
[1] (DE) Digestible energy; in units of percent gross energy (GE) in MJ/Day.
[2] (Y_m) Methane conversion rate is the fraction of gross energy (GE) in feed converted to methane.

Appendix Table A-10 Regional Estimates of Digestible Energy and Methane Conversion Rates for Dairy and Feedlot Cattle for 2013

Animal Type	Data	California	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Dairy Repl. Heif.	DE[1]	63.7	63.7	63.7	63.7	63.7	63.7	63.7
	Ym[2]	6.0%	6.0%	5.7%	6.5%	6.4%	5.7%	7.0%
Steer Feedlot	DE	82.5	82.5	82.5	82.5	82.5	82.5	82.5
	Ym	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%
Heifer Feedlot	DE	82.5	82.5	82.5	82.5	82.5	82.5	82.5
	Ym	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%
Dairy Cows	DE	66.7	66.7	66.7	66.7	66.7	66.7	66.7
	Ym	5.9%	5.9%	5.6%	6.4%	6.3%	5.6%	6.9%
Dairy Calves (4-6 mo)	DE	63.7	63.7	63.7	63.7	63.7	63.7	63.7
	Ym	7.8% (4 mo), 8.03% (5 mo), 8.27% (6 mo) - all regions						

Source: EPA 2015
[1] (DE) Digestible energy; in units of percent gross energy (GE) in megajoules (MJ) per day.
[2] (Y_m) Methane conversion rate is the fraction of gross energy (GE) in feed converted to methane.

Appendix Table A-11 Definition of Regions for Characterizing the Diets of Dairy Cattle (all years) and Foraging Cattle 1990-2006

Region & State(s)					
West	**Northern Great Plains**	**Midwest**	**Northeast**	**South Central**	**Southeast**
Alaska	Colorado	Illinois	Connecticut	Arkansas	Alabama
Arizona	Kansas	Indiana	Delaware	Louisiana	Florida
Hawaii	Montana	Iowa	Maine	Oklahoma	Georgia
Idaho	Nebraska	Michigan	Maryland	Texas	Kentucky
Nevada	North Dakota	Minnesota	Massachusetts		Mississippi
New Mexico	South Dakota	Missouri	New Hampshire		North Carolina
Oregon	Wyoming	Ohio	New Jersey		South Carolina
Utah		Wisconsin	New York		Tennessee
Washington	**California**		Pennsylvania		Virginia
	California		Rhode Island		
			Vermont		
			West Virginia		

Source: EPA 2015

Appendix Table A-12 Definition of Regions for Characterizing the Diets of Foraging Cattle from 2007-2013

Region & State(s)			
West	**Central**	**Northeast**	**Southeast**
Alaska	Illinois	Connecticut	Alabama
Arizona	Indiana	Delaware	Arkansas
California	Iowa	Maine	Florida
Colorado	Kansas	Maryland	Georgia
Hawaii	Michigan	Massachusetts	Kentucky
Idaho	Minnesota	New Hampshire	Louisiana
Montana	Missouri	New Jersey	Mississippi
Nevada	Nebraska	New York	North Carolina
New Mexico	North Dakota	Pennsylvania	Oklahoma
Oregon	Ohio	Rhode Island	South Carolina
Utah	South Dakota	Vermont	Tennessee
Washington	Wisconsin	West Virginia	Texas
Wyoming			Virginia

Source: EPA 2015

Appendix Table A-13 Methane Emissions from Cattle Enteric Fermentation, 1990-2013

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013
Animal Type						*kt CH_4*						
Dairy	**1,574**	**1,498**	**1,519**	**1,503**	**1,534**	**1,601**	**1,622**	**1,639**	**1,626**	**1,643**	**1,668**	**1,664**
Calves	62	59	59	54	55	58	58	58	57	57	58	58
Cows	1,242	1,183	1,209	1,197	1,219	1,271	1,289	1,304	1,287	1,301	1,324	1,325
Replacements 7-11 months	58	56	55	56	57	60	60	61	62	63	62	61
Replacements 12-23 months	212	201	196	196	203	213	216	216	221	222	224	220
Beef	**4,763**	**5,419**	**5,070**	**5,007**	**5,081**	**5,123**	**5,077**	**5,022**	**4,976**	**4,867**	**4,747**	**4,684**
Bulls	196	225	215	214	220	217	216	214	215	211	205	202
Calves	182	193	186	179	177	175	171	169	169	166	160	158
Cows	2,884	3,222	3,058	3,056	3,079	3,089	3,070	3,002	2,970	2,921	2,855	2,774
Replacements 7-11 months	69	85	74	80	82	82	79	78	75	74	75	77
Replacements 12-23 months	188	241	204	217	228	229	221	216	213	202	207	210
Steer Stockers	563	662	509	473	475	480	475	491	475	439	415	434
Heifer Stockers	306	375	323	299	299	296	290	300	301	283	267	269
Total Feedlot Cattle	375	416	502	488	521	556	554	552	559	570	559	560
Total	**6,338**	**6,917**	**6,589**	**6,510**	**6,615**	**6,725**	**6,700**	**6,661**	**6,602**	**6,510**	**6,416**	**6,348**

Note: Totals may not sum due to independent rounding; kt CH_4 is kilotons methane.
Source: EPA 2015

Appendix Table A-14 IPCC Emission Factors for Livestock

	Emission Factors
Animal Type	*(kg CH_4/head/year)*
DAIRY	
Calves	12
Cows	144
Replacements 7-11 months	46
Replacements 12-23 months	69
BEEF	
Bulls	98
Calves	11
Cows	95
Replacements 7-11 months	60
Replacements 12-23 months	70
Steer Stockers	58
Heifer Stockers	60
Total Feedlot	43
Sheep	8
Horses	18
Swine	2
Goats	5
American Bison	82
Mules and Asses	10

Note: kg CH_4 is kilograms methane.
Source: EPA 2015, IPCC 2006.

Appendix Table A-15 Summary of Greenhouse Gas Emissions from Managed[1] Waste by State in 2013

	CH_4	N_2O	***Total***
State	*MMT $C0_2$ eq.*		
Alabama	0.44	0.13	**0.57**
Alaska	0.01	0.00	**0.01**
Arizona	1.44	0.28	**1.73**
Arkansas	0.25	0.15	**0.40**
California	10.24	1.46	**11.70**
Colorado	1.15	0.76	**1.90**
Connecticut	0.03	0.01	**0.05**
Delaware	0.03	0.03	**0.06**
Florida	0.79	0.07	**0.86**
Georgia	0.80	0.20	**1.00**
Hawaii	0.03	0.01	**0.04**
Idaho	3.25	0.59	**3.84**
Illinois	1.55	0.32	**1.86**
Indiana	1.38	0.34	**1.72**
Iowa	8.93	1.56	**10.49**
Kansas	1.39	1.47	**2.86**
Kentucky	0.29	0.08	**0.38**
Louisiana	0.13	0.02	**0.14**
Maine	0.05	0.02	**0.06**
Maryland	0.11	0.06	**0.18**
Massachusetts	0.02	0.01	**0.02**
Michigan	1.50	0.43	**1.92**
Minnesota	2.77	0.82	**3.59**
Mississippi	0.55	0.11	**0.66**
Missouri	1.06	0.27	**1.33**
Montana	0.22	0.05	**0.26**
Nebraska	1.30	1.61	**2.91**
Nevada	0.19	0.03	**0.21**
New Hampshire	0.02	0.01	**0.03**
New Jersey	0.01	0.01	**0.02**
New Mexico	1.97	0.21	**2.19**
New York	0.83	0.30	**1.13**
North Carolina	4.60	0.40	**5.00**
North Dakota	0.13	0.06	**0.19**
Ohio	1.11	0.40	**1.50**
Oklahoma	1.59	0.33	**1.92**
Oregon	0.52	0.14	**0.66**
Pennsylvania	0.81	0.36	**1.17**
Rhode Island	0.00	0.00	**0.01**
South Carolina	0.32	0.06	**0.37**
South Dakota	0.75	0.33	**1.08**
Tennessee	0.19	0.05	**0.23**
Texas	3.62	2.00	**5.62**
Utah	0.72	0.13	**0.84**
Vermont	0.15	0.05	**0.21**
Virginia	0.28	0.10	**0.37**
Washington	1.24	0.32	**1.57**
West Virginia	0.04	0.02	**0.06**
Wisconsin	2.50	1.11	**3.60**
Wyoming	0.10	0.06	**0.16**
Total	**61.39**	**17.31**	**78.70**

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent. CH_4 is methane. N_2O is nitrous oxide.
Source: EPA 2015
[1]Methane totals include emissions from grazed-land manure.

Appendix Table A-16 Methane Emissions from Manure Management by State and Animal in 2013

	Dairy cattle	Beef cattle	Poultry	Swine	Goats	Horses	Sheep	*Total*
State				*MMT CO_2 eq.*				
Alabama	0.0133	0.0602	0.3143	0.0460	0.0004	0.0048	0.0002	**0.4392**
Alaska	0.0005	0.0005	0.0056	0.0001	0.0000	0.0001	0.0001	**0.0069**
Arizona	1.2876	0.0414	0.0181	0.0858	0.0007	0.0080	0.0025	**1.4441**
Arkansas	0.0073	0.0522	0.1214	0.0665	0.0004	0.0047	0.0002	**0.2527**
California	9.9547	0.1175	0.1042	0.0399	0.0013	0.0111	0.0100	**10.2387**
Colorado	0.7402	0.1095	0.1029	0.1810	0.0002	0.0059	0.0051	**1.1448**
Connecticut	0.0253	0.0004	0.0068	0.0003	0.0000	0.0010	0.0001	**0.0339**
Delaware	0.0067	0.0003	0.0221	0.0019	0.0000	0.0004	0.0001	**0.0315**
Florida	0.5376	0.0799	0.1576	0.0024	0.0005	0.0099	0.0002	**0.7881**
Georgia	0.1877	0.0444	0.5008	0.0611	0.0006	0.0056	0.0002	**0.8005**
Hawaii	0.0103	0.0072	0.0084	0.0046	0.0001	0.0004	0.0002	**0.0312**
Idaho	3.1659	0.0518	0.0166	0.0091	0.0001	0.0032	0.0028	**3.2495**
Illinois	0.2116	0.0311	0.0119	1.2863	0.0002	0.0033	0.0006	**1.5450**
Indiana	0.3529	0.0172	0.0389	0.9647	0.0002	0.0055	0.0006	**1.3802**
Iowa	0.5249	0.1286	0.0482	8.2221	0.0004	0.0033	0.0021	**8.9295**
Kansas	0.5689	0.2131	0.0017	0.5982	0.0003	0.0039	0.0008	**1.3869**
Kentucky	0.0391	0.0662	0.0435	0.1371	0.0004	0.0074	0.0005	**0.2943**
Louisiana	0.0159	0.0413	0.0618	0.0006	0.0002	0.0049	0.0002	**0.1248**
Maine	0.0359	0.0008	0.0077	0.0004	0.0000	0.0007	0.0001	**0.0457**
Maryland	0.0634	0.0033	0.0359	0.0063	0.0001	0.0015	0.0001	**0.1108**
Massachusetts	0.0129	0.0005	0.0009	0.0011	0.0001	0.0011	0.0001	**0.0166**
Michigan	1.1848	0.0159	0.0252	0.2660	0.0002	0.0047	0.0010	**1.4977**
Minnesota	0.8083	0.0433	0.0412	1.8686	0.0002	0.0034	0.0016	**2.7665**
Mississippi	0.0147	0.0455	0.2567	0.2284	0.0002	0.0047	0.0002	**0.5503**
Missouri	0.1437	0.1075	0.0845	0.7209	0.0007	0.0061	0.0009	**1.0643**
Montana	0.0445	0.1131	0.0103	0.0381	0.0001	0.0053	0.0028	**0.2141**
Nebraska	0.1890	0.2538	0.0199	0.8344	0.0002	0.0035	0.0009	**1.3017**
Nevada	0.1654	0.0166	0.0012	0.0005	0.0001	0.0013	0.0009	**0.1860**
New Hampshire	0.0162	0.0003	0.0024	0.0004	0.0000	0.0005	0.0001	**0.0199**
New Jersey	0.0066	0.0006	0.0025	0.0020	0.0000	0.0015	0.0001	**0.0134**
New Mexico	1.9197	0.0302	0.0170	0.0000	0.0002	0.0027	0.0012	**1.9710**
New York	0.7868	0.0088	0.0175	0.0151	0.0002	0.0050	0.0008	**0.8342**
North Carolina	0.0640	0.0232	0.3806	4.1306	0.0004	0.0035	0.0003	**4.6026**
North Dakota	0.0319	0.0611	0.0017	0.0340	0.0000	0.0025	0.0009	**0.1320**
Ohio	0.5041	0.0264	0.0336	0.5345	0.0003	0.0062	0.0014	**1.1066**
Oklahoma	0.2018	0.1344	0.1036	1.1355	0.0005	0.0086	0.0009	**1.5852**
Oregon	0.4455	0.0428	0.0246	0.0013	0.0002	0.0036	0.0025	**0.5205**
Pennsylvania	0.4334	0.0171	0.0392	0.3099	0.0003	0.0066	0.0010	**0.8076**
Rhode Island	0.0008	0.0001	0.0025	0.0002	0.0000	0.0001	0.0001	**0.0037**
South Carolina	0.0285	0.0165	0.1411	0.1240	0.0004	0.0045	0.0002	**0.3152**
South Dakota	0.3005	0.1242	0.0066	0.3150	0.0001	0.0038	0.0032	**0.7534**
Tennessee	0.0339	0.0566	0.0221	0.0694	0.0005	0.0048	0.0004	**0.1877**
Texas	2.4767	0.5980	0.1691	0.3246	0.0077	0.0318	0.0123	**3.6203**
Utah	0.4225	0.0244	0.0826	0.1800	0.0001	0.0032	0.0035	**0.7163**
Vermont	0.1501	0.0011	0.0009	0.0003	0.0001	0.0006	0.0001	**0.1531**
Virginia	0.0721	0.0451	0.0409	0.1133	0.0003	0.0047	0.0010	**0.2775**
Washington	1.1650	0.0313	0.0369	0.0061	0.0002	0.0033	0.0006	**1.2434**
West Virginia	0.0087	0.0131	0.0150	0.0007	0.0001	0.0013	0.0004	**0.0394**
Wisconsin	2.3711	0.0308	0.0137	0.0733	0.0004	0.0055	0.0010	**2.4957**
Wyoming	0.0214	0.0544	0.0008	0.0156	0.0001	0.0039	0.0044	**0.1005**
Total	**31.7743**	**3.0036**	**3.2233**	**23.0582**	**0.0199**	**0.2240**	**0.0715**	**61.3748**

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent. Managed manure includes emissions from grazed lands. Bison were not portioned at the State level because emissions were minimal.
Source: EPA 2015

Appendix Table A-17 Nitrous Oxide Emissions from Manure Management by State and Animal in 2013

	Dairy cattle	Beef cattle	Poultry	Swine	*Total*
State			*MMT CO_2 eq.*		
Alabama	0.0022	0.0050	0.1201	0.0027	**0.1299**
Alaska	0.0002	0.0000	0.0018	0.0000	**0.0021**
Arizona	0.1144	0.1543	0.0019	0.0045	**0.2751**
Arkansas	0.0022	0.0000	0.1421	0.0037	**0.1481**
California	1.1133	0.2755	0.0394	0.0026	**1.4308**
Colorado	0.1128	0.5975	0.0081	0.0207	**0.7392**
Connecticut	0.0076	0.0002	0.0040	0.0000	**0.0118**
Delaware	0.0021	0.0002	0.0224	0.0002	**0.0248**
Florida	0.0455	0.0027	0.0192	0.0001	**0.0675**
Georgia	0.0232	0.0039	0.1612	0.0035	**0.1919**
Hawaii	0.0020	0.0007	0.0018	0.0003	**0.0048**
Idaho	0.4462	0.1332	0.0019	0.0011	**0.5824**
Illinois	0.0707	0.0906	0.0115	0.1370	**0.3098**
Indiana	0.1030	0.0574	0.0585	0.1077	**0.3268**
Iowa	0.1578	0.7224	0.0766	0.5824	**1.5392**
Kansas	0.1209	1.2832	0.0018	0.0597	**1.4656**
Kentucky	0.0170	0.0080	0.0379	0.0090	**0.0719**
Louisiana	0.0025	0.0024	0.0096	0.0000	**0.0145**
Maine	0.0125	0.0004	0.0047	0.0000	**0.0177**
Maryland	0.0217	0.0057	0.0339	0.0006	**0.0619**
Massachusetts	0.0048	0.0002	0.0010	0.0001	**0.0060**
Michigan	0.2720	0.0871	0.0235	0.0317	**0.4145**
Minnesota	0.3562	0.1755	0.0582	0.2178	**0.8076**
Mississippi	0.0030	0.0048	0.0829	0.0132	**0.1040**
Missouri	0.0534	0.0289	0.0974	0.0772	**0.2570**
Montana	0.0108	0.0207	0.0015	0.0049	**0.0379**
Nebraska	0.0366	1.4551	0.0184	0.0903	**1.6004**
Nevada	0.0177	0.0048	0.0018	0.0000	**0.0243**
New Hampshire	0.0054	0.0001	0.0018	0.0000	**0.0074**
New Jersey	0.0029	0.0002	0.0018	0.0002	**0.0050**
New Mexico	0.1969	0.0107	0.0019	0.0000	**0.2095**
New York	0.2555	0.0142	0.0124	0.0018	**0.2839**
North Carolina	0.0130	0.0035	0.1299	0.2466	**0.3929**
North Dakota	0.0143	0.0272	0.0018	0.0039	**0.0472**
Ohio	0.1756	0.0929	0.0509	0.0601	**0.3796**
Oklahoma	0.0294	0.1987	0.0258	0.0636	**0.3176**
Oregon	0.0790	0.0377	0.0091	0.0001	**0.1259**
Pennsylvania	0.2138	0.0427	0.0546	0.0341	**0.3453**
Rhode Island	0.0004	0.0000	0.0018	0.0000	**0.0022**
South Carolina	0.0038	0.0014	0.0391	0.0074	**0.0518**
South Dakota	0.0730	0.1811	0.0071	0.0347	**0.2959**
Tennessee	0.0106	0.0024	0.0203	0.0047	**0.0380**
Texas	0.2850	1.5660	0.0868	0.0206	**1.9583**
Utah	0.0704	0.0156	0.0092	0.0210	**0.1162**
Vermont	0.0511	0.0006	0.0010	0.0000	**0.0527**
Virginia	0.0195	0.0131	0.0417	0.0075	**0.0819**
Washington	0.1620	0.1396	0.0149	0.0007	**0.3173**
West Virginia	0.0037	0.0024	0.0142	0.0001	**0.0204**
Wisconsin	0.9368	0.1358	0.0132	0.0082	**1.0941**
Wyoming	0.0045	0.0401	0.0008	0.0028	**0.0482**
Total	**5.739**	**7.647**	**1.583**	**1.890**	**16.8586**

Note: Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent. Other animal types were not portioned at the State level because emissions were minimal.
Source: EPA 2015

Appendix Table A-18 Waste Characteristics Data

Animal Group	Average TAM[1] (kg)	Nitrogen, N_{ex}[2] (kg/day per 1,000 kg mass)	Max Methane Generation Potential, B_o (m^3 CH_4/kg VS added)	Volatile Solids, VS (kg/day per 1,000 kg mass)
Dairy Cows	680	0.62	0.24	10.99
Dairy Heifers	406-408	0.50	0.17	10.08
Feedlot Steers	419-457	0.34	0.33	3.97
Feedlot Heifers	384-430	0.35	0.33	4.34
Bulls NOF[3]	831-917	0.21	0.17	5.03
Calves NOF	118	0.45	0.17	7.70
Heifers NOF	296-407	0.32	0.17	4.59
Steers NOF	314-335	0.31	0.17	8.16
Cows NOF	554-611	0.31	0.17	7.66
American Bison	579	0.70	0.17	12.10
Market Swine <50 lbs.	13	0.54	0.48	8.80
Market Swine 50-119 lbs.	39	0.54	0.48	5.40
Market Swine 120-179 lbs.	68	0.54	0.48	5.40
Market Swine >180 lbs.	91	0.20	0.48	5.40
Breeding Swine	198	0.45	0.48	2.70
Sheep	80	0.45	0.19	8.30
Goats	64	0.79	0.17	9.50
Horses	450	0.30	0.33	6.10
Mules and Asses	130	0.54	0.33	7.20
Hens ≥ 1 yr	1.8	0.79	0.39	10.20
Pullets	1.8	1.10	0.39	10.20
Other Chickens	1.8	0.96	0.39	11.00
Broilers	0.9	0.63	0.36	17.00
Turkeys	6.8	0.25	0.36	8.50

Source: EPA 2015.
[1](TAM) Typical animal mass.
[2](N_{ex}) Nitrogen excretion.
[3](NOF) Not on feed.

Appendix Table A-19 State Volatile Solids Production Rates in 2013

	Dairy Cow	Dairy Heifer	Beef Cow NOF[1]	Beef Heifer NOF	Beef Steer NOF	Beef Heifer OF[2]	Beef Steer OF
State	*kg/day/1,000 kg mass*						
Alabama	8.66	8.51	7.46	7.41	7.49	4.40	4.03
Alaska	7.64	8.51	8.48	8.59	8.61	4.40	4.02
Arizona	11.54	8.45	8.48	8.28	8.61	4.36	3.98
Arkansas	7.96	8.51	7.46	7.37	7.49	NA	NA
California	11.33	8.51	8.48	8.16	8.61	4.40	4.02
Colorado	11.73	8.45	8.48	8.03	8.61	4.36	3.98
Connecticut	10.63	8.49	7.51	7.47	7.54	4.39	4.02
Delaware	10.30	8.49	7.51	7.31	7.54	4.39	4.02
Florida	10.48	8.51	7.46	7.43	7.49	4.40	4.03
Georgia	10.52	8.51	7.46	7.38	7.49	4.40	4.02
Hawaii	8.46	8.51	8.48	8.46	8.61	4.40	4.03
Idaho	11.48	8.45	8.48	8.19	8.61	4.36	3.98
Illinois	10.26	8.46	7.12	6.83	7.12	4.37	3.99
Indiana	10.98	8.46	7.12	6.86	7.12	4.37	3.99
Iowa	11.09	8.46	7.12	6.63	7.12	4.37	3.99
Kansas	11.01	8.46	7.12	6.59	7.12	4.37	3.99
Kentucky	9.21	8.49	7.46	7.22	7.49	4.39	4.00
Louisiana	8.32	8.51	7.46	7.41	7.49	4.40	4.03
Maine	10.31	8.49	7.51	7.32	7.54	4.39	4.02
Maryland	10.28	8.49	7.51	7.28	7.54	4.39	4.01
Massachusetts	9.75	8.49	7.51	7.39	7.54	4.39	4.01
Michigan	11.69	8.46	7.12	6.79	7.12	4.37	3.99
Minnesota	10.36	8.46	7.12	6.78	7.12	4.37	3.99
Mississippi	8.63	8.51	7.46	7.36	7.49	4.40	4.03
Missouri	8.84	8.46	7.12	6.94	7.12	4.37	3.99
Montana	10.84	8.45	8.48	8.45	8.61	4.36	3.98
Nebraska	10.92	8.46	7.12	6.65	7.12	4.37	3.99
Nevada	11.11	8.45	8.48	8.34	8.61	4.36	3.98
New Hampshire	10.70	8.49	7.51	7.35	7.54	4.39	4.01
New Jersey	9.89	8.49	7.51	7.39	7.54	4.39	4.02
New Mexico	11.94	8.45	8.48	8.25	8.61	4.36	3.99
New York	11.07	8.49	7.51	7.27	7.54	4.39	4.01
North Carolina	10.77	8.49	7.46	7.39	7.49	4.39	4.01
North Dakota	10.15	8.46	7.12	6.88	7.12	4.37	4.00
Ohio	10.50	8.46	7.12	6.85	7.12	4.37	3.99
Oklahoma	9.73	8.45	7.46	7.17	7.49	4.36	3.98
Oregon	10.58	8.51	8.48	8.38	8.61	4.40	4.02
Pennsylvania	10.39	8.49	7.51	7.25	7.54	4.39	4.01
Rhode Island	10.15	8.49	7.51	7.47	7.54	4.39	4.01
South Carolina	9.61	8.51	7.46	7.39	7.49	4.40	4.03
South Dakota	10.91	8.46	7.12	6.79	7.12	4.37	3.99
Tennessee	9.46	8.49	7.46	7.35	7.49	4.39	4.03
Texas	11.07	8.45	7.46	7.06	7.49	4.36	3.98
Utah	11.09	8.45	8.48	8.31	8.61	4.36	3.98
Vermont	10.28	8.49	7.51	7.21	7.54	4.39	4.01
Virginia	10.17	8.49	7.46	7.31	7.49	4.39	4.01
Washington	11.60	8.51	8.48	8.09	8.61	4.40	4.02
West Virginia	9.00	8.49	7.51	7.34	7.54	4.39	4.01
Wisconsin	10.96	8.46	7.12	6.93	7.12	4.37	3.99
Wyoming	10.86	8.45	8.48	8.38	8.61	4.36	3.98

Source: EPA 2015.
[1](NOF) Not on feed.
[2](OF) On feed.

Appendix Table A-20 State-Based Methane Conversion Factors[1] for Liquid Waste Management Systems in 2013

	Dairy		Swine		Beef	Poultry
	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Anaerobic Lagoon	Liquid/Slurry and Deep Pit	Liquid/Slurry	Anaerobic Lagoon
State	*percent*					
Alabama	75	37	75	36	38	75
Alaska	47	15	47	15	15	47
Arizona	78	57	77	47	52	74
Arkansas	75	34	76	37	35	75
California	73	32	72	31	41	74
Colorado	65	22	68	24	24	65
Connecticut	69	25	69	25	26	69
Delaware	73	31	73	31	31	73
Florida	79	55	79	53	53	79
Georgia	76	39	75	38	37	75
Hawaii	76	57	76	57	57	76
Idaho	69	25	66	22	22	68
Illinois	72	29	72	28	27	72
Indiana	70	27	71	27	27	71
Iowa	70	25	70	26	26	70
Kansas	74	32	74	32	32	74
Kentucky	73	31	73	31	30	73
Louisiana	77	45	77	46	46	77
Maine	63	21	63	21	21	64
Maryland	72	30	72	30	31	73
Massachusetts	67	24	68	25	25	68
Michigan	67	23	67	24	24	67
Minnesota	68	24	69	24	24	67
Mississippi	76	40	76	39	41	76
Missouri	73	30	73	30	30	74
Montana	61	19	64	21	21	64
Nebraska	72	27	72	27	27	72
Nevada	70	26	71	27	25	70
New Hampshire	64	22	65	22	22	65
New Jersey	71	28	71	29	28	71
New Mexico	73	31	71	28	30	70
New York	65	23	66	23	23	66
North Carolina	73	31	75	36	30	73
North Dakota	66	22	66	22	22	66
Ohio	69	26	70	27	27	70
Oklahoma	76	37	76	35	36	76
Oregon	64	21	63	21	22	63
Pennsylvania	69	26	70	27	27	70
Rhode Island	69	26	69	26	26	69
South Carolina	75	37	75	38	36	75
South Dakota	69	24	70	25	25	70
Tennessee	73	31	74	32	31	73
Texas	76	41	76	44	38	77
Utah	65	22	68	24	24	65
Vermont	63	21	63	21	21	63
Virginia	71	28	72	31	29	71
Washington	64	21	66	22	23	65
West Virginia	69	26	70	26	26	69
Wisconsin	66	23	68	24	23	67
Wyoming	63	20	64	21	22	64

Source: EPA 2015, IPCC 2006.

[1](MCF) Methane conversion factors represent weighted average of multiple animal types.

Appendix Table A-21 Maximum Methane Generation Potential, B_0

Animal Group	m^3 CH_4/kg VS added[1]	Source
Dairy Cows	0.24	Morris 1976
Dairy Heifers	0.17	Bryant et al. 1976
Feedlot Steers/Heifers	0.33	Hashimoto 1981
NOF Beef	0.17	Hashimoto 1981
American Bison	0.17	Based on the beef NOF bull B_0
Swine	0.48	Hashimoto 1984
Sheep*	0.34	EPA 1992
Goats	0.17	EPA 1992
Horses	0.33	EPA 1992
Mules	0.33	Based on the horse B_0
Broilers	0.36	Hill 1984
Other Chickens	0.39	Hill 1982
Turkeys	0.36	Hill 1984
Dairy Cows	0.24	Morris 1976

Source: EPA 2015, IPCC 2006.

[1] m^3 CH_4/kg VS added is cubic meter methane per kilogram of volatile solids.

Appendix Table A-22 Methane Conversion Factors for Dry Systems

Waste Management System	Cool Climate MCF[1]	Temperate Climate MCF	Warm Climate MCF
		percent	
Aerobic Treatment	0	0	0
Anaerobic Digester	0	0	0
Cattle Deep Litter (<1 month)	3	3	30
Cattle Deep Litter (>1 month)	21	44	76
Composting - In Vessel	0.5	0.5	0.5
Composting - Static Pile	0.5	0.5	0.5
Composting-Extensive/Passive	0.5	1	1.5
Composting-Intensive	0.5	1	1.5
Daily Spread	0.1	0.5	1
Dry Lot	1	1.5	5
Fuel	10	10	10
Pasture	1	1.5	2
Poultry with bedding	1.5	1.5	1.5
Poultry without bedding	1.5	1.5	1.5
Solid Storage	2	4	5

Source: EPA 2015, IPCC 2006.

[1] MCF is methane conversion factor.

Appendix Table A-23 Methane Conversion Factors for Livestock Waste Emissions in 2013

State	Beef Feedlot Heifer	Beef Feedlot Steer	Dairy Cow	Dairy Heifer	Swine Market	Swine Breeding	Layer	Broiler	Turkey	Sheep	Goats	Horses
						percent						
Alabama	2.0	2.0	16.9	1.9	54.2	53.9	32.3	1.5	1.5	1.5	1.5	1.5
Alaska	1.2	1.2	16.4	1.1	8.1	8.1	12.9	1.5	1.5	1.0	1.0	1.0
Arizona	21.0	21.0	79.5	21.9	77.3	75.5	61.0	3.0	3.0	3.0	3.0	3.0
Arkansas	1.4	1.4	9.7	1.3	50.1	50.0	1.5	1.5	1.5	1.5	1.5	1.5
California	2.0	2.0	49.8	1.8	47.7	47.7	10.2	1.5	1.5	1.5	1.5	1.5
Colorado	1.1	1.1	47.2	1.1	29.2	29.0	39.6	1.5	1.5	1.0	1.0	1.0
Connecticut	1.3	1.3	13.2	1.2	8.3	8.3	4.9	1.5	1.5	1.0	1.0	1.0
Delaware	1.3	1.3	14.3	1.3	34.7	34.7	5.1	1.5	1.5	1.0	1.0	1.0
Florida	2.2	2.2	42.4	2.0	17.0	16.8	34.0	1.5	1.5	1.5	1.5	1.5
Georgia	2.0	2.0	22.3	1.9	54.8	54.3	32.1	1.5	1.5	1.5	1.5	1.5
Hawaii	2.2	2.2	57.7	2.1	40.7	40.7	20.2	1.5	1.5	1.5	1.5	1.5
Idaho	1.1	1.1	48.0	1.1	25.3	25.3	41.3	1.5	1.5	1.0	1.0	1.0
Illinois	1.2	1.2	21.1	1.1	32.8	33.0	2.9	1.5	1.5	1.0	1.0	1.0
Indiana	1.2	1.2	18.6	1.1	31.7	31.8	1.5	1.5	1.5	1.0	1.0	1.0
Iowa	1.2	1.2	23.2	1.1	48.5	48.7	1.5	1.5	1.5	1.0	1.0	1.0
Kansas	1.2	1.2	39.4	1.2	35.2	35.2	3.0	1.5	1.5	1.0	1.0	1.0
Kentucky	1.3	1.3	5.6	1.2	48.7	48.7	5.1	1.5	1.5	1.0	1.0	1.0
Louisiana	2.1	2.1	11.8	2.0	7.4	7.4	46.9	1.5	1.5	1.5	1.5	1.5
Maine	1.2	1.2	10.8	1.2	10.8	10.8	4.6	1.5	1.5	1.0	1.0	1.0
Maryland	1.3	1.3	12.0	1.2	33.5	33.9	5.1	1.5	1.5	1.0	1.0	1.0
Massachusetts	1.3	1.3	10.4	1.2	14.9	14.8	4.8	1.5	1.5	1.0	1.0	1.0
Michigan	1.1	1.1	27.1	1.1	28.6	28.3	2.8	1.5	1.5	1.0	1.0	1.0
Minnesota	1.1	1.1	16.7	1.1	30.6	30.5	1.5	1.5	1.5	1.0	1.0	1.0
Mississippi	2.0	2.0	11.8	1.9	57.0	58.2	46.4	1.5	1.5	1.5	1.5	1.5
Missouri	1.2	1.2	17.5	1.2	32.0	32.2	1.5	1.5	1.5	1.0	1.0	1.0
Montana	1.1	1.1	29.5	1.1	26.2	26.2	38.7	1.5	1.5	1.0	1.0	1.0
Nebraska	1.2	1.2	31.2	1.1	31.8	31.8	2.9	1.5	1.5	1.0	1.0	1.0
Nevada	13.1	13.1	64.4	12.9	35.6	35.2	13.5	2.5	2.5	2.0	2.0	2.0
New Hampshire	12.8	12.8	22.2	12.8	23.0	22.9	16.2	2.5	2.5	2.0	2.0	2.0
New Jersey	14.7	14.7	22.3	14.8	37.5	37.5	18.5	2.5	2.5	2.0	2.0	2.0
New Mexico	15.1	15.1	66.6	15.4	14.4	14.6	55.4	2.5	2.5	2.0	2.0	2.0
New York	1.2	1.2	11.2	1.2	25.8	25.9	4.7	1.5	1.5	1.0	1.0	1.0
North Carolina	1.3	1.3	12.9	1.2	56.4	56.2	31.5	1.5	1.5	1.0	1.0	1.0
North Dakota	1.1	1.1	17.4	1.1	27.8	27.4	2.8	1.5	1.5	1.0	1.0	1.0
Ohio	1.2	1.2	17.8	1.1	31.0	31.0	1.5	1.5	1.5	1.0	1.0	1.0
Oklahoma	1.1	1.1	45.4	1.6	56.7	57.1	46.0	1.5	1.5	1.0	1.0	1.0
Oregon	1.3	1.3	34.5	1.2	15.5	15.5	16.8	1.5	1.5	1.0	1.0	1.0
Pennsylvania	1.3	1.3	7.6	1.2	31.3	30.9	1.5	1.5	1.5	1.0	1.0	1.0
Rhode Island	1.3	1.3	8.0	1.2	10.2	10.2	4.9	1.5	1.5	1.0	1.0	1.0
South Carolina	2.0	2.0	18.4	1.9	56.4	56.1	45.8	1.5	1.5	1.5	1.5	1.5
South Dakota	1.1	1.1	30.1	1.1	31.1	31.1	2.9	1.5	1.5	1.0	1.0	1.0
Tennessee	1.3	1.3	7.3	1.2	43.9	43.6	5.1	1.5	1.5	1.0	1.0	1.0
Texas	1.7	1.7	51.9	1.6	50.3	50.4	10.5	1.5	1.5	1.5	1.5	1.5
Utah	1.1	1.1	42.7	1.1	30.7	27.6	39.6	1.5	1.5	1.0	1.0	1.0
Vermont	1.2	1.2	10.8	1.2	11.4	11.5	4.6	1.5	1.5	1.0	1.0	1.0
Virginia	1.3	1.3	7.4	1.2	50.5	50.3	5.0	1.5	1.5	1.0	1.0	1.0
Washington	1.3	1.3	38.4	1.2	17.1	16.7	9.1	1.5	1.5	1.0	1.0	1.0
West Virginia	14.2	14.2	22.4	14.2	27.1	27.0	17.6	2.5	2.5	2.0	2.0	2.0
Wisconsin	1.1	1.1	16.3	1.1	27.0	26.9	2.8	1.5	1.5	1.0	1.0	1.0
Wyoming	1.1	1.1	33.1	1.1	16.7	16.7	38.7	1.5	1.5	1.0	1.0	1.0

Note: Methane conversion factors are weighted by the distribution of waste management systems for each animal type within a State.
Source: EPA 2015

Appendix Table A-24 Direct Nitrous Oxide Emission Factors for 2013

Waste Management System	**Direct N_2O Emission Factor**
	kg N_2O-N/kg Kjdl N[1]
Aerobic Treatment (forced aeration)	0.005
Aerobic Treatment (natural aeration)	0.01
Anaerobic Digester	0
Anaerobic Lagoon	0
Cattle Deep Bed (active mix)	0.07
Cattle Deep Bed (no mix)	0.01
Composting in vessel	0.006
Composting intensive	0.1
Composting passive	0.01
Composting static	0.006
Daily Spread	0
Deep Pit	0.002
Dry Lot	0.02
Fuel	0
Liquid/Slurry	0.005
Pasture[2]	0
Poultry with bedding	0.001
Poultry without bedding	0.001
Solid Storage	0.005

Note: N_2O is nitrous oxide.
Source: EPA 2015, IPCC 2006.
[1] kg N_2O-N/kg Kjdl N is kilograms nitrogen in nitrous oxide per kilograms kjeldahl nitrogen.
[2] Calculated using Tier 3 DayCent Model simulations.

Appendix Table A-25 Nitrogen in Livestock Waste on Grazed Lands

Year	*MMT N*
1990	4.1
1991	4.1
1992	4.3
1993	4.3
1994	4.4
1995	4.5
1996	4.5
1997	4.4
1998	4.3
1999	4.2
2000	4.1
2001	4.1
2002	4.1
2003	4.1
2004	4.1
2005	4.1
2006	4.2
2007	4.0
2008	4.0
2009	4.0
2010	3.9
2011	3.8
2012	3.7
2013	3.7

Note: MMT N is million metric tons nitrogen.
Source: EPA 2015

Appendix Table A-26 MLRA-Level Estimates of Mean Annual Soil Carbon Stock Changes from Non-Federal Grasslands, 2003-2007

MLRA[1]	Area	Total dSOC
	ha	*Gg CO_2 eq.*[2]
1	54,597	-52.8
2	243,632	-333.8
3	17,773	-86.5
5	263,473	-345.0
6	179,315	-35.1
7	409,089	-4.4
8	2,379,429	-4.3
9	796,574	41.0
10	2,071,584	142.9
11	722,976	73.4
12	145,949	-1.5
13	625,994	24.5
14	140,555	-33.4
15	2,036,110	-174.5
17	1,025,755	-95.4
18	850,862	-14.4
19	167,401	-51.9
20	710,349	-71.3
21	578,811	-89.1
23	987,306	6.0
24	531,483	162.7
25	1,567,731	133.9
26	310,276	6.3
27	799,461	154.2
29	333,839	-28.3
30	1,193,928	-39.1
31	146,278	-22.0
32	807,861	-90.1
35	8,939,750	568.5
36	1,339,729	35.6
38	1,678,101	-57.5
39	300,000	36.2
40	2,644,850	113.4
41	2,032,033	-11.1
42	7,117,114	231.7
44	1,386,170	155.0
46	2,334,195	473.0
47	1,299,930	198.1
49	1,451,736	143.7
51	576,854	-128.6
52	2,037,706	825.3
54	4,052,914	272.8
56	272,722	-92.5
57	217,910	-49.5
61	237,646	17.1
62	133,877	54.6
64	1,962,501	-58.9
65	4,703,281	-109.5
66	970,886	-45.6
69	2,245,770	71.1
71	1,012,309	167.5
72	2,419,203	70.8
73	2,267,127	248.5
74	607,367	-61.8
75	323,527	-31.5
76	1,510,595	-188.1
79	411,928	-27.4
85	1,369,323	-235.2
88	63,503	-81.8
89	31,158	-18.9
92	36,473	-22.0
96	51,706	-16.5
97	47,882	-12.3
98	301,989	-130.2
99	63,472	-18.7
101	154,267	-35.1
103	328,349	-218.8
104	140,345	-166.1
105	626,326	-425.5
106	572,613	-144.4
109	926,578	-483.5
110	66,940	-41.0
112	2,230,417	-661.1
113	277,306	-143.2
117	240,831	-88.5
119	341,603	-70.6
121	632,837	-315.7
122	940,743	-464.0
123	339,212	-176.0
124	250,471	-89.7
125	201,304	-77.0
126	385,164	-163.5
127	189,799	-46.5
128	861,793	-490.2
129	204,725	-115.4
134	737,073	-603.6
136	1,117,885	-865.2
137	46,206	-43.2
138	72,997	-37.6
139	144,352	-81.1
140	371,164	-130.4
141	8,165	-2.4
142	126,775	-68.8
143	39,121	-15.6
145	10,074	-5.0
147	404,552	-180.0
148	338,595	-126.7
151	78,578	1.8
154	260,436	-82.6
155	1,209,929	-356.8
102A	802,261	-627.7
102B	56,522	-67.9
102C	451,346	-247.1
107A	62,367	-213.7
107B	341,131	-1011.1
108A	42,462	-27.2
108B	106,015	-92.6
108C	143,023	-321.7
108D	230,418	-572.3
111A	144,848	-93.2
111B	119,404	-42.9
111C	41,763	-12.2
111D	59,226	-6.3
111E	27,900	-22.7
114A	104,534	-42.2
114B	121,249	-71.0
115A	53,780	-36.7
115B	305,634	-137.4
115C	345,948	-216.1
116A	2,126,540	-821.3
116B	507,825	-294.8
116C	66,379	-28.6
118A	616,870	-162.0
118B	291,406	-82.2
120A	265,303	-171.6
120B	63,592	-25.8

Continued - Appendix Table A-26 MLRA-Level Estimates of Mean Annual Soil Carbon Stock Changes from Non-Federal Grasslands, 2003-2007

120C	11,235	-1.7
130A	12,035	-8.3
130B	203,692	-114.0
131A	241,071	-158.0
131B	42,168	-18.0
131C	140,088	-71.6
131D	29,985	-12.4
133A	1,441,544	-1125.0
133B	1,187,959	-354.9
135A	381,841	-304.5
135B	309,250	-82.7
144A	119,969	-55.9
144B	79,998	-46.5
149A	31,531	-6.8
149B	3,112	-0.9
150A	1,165,952	-111.6
150B	249,079	-13.3
152A	38,047	-21.8
152B	79,521	-57.7
153A	86,206	-44.0
153B	9,909	-11.4
153C	15,220	-11.8
153D	14,083	-13.5
156A	67,768	-8.4
156B	104,655	-17.2
22A	82,010	6.8
28A	1,330,232	262.1
28B	305,998	31.5
34A	3,017,610	140.3
34B	731,884	133.5
43A	364,330	-26.6
43B	2,443,145	375.3
43C	233,023	-35.6
48A	1,536,456	379.2
48B	317,086	-37.9
4A	58,168	-8.3
4B	85,756	-6.2
53A	958,782	103.0
53B	1,768,162	-4.4
53C	422,626	69.4
55A	419,991	0.5
55B	590,906	-39.5
55C	863,882	28.7
58A	6,188,798	968.9
58B	3,783,888	632.0
58C	199,531	30.8
58D	528,343	44.2
60A	1,792,553	10.6
60B	668,113	106.7
63A	1,647,732	-78.1
63B	658,307	-8.5
67A	1,454,712	344.7
67B	2,202,593	186.4
70A	1,974,891	311.2
70B	1,854,571	90.9
70C	2,043,147	164.1
70D	279,833	11.7
77A	702,904	-86.2
77B	640,671	-27.9
77C	1,205,012	-52.8
77D	1,405,153	266.8
77E	1,664,797	91.9
78A	639,230	40.8
78B	2,491,438	123.8
78C	2,445,635	-63.2
80A	1,963,077	-347.1
80B	968,445	53.3
81A	2,866,367	-2.8
81B	1,940,970	97.6
81C	1,236,724	120.7
81D	516,702	-37.7
82A	401,734	13.3
82B	57,923	-1.0
83A	1,706,897	123.5
83B	1,463,751	1.2
83C	755,825	55.5
83D	129,375	-7.5
83E	659,343	35.3
84A	875,391	-131.7
84B	745,691	-134.3
84C	113,856	-30.2
86A	1,453,945	-373.1
86B	351,296	5.5
87A	1,544,144	-23.5
87B	410,138	-149.7
90A	265,868	-168.5
90B	248,178	-208.1
91A	161,283	-85.5
91B	52,108	-43.2
94A	130,138	-102.6
94B	61,815	-50.0
94C	25,098	-15.9
95A	91,989	-91.8
95B	223,059	-195.9
Total	180,415,846	**-10889.0**

Note: dSOC is dissolved soil organic carbon.
[1] MLRA = Major Land Resource Area
[2] Gg CO_2 eq. = Gigagrams carbon dioxide equivalent

Appendix Table A-27 MLRA-Level Estimates of Mean Annual Direct and Indirect N_2O Emissions from Non-Federal Grasslands, 2003-2007

MLRA[1]	Area	Direct Soil N_2O	Indirect N_2O from NO_3 Leached/Runoff	Indirect N_2O from NH_3/NO_x Volitilization
	ha		*Gg CO_2 eq.*[2]	
1	54,597	81.5	11.3	2.3
2	243,632	466.8	49.1	14.0
3	17,773	68.2	3.0	1.1
5	263,473	674.3	44.9	16.3
6	179,315	265.0	1.6	2.8
7	409,089	105.7	0.0	4.1
8	2,379,429	1030.9	2.5	27.1
9	796,574	567.3	3.3	11.6
10	2,071,584	978.2	2.8	27.6
11	722,976	242.5	0.0	8.3
12	145,949	84.6	0.1	1.8
13	625,994	287.2	0.4	7.4
14	140,555	15.1	2.5	1.7
15	2,036,110	133.0	12.2	18.7
17	1,025,755	69.8	3.5	9.7
18	850,862	96.5	7.5	8.7
19	167,401	7.4	0.4	1.4
20	710,349	28.5	0.3	5.1
21	578,811	891.9	7.2	12.2
23	987,306	391.0	0.0	12.8
24	531,483	167.0	0.0	5.3
25	1,567,731	563.7	0.1	20.0
26	310,276	170.3	0.3	3.3
27	799,461	88.6	0.0	7.2
29	333,839	33.4	0.1	2.1
30	1,193,928	44.7	0.0	7.9
31	146,278	4.9	0.0	1.0
32	807,861	193.7	0.0	12.1
35	8,939,750	986.7	0.0	102.5
36	1,339,729	406.0	0.2	19.8
38	1,678,101	90.4	0.0	12.4
39	300,000	30.6	0.0	4.1
40	2,644,850	76.8	0.0	14.4
41	2,032,033	64.4	0.0	11.0
42	7,117,114	1321.3	0.0	145.8
44	1,386,170	1239.4	6.8	22.1
46	2,334,195	1115.9	2.2	38.1
47	1,299,930	634.0	1.7	17.7
49	1,451,736	432.1	0.0	27.6
51	576,854	197.2	0.1	8.9
52	2,037,706	510.9	0.0	29.4
54	4,052,914	884.0	0.0	64.7
56	272,722	112.3	0.4	7.9
57	217,910	142.1	4.2	8.1
61	237,646	56.3	0.2	3.9

Continued - Appendix Table A-27 MLRA-Level Estimates of Mean Annual Direct and Indirect N_2O Emissions from Non-Federal Grasslands, 2003-2007

MLRA[1]	Area	Direct Soil N_2O	Indirect N_2O from NO_3 Leached/Runoff	Indirect N_2O from NH_3/NO_x Volitilization
	ha		*Gg CO_2 eq.*[2]	
62	133,877	31.4	0.3	2.3
64	1,962,501	386.5	0.0	38.3
65	4,703,281	1194.1	0.6	117.9
66	970,886	229.9	0.0	22.3
69	2,245,770	674.5	0.0	43.1
71	1,012,309	343.5	0.5	22.0
72	2,419,203	774.3	0.0	58.8
73	2,267,127	1022.8	0.2	56.9
74	607,367	277.6	5.1	16.0
75	323,527	134.5	1.1	7.9
76	1,510,595	871.1	18.8	39.1
79	411,928	109.0	0.9	11.6
85	1,369,323	1174.6	24.5	63.1
88	63,503	91.5	1.5	3.6
89	31,158	53.2	2.9	1.6
92	36,473	94.5	1.1	2.1
96	51,706	68.9	3.3	1.9
97	47,882	80.2	3.3	2.2
98	301,989	353.5	17.1	13.4
99	63,472	50.3	2.2	2.2
101	154,267	349.7	9.0	6.5
103	328,349	283.5	9.5	10.6
104	140,345	208.8	6.5	5.7
105	626,326	789.1	22.3	22.6
106	572,613	298.1	3.0	13.9
109	926,578	949.5	52.2	32.1
110	66,940	92.3	3.2	2.4
112	2,230,417	1228.1	37.7	56.8
113	277,306	248.7	9.6	9.3
117	240,831	115.6	14.6	8.3
119	341,603	151.3	20.9	10.6
121	632,837	852.0	42.0	22.0
122	940,743	658.1	63.5	39.1
123	339,212	218.9	22.2	12.1
124	250,471	342.1	16.5	9.5
125	201,304	164.7	19.4	7.8
126	385,164	483.7	22.3	13.9
127	189,799	287.8	12.8	8.3
128	861,793	603.4	55.4	36.3
129	204,725	66.3	13.0	9.6
134	737,073	344.1	26.8	32.4
136	1,117,885	827.3	81.1	77.7
137	46,206	22.9	5.3	3.6
138	72,997	20.7	5.2	5.2
139	144,352	241.8	6.5	6.3
140	371,164	799.8	23.1	18.6
141	8,165	19.6	0.4	0.4

Continued - Appendix Table A-27 MLRA-Level Estimates of Mean Annual Direct and Indirect N_2O Emissions from Non-Federal Grasslands, 2003-2007

MLRA[1]	Area	Direct Soil N_2O	Indirect N_2O from NO_3 Leached/Runoff	Indirect N_2O from NH_3/NO_x Volitilization
	ha	*Gg CO_2 eq.*[2]		
142	126,775	252.3	5.6	5.0
143	39,121	73.9	2.6	1.5
145	10,074	17.9	0.6	0.4
147	404,552	472.2	28.4	22.3
148	338,595	308.7	19.2	16.0
151	78,578	44.0	0.8	1.8
154	260,436	91.1	25.0	14.2
155	1,209,929	335.6	76.4	45.4
102A	802,261	311.0	3.0	18.5
102B	56,522	15.0	0.0	1.1
102C	451,346	153.5	1.4	9.7
107A	62,367	77.9	1.1	2.7
107B	341,131	287.0	3.5	11.8
108A	42,462	55.1	1.3	1.5
108B	106,015	127.4	2.7	3.7
108C	143,023	245.9	9.8	6.5
108D	230,418	285.6	12.0	9.4
111A	144,848	147.4	8.2	4.7
111B	119,404	89.6	4.0	3.9
111C	41,763	33.1	2.5	1.6
111D	59,226	73.5	3.8	2.0
111E	27,900	34.2	1.5	1.1
114A	104,534	113.7	5.0	3.8
114B	121,249	146.4	6.6	4.4
115A	53,780	56.5	2.5	2.1
115B	305,634	282.0	8.7	8.8
115C	345,948	353.1	8.2	11.8
116A	2,126,540	1554.0	113.0	74.3
116B	507,825	367.5	20.0	18.9
116C	66,379	71.4	3.0	1.9
118A	616,870	248.2	33.2	17.6
118B	291,406	116.3	8.5	7.5
120A	265,303	226.2	13.5	10.6
120B	63,592	76.7	4.0	2.5
120C	11,235	14.5	0.8	0.4
130A	12,035	12.2	0.8	0.5
130B	203,692	161.1	13.1	8.6
131A	241,071	149.7	6.1	9.0
131B	42,168	30.8	1.3	1.3
131C	140,088	101.5	3.3	5.5
131D	29,985	14.1	1.5	1.0
133A	1,441,544	567.7	108.2	81.9
133B	1,187,959	413.2	59.1	41.4
135A	381,841	315.0	18.7	17.6
135B	309,250	194.0	15.3	10.6
144A	119,969	202.9	8.0	5.0
144B	79,998	148.5	4.7	3.0

Continued - Appendix Table A-27 MLRA-Level Estimates of Mean Annual Direct and Indirect N_2O Emissions from Non-Federal Grasslands, 2003-2007

MLRA[1]	Area	Direct Soil N_2O	Indirect N_2O from NO_3 Leached/Runoff	Indirect N_2O from NH_3/NO_x Volitilization
	ha		*Gg CO_2 eq.*[2]	
149A	31,531	20.7	2.6	1.5
149B	3,112	1.7	0.2	0.1
150A	1,165,952	380.2	16.6	35.9
150B	249,079	53.9	2.4	5.3
152A	38,047	11.3	1.9	2.0
152B	79,521	23.1	2.9	3.2
153A	86,206	30.3	6.8	5.8
153B	9,909	3.7	0.4	0.6
153C	15,220	10.3	1.3	1.0
153D	14,083	9.1	1.2	0.9
156A	67,768	12.3	2.3	1.8
156B	104,655	27.2	5.4	3.4
22A	82,010	71.0	0.9	1.0
28A	1,330,232	476.9	0.1	17.6
28B	305,998	77.7	0.0	3.2
34A	3,017,610	963.9	0.4	39.0
34B	731,884	217.6	0.3	9.4
43A	364,330	516.3	2.2	6.7
43B	2,443,145	1403.7	5.7	36.3
43C	233,023	203.7	1.4	3.3
48A	1,536,456	866.2	3.4	22.1
48B	317,086	168.4	0.7	4.1
4A	58,168	51.4	11.2	1.8
4B	85,756	16.0	5.1	1.5
53A	958,782	194.8	0.0	14.3
53B	1,768,162	349.2	0.0	27.5
53C	422,626	102.9	0.0	7.6
55A	419,991	84.5	0.0	6.9
55B	590,906	148.2	0.0	9.7
55C	863,882	226.8	0.0	17.0
58A	6,188,798	2457.9	0.1	107.6
58B	3,783,888	943.3	0.4	57.8
58C	199,531	41.0	0.0	3.0
58D	528,343	97.6	0.0	9.7
60A	1,792,553	521.0	0.0	22.6
60B	668,113	336.3	0.0	10.0
63A	1,647,732	656.5	0.0	18.2
63B	658,307	291.9	0.0	9.4
67A	1,454,712	323.9	0.0	31.8
67B	2,202,593	549.2	0.0	48.0
70A	1,974,891	432.4	0.0	43.7
70B	1,854,571	315.7	0.0	39.5
70C	2,043,147	314.1	0.0	41.0
70D	279,833	29.7	0.0	4.3
77A	702,904	228.2	0.0	18.1
77B	640,671	126.6	0.0	14.0
77C	1,205,012	352.9	0.0	27.2

Continued - Appendix Table A-27 MLRA-Level Estimates of Mean Annual Direct and Indirect N_2O Emissions from Non-Federal Grasslands, 2003-2007

MLRA[1]	Area	Direct Soil N_2O	Indirect N_2O from NO_3 Leached/Runoff	Indirect N_2O from NH_3/NO_x Volitilization
	ha	*Gg CO_2 eq.*[2]		
77D	1,405,153	179.5	0.0	26.7
77E	1,664,797	511.3	0.0	44.9
78A	639,230	211.2	0.0	15.3
78B	2,491,438	766.2	0.0	58.9
78C	2,445,635	835.2	0.0	60.2
80A	1,963,077	741.6	17.3	53.0
80B	968,445	346.7	0.0	28.3
81A	2,866,367	525.9	0.0	68.4
81B	1,940,970	444.0	0.0	50.3
81C	1,236,724	320.4	0.0	32.5
81D	516,702	53.5	0.0	11.1
82A	401,734	54.2	0.0	10.1
82B	57,923	25.2	0.0	1.7
83A	1,706,897	359.0	0.0	38.9
83B	1,463,751	504.3	0.0	31.7
83C	755,825	122.0	0.0	17.5
83D	129,375	18.5	0.0	3.0
83E	659,343	76.4	0.1	15.1
84A	875,391	313.1	26.9	24.4
84B	745,691	585.5	14.5	35.5
84C	113,856	78.3	3.8	5.7
86A	1,453,945	1742.6	34.9	53.4
86B	351,296	220.6	7.7	10.7
87A	1,544,144	444.7	17.6	42.9
87B	410,138	182.0	17.6	13.2
90A	265,868	440.0	13.3	12.8
90B	248,178	422.6	11.8	11.9
91A	161,283	135.5	6.8	7.4
91B	52,108	87.0	6.5	2.6
94A	130,138	223.3	8.9	5.6
94B	61,815	152.5	4.0	3.0
94C	25,098	56.6	1.7	1.1
95A	91,989	174.6	8.2	5.2
95B	223,059	379.0	15.3	11.3
Total	180,415,846	70678.7	1828.9	3944.0

Note: N_2O is nitrous oxide. NO_3 is nitric oxide.
[1] MLRA = Major Land Resource Area
[2] Gg CO_2 eq. = Gigagrams carbon dioxide equivalents

Chapter 3

Download data: http://dx.doi.org/10.15482/USDA.ADC/1264151

Cropland Agriculture

3.1 Summary of U.S. Greenhouse Gas Emissions From Cropland Agriculture

Based on IPCC Tier 1 (default emission factors) and Tier 3 (DayCent model simulations) methods, cropland agriculture resulted in approximately 209 MMT CO_2 eq. total emissions of greenhouse gases (GHG) in 2013 (Table 3-1). Cropland agriculture is responsible for almost half (46 percent) of all emissions from the agricultural sector (EPA 2015). Nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) emissions from cropped soils totaled 168, 33, and 9 MMT CO_2 eq. in 2013. However, that amount was offset by a storage, or carbon sequestration, of 34 MMT CO_2 eq. in cropped mineral soils in 2013. When carbon sequestration is taken into account, net emissions of GHG from cropland agriculture amount to approximately 175 MMT CO_2 eq. The 95-percent confidence interval for net emissions in 2013 is estimated to lie between 129 and 249 MMT CO_2 eq. (Table 3-1).

Annual fluctuations in CO_2 sequestration are primarily a result of changes in land use and variability in weather patterns. In 2013, net emissions from cropland agriculture were about 50 percent higher than the baseline year (1990), mainly from an increase in N_2O emissions associated with increased cropping and a simultaneous reduction in the CO_2 sink in cropland mineral soils. Greenhouse gas emissions from agricultural soils fluctuated between 1990 and 2013, with CH_4 and N_2O reaching their highest levels in 2010 and 2012 respectively (Table 3-2). Net CO_2 flux showed substantial inter-annual variability, mainly due to fluctuations in the size of the mineral soil CO_2 sink.

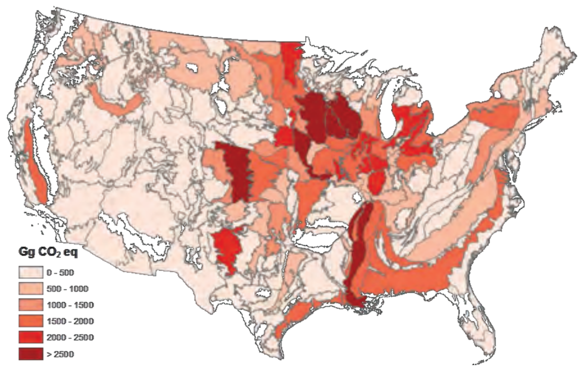
Greenhouse gas emissions from agricultural soils, primarily N_2O, were responsible for the majority of total emissions (80 percent), while CH_4 and N_2O from residue burning and rice cultivation caused about 4 percent of emissions in 2013 (Tables 3-1, 3-2). Soil CO_2 emissions from cultivation of organic soils (13 percent) and from liming (3 percent) are the remaining sources. Nitrous oxide emissions from soils are the largest source in the United States because N_2O is a potent greenhouse gas (see Chapter 1 Box 1-1). Large amounts of nitrogen are added to crops from fertilizer amendments and legume cropping, which both stimulate N_2O production. Emissions from residue burning are minor because only ~3 percent of crop residue is assumed to be burned in the United States (EPA 2015). Cropped mineral soils in the United States are a net CO_2 sink for various reasons, including improved crop varieties and better management leading to increased carbon inputs from residues and reduced tillage intensity that has become more popular in recent years, reducing carbon losses from decomposition. In addition, lands used for perennial hay cropping, as well as idle cropland enrolled in the Conservation Reserve Program (CRP), continue to store carbon. However, the magnitude of this sequestration in recent years is not as great as it was during the 1990s, partially due to land conversion from CRP back to cropping and lands that have been in CRP for about 10 years or more, storing less carbon than they did initially or even becoming carbon neutral.

Nitrous oxide emissions are largest in areas where a large portion of land is used for intensive agriculture (Map 3-1a, Figures 3-1a, 3-1b). For example, more than 50 percent of the land area in some Major Land Resource Areas (MLRAs) that lie within the Corn Belt is intensively cropped. Row crops such as corn, soybeans, and sorghum make up close to 40 percent of total cropland and have the highest N_2O emissions, followed by small grain crops such as wheat, barley and rye, other cropland, and hay

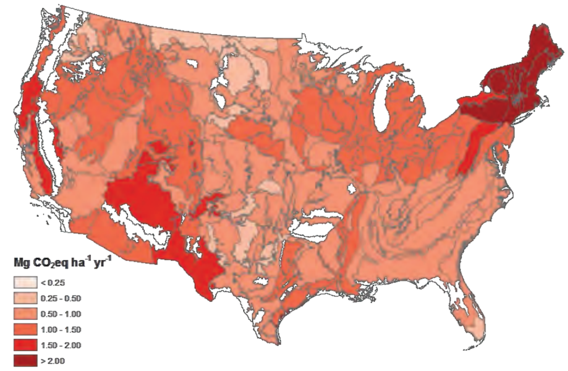
Table 3-1 Estimates and Uncertainties for Cropland Greenhouse Gas Emissions, 2013

Source	GHG Emissions	Lower Bound	Upper Bound
	MMT CO_2 eq.		
N_2O	**168**	**142**	**230**
Soils Direct	136	189	282
Soils Indirect[1]	32	21	102
Residue Burning	0.1	0.1	0.1
CH_4	**9**	**4**	**16**
Residue Burning	0.3	0.2	0.4
Rice Cultivation	8	4	14
CO_2[2]	**(1)**	**(39)**	**38**
Mineral Soils	(34)	(71)	2
Organic Soils	27	18	39
Liming of Soils	6	0	8
Total Emissions	**209**	**165**	**294**
Net Emissions[3]	**175**	**129**	**249**

Note: Parentheses indicate a net sequestration. MMT CO_2 eq. is million metric tons carbon dioxide equivalent. CH_4 is methane; N_2O is nitrous oxide; CO_2 is carbon dioxide.
[1] Soils Indirect N_2O emissions account for both volatilization and leaching/runoff.
[2] Does not include CO_2 emissions from urea fertilization.
[3] Includes sources and sinks.



Map 3-1a Total Nitrous Oxide (Direct and Indirect) for Major Land Resource Areas, Tier 3 Crops, Annual Means 2003–2007 *(Gg CO_2 eq. is gigagrams carbon dioxide equivalent.)*



Map 3-1b Unit Area Nitrous Oxide (Direct and Indirect) for Major Land Resource Areas, Tier 3 Crops, Annual Means 2003–2007 *(Mg CO_2 eq. ha^{-1} yr^{-1} is megagrams carbon dioxide equivalent per hectare per year.)*

cropping (Table 3-3). Unit area emissions were highest in the Northeast (Map 3-1b) largely because of N_2O pulses during spring when snow cover and soil surface layers melt while subsoil remains frozen, thus causing water ponding and associated emissions. Changes in emissions through time are driven largely by land conversion (e.g., land previously left fallow or used for small grain cropping that has been converted to row cropping). Similar to Figure 3-1a, Map 3-1 and Table 3-3 only include areas and emissions from Tier 3 cropped land, which covers ~87 percent of total cropped land. Appendix Table B-1 provides recent MLRA-level land area estimates for the same major crop rotations presented in Figure 3-1a.

Cropland agriculture results in GHG emissions from multiple sources, with the magnitude of emissions determined, in part, by land management practices. Application of synthetic and organic fertilizers, cultivation of N-fixing crops and rice, cultivation and management of soils, and field burning of crop residues lead to emissions of N_2O, CH_4, and CO_2. However, agricultural soils can also mitigate GHG emissions through the biological uptake of organic carbon in soils, resulting in CO_2 removals from the atmosphere. This chapter covers both GHG emissions from cropland agriculture and biological uptake of CO_2 in agricultural soils. National estimates of these sources, published in the U.S. GHG Inventory, are reported in this section and, where appropriate, MLRA and State-level emissions estimates are provided. Sources and sinks of N_2O, CH_4, and CO_2 and the mechanisms that control fluxes are discussed in detail. Methodologies used to estimate emissions are summarized and mitigation opportunities are discussed and quantified where possible. The methodologies used here are similar to those reported in the second edition of the USDA GHG report (USDA 2011a), with some improvements in model algorithms and model input data.

Table 3-2 Summary of Greenhouse Gas Emissions from Cropland Agriculture, 1990, 1995, 2000, 2005-2013

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013
Source	*MMT CO_2 eq.*											
N_2O	**143.6**	**158.3**	**141.9**	**158.7**	**156.9**	**164.6**	**169.8**	**167.9**	**168.2**	**169.9**	**170.6**	**167.9**
Soils Direct	117.1	127.3	115.7	130.6	129.1	134.2	137.4	136.0	136.2	137.2	137.6	135.7
Soils Indirect[1]	26.4	30.9	26.1	28.1	27.7	30.3	32.3	31.8	31.9	32.6	32.9	32.1
Residue Burning	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
CH_4	**9.5**	**10.1**	**9.9**	**9.2**	**8.0**	**8.3**	**9.6**	**9.7**	**11.4**	**8.8**	**9.6**	**8.6**
Residue Burning	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Rice Cultivation	9.2	9.8	9.6	8.9	7.7	8.0	9.3	9.4	11.1	8.5	9.3	8.3
CO_2[2]	**(36.0)**	**(6.9)**	**(18.8)**	**(3.9)**	**(7.5)**	**(9.4)**	**(6.8)**	**(7.6)**	**(4.9)**	**(5.7)**	**(3.1)**	**(1.4)**
Mineral Soils	(66.7)	(38.6)	(49.4)	(35.7)	(38.9)	(40.8)	(38.8)	(38.2)	(36.6)	(36.5)	(35.8)	(34.2)
Organic Soils	26.0	27.3	26.4	27.5	27.2	26.9	26.9	26.9	26.9	26.9	26.9	26.9
Liming of Soils	4.7	4.4	4.3	4.3	4.2	4.5	5.0	3.7	4.8	3.9	5.8	5.9
Total Emissions	**183.8**	**200.1**	**182.5**	**199.7**	**196.3**	**204.3**	**211.3**	**208.2**	**211.3**	**209.5**	**212.9**	**209.3**
Net Emissions[3]	**117.0**	**161.5**	**133.1**	**164.0**	**157.3**	**163.5**	**172.5**	**170.0**	**174.7**	**173.0**	**177.1**	**175.1**

Note: Parentheses indicate a net sequestration. MMT CO_2 eq. is million metric tons carbon dioxide equivalent. CH_4 is methane; N_2O is nitrous oxide; CO_2 is carbon dioxide.
[1] Soils Indirect N_2O emissions account for both volatilization and leaching/runoff.
[2] Does not include CO_2 emissions from urea fertilization.
[3] Includes sources and sinks.

In contrast to previous editions of the inventory that reported emissions from individual crops at the State level, emissions are now partitioned by crop rotations and reported at the MLRA level. Partitioning was performed for rotations because emissions are thought to be better correlated to farming systems as opposed to individual crops, because the emissions in a given year reflect management history. For example, wheat might be growing during a particular year, but the emissions for that year are partly (and sometimes largely) due to what happened the previous year(s). Emissions were partitioned into nine major cropping rotations (Figure 3-1a) by generating queries for each MLRA. That is, for each MLRA, the emissions and land area for a particular rotation were extracted from the databases. The queries were performed in a particular order (top to bottom in Figure 3-1a, Table 3-3) and were mutually exclusive. For example, land area used predominately for production of row crops that was also irrigated

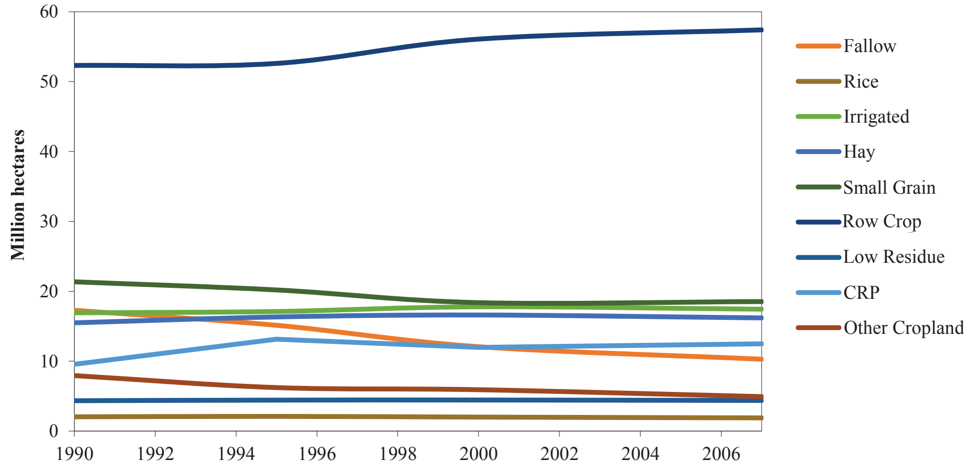


Figure 3-1a U.S. Planted Cropland Area by Rotation Category, 1990-2007
(CRP is USDA Conservation Reserve Program)

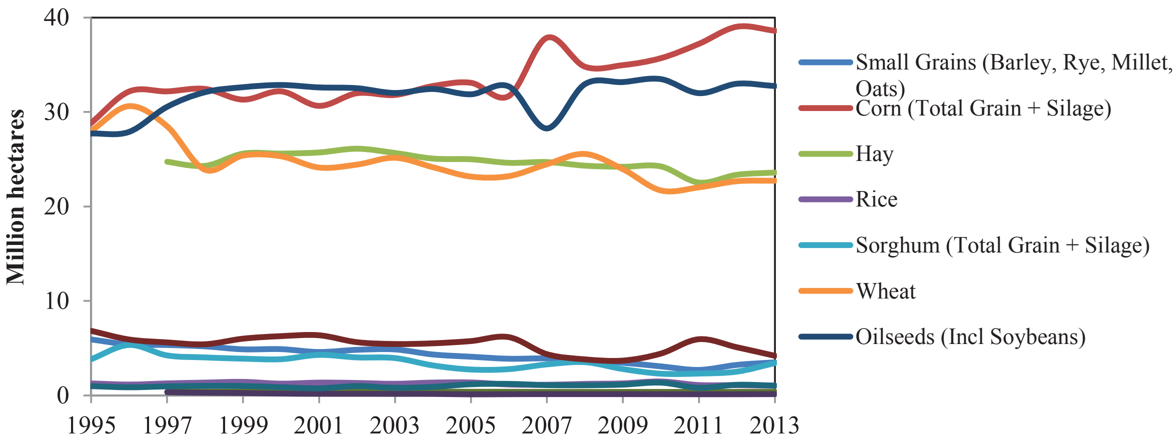


Figure 3-1b U.S. Planted Cropland Area by Crop Type, 1995-2013

would appear in the irrigated category and not be included in the row crops category. If queries were not mutually exclusive, then there would be double accounting because the land areas of some rotations partially overlap.

The data reported represent 5-year means (except from years 1990-1992) to reduce interannual variation due to weather and other factors. Rotations were defined using a general majority rule. For example, if a land area was fallow at least 3 out of 5 years it was classified as fallow, if land was in rice production at least 3 out of 5 years, it was classified as rice, and so on. Based on availability of land use data, we considered four time periods and reported emissions for the median years. These were 1990–1992, 1993–1997, 1998–2002, and 2003–2007. Figure 3-1a does not include years beyond 2007 because that was the most recent year for which land use data were available and subsequent years were assumed to have identical land use. In addition to rotations, areas are also shown for individual crops (Figure 3-1b). In contrast to Figure 3-1a, which includes only Tier 3 cropland areas up to 2007, Figure 3-1b represents total areas up to 2013. Tier 3 cropped lands were simulated using the DayCent model while Tier 1 emission factors were used to estimate emissions for remaining cropped land, see section 3.3 for details.

Table 3-3 Tier 3 Cropland Area by Management Practice, 2013

	Area	Total Tier 3 Cropland
Current Management	*million ha*	%
Fallow	10.3	7.2
Rice	1.9	1.3
Irrigated	17.4	12.1
Hay	16.2	11.3
Small Grain	18.5	12.9
Row Crop	57.4	40.0
Low Residue	4.4	3.0
USDA Conservation Reserve Program	12.5	8.7
Other Cropland	4.9	3.4

3.2 Sources and Sinks of Greenhouse Gas Emissions in Cropland Agriculture

3.2.1 Cropped Soils

Agricultural soils act as both a source of GHGs and a mechanism to remove CO_2 from the atmosphere. Nitrous oxide, CH_4, and CO_2 emissions and sinks are a function of underlying biochemical processes. Nitrous oxide is produced as an intermediate during nitrification and denitrification in soils (Firestone & Davidson 1989). In nitrification, soil microorganisms ("microbes") convert ammonium (NH4) to nitrate (NO_3) through aerobic oxidation (IPCC 2006). In denitrification, microbes convert nitrate to nitrogen oxides (NO_x) and nitrogen gas (N_2) by anaerobic reduction. During nitrification and denitrification, N_2O is created as a byproduct, which can diffuse from the soil and enter the earth's atmosphere (IPCC 2006). Cropland soil amendments that add nitrogen to soils drive the production of N_2O by providing additional substrate, which enhances nitrification and denitrification. Synthetic fertilizer, livestock manure, sewage sludge, cultivation of N-fixing crops, and incorporation of crop residues all add various forms of N to soils. In addition, cultivation, particularly of soils high in organic matter (i.e., histosols), enhances mineralization of nitrogen-rich organic matter, making more nitrogen available for nitrification and denitrification (EPA 2015). Compared to soil N_2O emissions, other GHG sources from croplands are relatively small. Methane gas is produced and emitted primarily from rice paddies. This, however, is responsible only for a small portion of total emissions from cropped soils in the United States due to the small land area cropped with paddy rice in this country. Emissions from crop residue burning are also not a large source compared to soils due to the small portion of residues burned in the United States.

Nitrous oxide is the major GHG emitted from cropland agriculture in the United States. Nitrogen can be converted to N_2O and emitted directly from agricultural fields (direct emissions), or it can be transported from the field in a form other than N_2O and then converted to N_2O elsewhere (indirect emissions). A major source of indirect N_2O emissions is from nitrate that either leaches into the groundwater or runs off the soil surface and then is converted to N_2O via aquatic denitrification (Del Grosso et al. 2006). A second source of indirect N_2O emissions comes from N that is volatilized to the atmosphere, then is deposited back onto soils and converted to N_2O (Del Grosso et al. 2006).

Cropped soils can be a source or sink of CO_2. Net CO_2 flux is related to changes soil organic carbon (SOC) stocks (IPCC 2006). Changes in SOC content are controlled by the balance between C inputs (e.g., atmospheric CO_2 fixed as carbon in plants through photosynthesis) and losses from plant (autotrophic) respiration and decomposition of soil organic matter and plant litter (IPCC 2006). The net balance of CO_2 uptake and loss in soils is driven in part by biological processes, which are affected by soil characteristics and climate. In addition, land use and management can affect the net balance of CO_2 through modifying inputs and rates of decomposition (IPCC 2006). Changes in agricultural practices such as vegetation clearing, water drainage, tillage, crop selection, irrigation, grazing, crop residue management, fertilization, and flooding can modify both organic matter inputs and decomposition and thereby result in a net flux of CO_2 to or from soils.

Most agricultural soils contain comparatively low amounts of organic carbon as a percentage of total soil mass, typically in the range of 1 to 6 percent organic C by weight, and are thus classified as mineral soils (NRCS 1999). However, on an area basis, this amount of carbon typically exceeds that stored in vegetation in most ecosystems. Historically, conversion of native ecosystems to agricultural uses resulted in large soil carbon losses, as much as 30 to 50 percent or more of the C present in the native condition (Haas et al. 1957, Schlesinger 1986, Guo & Gifford 2002, Lal 2004). Presently, after many decades of cultivation, most soils have likely stabilized at lower carbon levels or are increasing their organic matter levels as a result of increasing crop productivity (providing more residues), less intensive tillage, and other improvements in agricultural management practices (Paustian et al. 1997, Allmaras et al. 2000, Follett 2001). Changes in land use or management practices that result in increased organic inputs or decreased oxidation of organic matter (e.g., taking cropland out of production, improved crop rotations, cover crops, application of organic amendments and manure, and reduction or elimination of tillage) usually result in a net accumulation of SOC until a new equilibrium is achieved.

Cultivated organic soils, also referred to as histosols, contain more than 12 to 20 percent organic matter by weight and constitute a special case (NRCS 1999, Brady & Weil 1999). Organic soils form as a result of water-logged conditions, in which decomposition of plant residue is inhibited. When organic soils are drained and cultivated, the rate of decomposition, and hence CO_2 emissions, is greatly accelerated. Due to the depth and richness of the organic layers, carbon loss from cultivated organic soils can continue over long periods of time.

In addition, lime is often added to mineral and organic agricultural soils to reduce acidic conditions. Lime contains carbonate compounds (e.g., limestone and dolomite) that when added to soils release CO_2 through the bicarbonate equilibrium reaction to increase alkalinity (IPCC 2006).

3.2.2 Rice Cultivation

Rice is usually cultivated on flooded fields and is almost always grown in flooded fields in the United States (EPA 2015). This water regime causes CH_4 emissions as a result of waterlogged soils restricting oxygen diffusion and creating conditions for anaerobic decomposition of organic matter, facilitated by CH_4-emitting, methanogenic bacteria (IPCC 2006, Le Mer & Roger 2001). Methane from paddy rice fields reaches the atmosphere in three ways: bubbling up through the soil, diffusion losses from the water surface, and diffusion through the vascular elements of plants (IPCC 2006). Diffusion through plants is considered the primary pathway, with diffusion losses from surface water being the least important process (IPCC 2006). Soil composition, texture, and temperature are important variables affecting CH_4 emissions from rice cultivation, as are the availability of carbon substrate and other nutrients, soil pH, and partial pressure of CH_4 (IPCC 2006). Since U.S. paddy rice acreage is relatively small compared to other crops, CH_4 emissions from rice cultivation are small compared to other domestic cropland agriculture sources (EPA 2015).

3.2.3 Residue Burning

Crop residues are sometimes burned in fields to prepare for cultivation and control for pests, although this is no longer a common practice in the United States (EPA 2015). While CO_2 is a product of residue combustion, residue burning is not considered a net source of CO_2 to the atmosphere because CO_2 released from burning crop biomass is replaced by uptake of CO_2 in crops growing the following season (IPCC 2006). However, CH_4 and N_2O, also products of residue combustion, are not recycled into crop biomass through biological uptake the following season. Therefore, residue burning is considered a net source of CH_4 and N_2O to the atmosphere. Overall, GHG emissions from field burning of crop residues are comparatively small in the United States (EPA 2015).

3.3 Nitrous Oxide Emissions from Cropped Soils

In 2013, 65 percent of total cropland soil emissions were direct soil N_2O emissions (Table 3-2). Of the 19 percent of total emissions from indirect N_2O, 53 percent are from NO_3 leaching/runoff and the remainder are associated with volatilization (Table 3-4). Emissions are highest from row cops (mostly corn and soybean) because row crops cover the largest land area (Map 3-2) and nitrogen inputs from fertilizer and biological fixation in legumes are high (Figure 3-2). Other factors contributing to high emissions for these crops are that they are grown mostly in the north central region where many of the soils are high in organic matter and some of the soils are poorly drained, both of which enhance denitrification rates. Emissions from the small grain rotation category, or cereals, were the second highest, followed closely by irrigated cropland and hay. Emissions from hay cropping are substantial, despite minimal fertilizer N additions, because a large portion of hay includes N-fixing plants (e.g., alfalfa). Emissions from paddy rice are low, as the cropland areas for this crop are small compared to the other major crops in the United States. Emissions from histosol cultivation are small (~2 percent of total direct emissions) because histosols represent only ~1 million ha, which is less than 1 percent of U.S. cropped land. As explained in Section 3-1, partitioning was performed for rotations (Table 3-4) because emissions are thought to be better correlated to farming systems as opposed to individual crops. Appendix Tables B-2, B-3 and B-4 report direct and indirect N_2O emissions data at a finer spatial resolution (i.e., MLRA level) for the same cropping rotations presented in Table 3-4. Years beyond 2007 are not included in Table 3-4 and Figure 3-2 because that was the most recent year for which land use data were available and subsequent years were assumed to have identical land use.

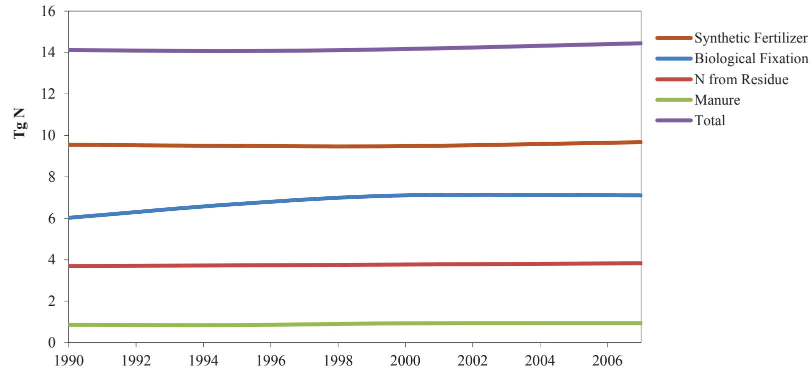


Figure 3-2 Annual Nitrogen Inputs to Cropland Soil, 1990-2007
(Tg N is teragrams nitrogen)

Nitrous oxide emissions are largely driven by nitrogen additions, weather, and soil physical properties. External nitrogen inputs (i.e., addition of synthetic fertilizers and manure, as well as biological fixation) to cropped soils varied between ~17 and 20 MMT N per year between 1990 and 2007 (Fig. 3-2), while N_2O emissions varied between 141 and 172 MMT CO_2 eq. However, variation in N inputs explained less than 5 percent of the variability in soil N_2O emissions. Also, the years with highest nitrogen inputs did not necessarily lead to the highest N_2O emissions. This indicates that other factors such as changes in weather patterns strongly influence the annual variability in estimated N_2O emissions. Specifically, amount and timing of precipitation, temperature patterns, and soil carbon and nitrogen availability interact to influence N_2O emissions. Because the responses of N_2O emissions to the controlling variables are often non-linear and the interactions complex, the correlations between any single variable (or even groups of variables) and measured emissions are typically weak (Stehfest and Bouwman 2006, Nishina et al. 2012, Philibert 2012).

Table 3-4 Nitrous Oxide Emissions from Differently Cropped Soils, 5-Year Means

	1992	1997	2002	2007
Rotations[1]		*MMT CO_2 eq.*		
USDA Conservation Reserve Program	**2.6**	**3.3**	**2.8**	**2.8**
Direct	2.2	2.8	2.4	2.3
Volatilization	0.4	0.5	0.4	0.4
Leaching & Runoff	0.1	0.1	0.1	0.0
Fallow	**6.6**	**6.3**	**4.6**	**4.5**
Direct	5.8	5.6	3.8	3.9
Volatilization	0.5	0.5	0.4	0.3
Leaching & Runoff	0.3	0.3	0.4	0.3
Hay	**15.4**	**17.8**	**16.1**	**16.5**
Direct	13.6	15.9	13.9	14.6
Volatilization	0.9	0.9	1.0	1.0
Leaching & Runoff	1.0	1.0	1.2	1.0
Irrigated	**19.3**	**22.6**	**22.2**	**21.3**
Direct	14.1	15.7	15.2	15.3
Volatilization	1.5	1.5	1.5	1.6
Leaching & Runoff	3.7	5.4	5.5	4.5
Low Residue	**2.6**	**3.0**	**3.3**	**3.4**
Direct	2.0	2.3	2.6	2.7
Volatilization	0.2	0.2	0.2	0.3
Leaching & Runoff	0.4	0.5	0.5	0.5
Other Cropland	**5.4**	**4.9**	**3.6**	**3.3**
Direct	4.5	4.0	3.1	2.8
Volatilization	0.5	0.4	0.3	0.3
Leaching & Runoff	0.4	0.5	0.2	0.2
Rice	**4.0**	**4.0**	**4.4**	**4.2**
Direct	3.5	3.5	4.0	3.8
Volatilization	0.2	0.2	0.2	0.2
Leaching & Runoff	0.3	0.3	0.3	0.2
Row Crop	**52.4**	**57.2**	**57.5**	**60.8**
Direct	42.9	47.5	46.0	50.5
Volatilization	5.5	5.9	6.5	6.9
Leaching & Runoff	4.0	3.7	5.0	3.4
Small Grain	**13.3**	**12.7**	**10.5**	**10.5**
Direct	11.7	11.2	9.1	9.1
Volatilization	1.1	0.8	0.9	0.9
Leaching & Runoff	0.6	0.7	0.4	0.4
Tier 1 cropped land	**24.5**	**27.7**	**26.9**	**28.0**
Direct	18.8	21.1	20.5	21.3
Volatilization	2.3	2.6	2.5	2.6
Leaching & Runoff	3.4	4.0	3.9	4.1
Histosol Cultivation[2]	**2.7**	**2.6**	**2.5**	**2.6**
All Direct	**119.1**	**129.7**	**120.4**	**126.2**
All Volatilization	**13.0**	**13.5**	**14.0**	**14.6**
All Leaching & Runoff	**14.0**	**16.3**	**17.5**	**14.5**
Total	**148.8**	**162.1**	**154.5**	**157.9**

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent

[1] Emissions from residue burning are not included.

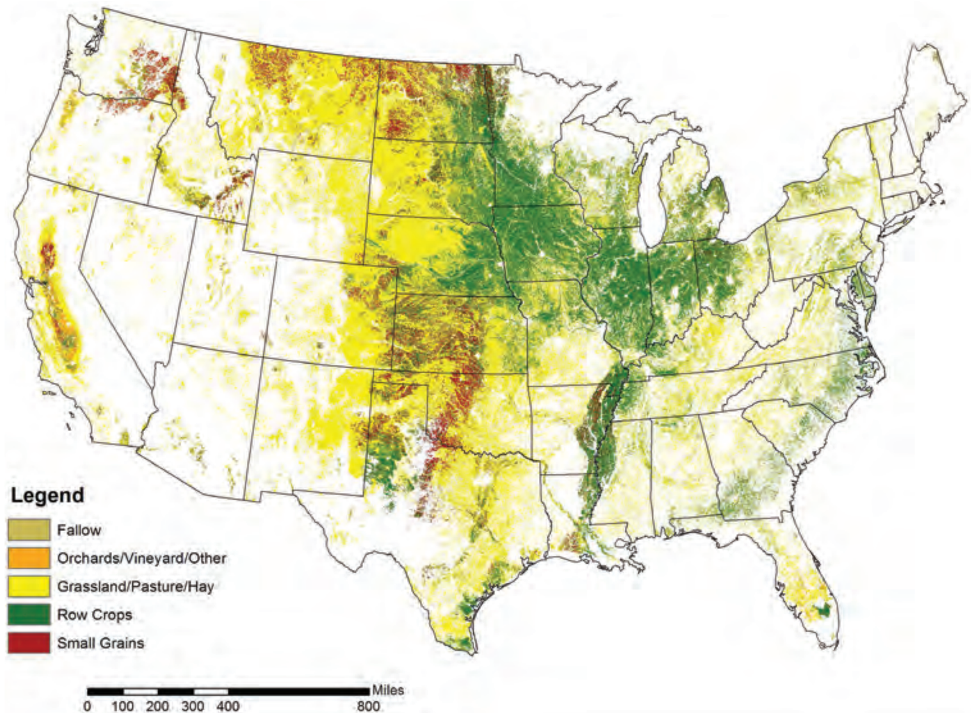
[2] Direct emissions.

3.3.1 Methods for Estimating N_2O Emissions from Cropped Soils

Emissions of N_2O from nitrogen additions to cropland soils and cultivation of histosol soils are source categories analogous to those covered in Agricultural Soil Management in the U.S. GHG Inventory (EPA 2015), with some exceptions. The U.S. GHG Inventory (EPA 2015) includes direct emissions of N_2O from livestock on grazed lands, while the USDA GHG Inventory includes this source under Livestock GHG Emissions in Chapter 2 of this report. For this report, indirect N_2O from grazing is included in the livestock chapter while indirect emissions from urban areas and other non-agricultural sources are not covered at all.

Briefly, the DayCent ecosystem model was used to estimate direct soil N_2O emissions, NO_3 leaching, and nitrogen volatilization from most land area covered by major crop types and many specialty crops. Default Tier 1 emission factors from IPCC (2006) were used to estimate direct and indirect emissions from cropped soils not included in the DayCent simulations and to calculate indirect emissions from DayCent estimates of NO_3 leaching and volatilization. IPCC (2006) methodology was also used to estimate emissions from cultivation of organic soils. Use of a process-based model, such as DayCent, for inventories is known as a Tier 3 approach, while use of IPCC (2006) methodology is referred to as a Tier 1 approach. The methodology summarized below shows how the Tier 1 and Tier 3 approaches can be combined to derive overall emission estimates. Refer to EPA (2015) for a complete description of the methodologies used to estimate N_2O emissions.

Map 3-2 U.S. Cropped Land



Data obtained from the 2011 National Land Cover Database at http://www.mrlc.gov

3.3.2.1 IPCC Tier 3 DayCent Simulations for Most Cropped Soils

The DayCent ecosystem model (Del Grosso et al. 2001, Parton et al. 1998) was used to estimate direct N_2O emissions from most mineral soils producing most commodity and specialty crops, including alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, wheat, and other crops) which represent approximately 87 percent of total cropland in the United States. DayCent simulates crop growth, soil organic matter decomposition, greenhouse gas fluxes, and key biogeochemical processes affecting N_2O emissions. The simulations are driven by model input data generated from daily weather records, land management, and soil physical properties determined in national soil surveys.

DayCent simulates carbon and nitrogen dynamics, soil water content and temperature, and other ecosystem variables (Parton et al.1994). Key sub models include: plant growth, senescence of biomass, decomposition of dead plant material and soil organic matter, and mineralization of nitrogen. Model inputs are monthly maximum/minimum air temperature and precipitation, surface soil texture class, soil hydric condition, vegetation type, and land management information (e.g., cultivation timing and intensity, timing and amount of fertilizer and organic matter amendments). Soil organic matter is simulated to a depth of 20-30 cm, while water, temperature, and mineral nitrogen are simulated throughout the soil profile. Soil organic matter is divided into three pools based on decomposability: active (turns over in months to years), slow (turns over in decades), and passive (turns over in centuries). The model accounts for the effects of nutrient availability, water, and temperature on plant growth (CO_2 uptake) and the effects of these factors, as well as cultivation, on decomposition (CO_2 release). The ability of the model to integrate carbon gains and losses and simulate plant growth and soil carbon levels reliably has been demonstrated using data from many sites in the United States and around the world (Parton et al.1994, Cerri et al. 2007, Ogle et al. 2007). The model has been shown to work in all the major biomes of the earth and can accurately reproduce the impacts of climate, soil texture, and land management on carbon fluxes (Parton et al. 1993, Kelly et al. 1997, Lugato 2007, Bricklemyer 2007). DayCent has been parameterized to represent the major commodity crops, as well as many specialty crops, grown in the United States. In addition to not being parameterized to simulate all crops, the model also does not simulate any crops grown on organic soils.

DayCent simulations were conducted at the National Resources Inventory (NRI) point resolution. The NRI has information on cropping and land-use histories (USDA 2009). The NRI is a statistically based sample of all non-Federal land, and includes 380,956 points in agricultural land for the conterminous United States that are included in the Tier 3 methods. Each point is associated with an expansion factor that allows scaling of N_2O emissions from NRI points to the entire country (i.e., each expansion factor represents the amount of area with similar land-use/ management history as the sample point). Land use and some management information (e.g., crop type, soil attributes, and irrigation) were originally collected for each NRI point on a 5-year cycle beginning in 1982. For cropland, data were collected for 4 out of 5 years in the cycle (i.e., 1979–1982, 1984–1987, 1989–1992, and 1994–1997). In 1998, the NRI program began collecting annual data, and at the time of this report's analysis, data were currently available through 2007.

The simulations reported here assumed conventional tillage cultivation, gradual improvement of cultivars, and gradual increases in fertilizer application until 1978. We accounted for improvements of cultivars (cultivated varieties) because, for example, it is unrealistic to assume that modern corn is identical, in terms of yield potential, nitrogen demand, etc., to corn grown in 1900. Realistic simulations of historical land management and vegetation type are important because they influence present day soil carbon and nitrogen levels, which influence present day nitrogen cycling and associated N_2O emissions. In addition to simulating historical crop management, the model also represented at least 1,000 years of native vegetation before land was initially plowed.

Nitrous oxide emission estimates from DayCent include the influence of N additions, crop type, irrigation, and other factors in aggregate, and therefore it is not possible to reliably partition N_2O emissions by anthropogenic activity (e.g., N_2O emissions from synthetic fertilizer applications cannot be distinguished from those resulting from manure applications). Consequently, emissions are not subdivided according to activity (e.g., N fertilization, manure amendments), as is suggested in the IPCC Guidelines, but the overall estimates are likely more accurate than the more simplistic Tier 1 method, which is not capable of addressing the broader set of driving variables influencing N_2O emissions. Thus DayCent forms the basis for a more complete estimation of N_2O emissions than is possible with the Tier 1 methodology.

3.3.2.2 Sources of Uncertainty for DayCent Simulations

The DayCent model results imbed three types of uncertainty: model input uncertainty, model structural uncertainty, and land-area scaling uncertainty. Uncertainty in three types of model inputs (N additions from synthetic fertilizer, N and C additions from manure, and tillage intensity) was addressed using Monte Carlo analysis (Del Grosso et al. 2010). For example, although mean amounts of N fertilizer applied to different crops are known, the amounts of fertilizer applied by particular farmers are uncertain. Monte Carlo analysis provides a method to quantify how this type of uncertainty impacts N_2O emissions. Probability distribution functions (PDFs) were derived from surveys at the county scale for the inputs in most cases. A Monte Carlo analysis was used with 100 iterations for each NRI point; random draws were made from PDFs for fertilizer, manure application, and tillage. An adjustment factor was also selected from PDFs with normal densities to represent the dependence between manure amendments and N fertilizer application rates.

Model structural error stems from models not being perfect representations of reality. That is, models contain assumptions and imperfectly represent the processes that control crop growth and N_2O emissions. This component is the largest source of uncertainty in the Tier 3 model-based inventory analysis, accounting for more than 80 percent of the overall uncertainty in the final estimates (Ogle et al. 2009, Del Grosso et al. 2010). To quantify model structural error, N_2O emissions generated by DayCent were compared with emissions measured in 24 field plots at various locations around the world, but mostly from the United States. Specifically, an empirically based procedure was applied to develop a structural uncertainty estimator from the relationship between modeled results and field measurements (Ogle et al. 2007). Model inputs are assumed to be precisely known for the experiments so structural uncertainty can be isolated.

The third element is the uncertainty associated with scaling the DayCent results for each NRI point to the entire land base by using the expansion factors provided with the NRI survey dataset. The expansion factors represent the number of hectares associated with the land use and management history for a particular point. This uncertainty is determined by computing the variances from a set of replicated weights for the expansion factor.

3.3.2.3 Activity Data for DayCent Simulations

The National Resources Inventory provided land use information for the DayCent simulations. The NRI has a stratified multi-stage sampling design, where primary sample units are stratified on the basis of county and township boundaries defined by the U.S. Public Land Survey (Nusser and Goebel 1997). Within a primary sample unit, typically a 160-acre (64.75 ha) square quarter-section, three sample points are selected according to a restricted randomization procedure. Each point in the survey is assigned an expansion factor based on other known areas and land-use information (Nusser and Goebel 1997). In principle, the expansion factors represent the amount of area with the land use and land-use change history that is the same as the point location. It is important to note that the NRI uses a sampling approach, and therefore there is some uncertainty associated with scaling the point data to a region or the country using the expansion factors. In general, those uncertainties decline at courser scales, such as States, compared to smaller county units, because of a larger sample size. An extensive amount of soils, land use, and land management data have been collected through the survey (Nusser et al. 1998). Primary sources for data include aerial photography and remote sensing imagery as well as field visits and county office records. In addition to providing land cover information, NRI differentiates between irrigated and non-irrigated land, but does not provide more detailed information on the type and intensity of irrigation. Hence, irrigation is modeled by assuming that applied water to field capacity with intervals between irrigation events where the soils drain to about 60 percent of field capacity.

The annual NRI data product provides crop data for most years between 1979 and 2007, with the exception of 1983, 1988, and 1993. These years are gap-filled using an automated set of rules so that cropping sequences are filled with the most likely crop type given the historical cropping pattern at each NRI point location. NRI points are included in the land base for the agricultural soil N_2O emissions inventory if they were identified as cropland or grassland between 1990 and 2007. Land use for 2008 to 2013 is assumed to be the same as 2007, but will be updated with newer NRI as it becomes available (i.e., USDA 2013). Note that the NRI includes only non-Federal lands because Federal lands are not classified into land uses as part of the NRI survey (i.e., they are only designated as Federal lands).

Data on N fertilizer rates were based primarily on the USDA Agricultural Resource Management Survey (USDA 1997a, 2011b). In these surveys, data on inorganic N fertilization rates are collected for most of the crops simulated by DayCent in the high-production States and for a subset of low-production States. These data are used to build a time series of fertilizer application rates for specific crops and States for 1990–2013. Mean fertilizer rates and standard deviations for irrigated and rainfed crops are produced for each State. If a State is not surveyed for a particular crop or if there are not enough data to produce a State-level estimate, then data are aggregated to USDA Farm Production Regions in order to estimate a mean and standard deviation for fertilization rates (Farm Production Regions are groups of States in the United States with similar agricultural commodities) (USDA 2014). If Farm Production Region data are not available, crop data are aggregated to the entire United States to estimate a mean and standard deviation. Standard deviations for fertilizer rates are used to construct PDFs with log-normal densities in order to address uncertainties in application rates. The survey summaries also present estimates for fraction of crop acres receiving fertilizer, and these fractions are used to determine if a crop is receiving fertilizer. Alfalfa hay and grass-clover hay are assumed to not be fertilized, but grass hay is fertilized according to rates from published farm enterprise budgets (NRIAI 2003).

Manure N addition rates were based on data developed by the USDA Natural Resources Conservation Service (NRCS) (Edmonds et al. 2003). USDA-NRCS has coupled estimates of manure N produced with estimates of manure N recoverability by animal waste management system to produce county-level rates of manure N application to cropland and pasture. Edmonds et al. (2003) estimated the area amended with manure and application rates in 1997 for both manure-producing farms and manure-receiving farms within a county for two scenarios, one before implementation of Comprehensive Nutrient Management Plans (baseline) and one after implementation (Edmonds et al. 2003).

For DayCent simulations, the rates for manure-producing farms and manure-receiving farms have been area weighted and combined to produce a single county-level estimate for the amount of land amended with manure and the manure N application rate for each crop in each county. The estimates were based on the assumption that Comprehensive Nutrient Management Plans have not been fully implemented. This is a conservative assumption because it allows for higher leaching rates due to some over application of manure to soils. In order to address uncertainty in these data, uniform probability distributions are constructed based on the proportion of land receiving manure versus the amount not receiving manure for each crop type and pasture. For example, if 20 percent of land producing corn in a county is amended with manure, randomly drawing a value equal to or greater than 0 and less than 20 would lead to a simulation with a manure amendment, while drawing a value greater than or equal to 20 and less than 100 would lead to no amendment in the simulation.

Edmonds et al. (2003) only provides manure application rate data for 1997, but the amount of managed manure available for soil application changes annually, so the area amended with manure is adjusted relative to 1997 to account for all the manure available for application in other years. Specifically, the manure N available for application in other years is divided by the manure N available in 1997. If the ratio is greater than 1, there is more manure N available in that county relative to the amount in 1997, and so it is assumed a larger area is amended with manure. In contrast, ratios less than 1 imply less area is amended with manure because there is a lower amount available in the year compared to 1997. The amendment area in each county for 1997 is multiplied by the ratio to reflect the impact of manure N availability on the area amended. The amount of managed manure N available for application to soils is calculated by determining the populations of livestock on feedlots or otherwise housed, requiring collection and management of the manure. To estimate C inputs (associated with manure N application rates derived from Edmonds et al. (2003), carbon-nitrogen (C:N) ratios for livestock-specific manure types are adapted from the Agricultural Waste Management Field Handbook (USDA 1996), On-Farm Composting Handbook (NRAES 1992), and recoverability factors provided by Edmonds et al (2003). The C:N ratios are applied to county-level estimates of manure N excreted by animal type and management system to produce a weighted county average C:N ratio for manure amendments. The average C:N ratio is used to determine the associated C input for crop amendments derived from Edmonds et al. (2003). To account for the common practice of reducing inorganic N fertilizer inputs when manure is added to a cropland soil, crop-specific reduction factors are derived from mineral fertilization data for land amended with manure versus land not amended with manure in the ERS 1995 Cropping Practices Survey (USDA 1997a). Mineral N fertilization rates are reduced for crops receiving manure N based on a fraction of the amount of manure N applied, depending on the crop and whether it is irrigated or rainfed. The reduction factors are randomly selected from PDFs with normal densities in order to address uncertainties in the dependence between manure amendments and mineral fertilizer application.

Tillage practices are estimated for each cropping system based on data from the Conservation Technology Information Center (CTIC 2004). CTIC compiles data on cropland area under five tillage classes by major crop species and year for each county in the United States. Because the surveys involve county-level aggregate area, they do not fully characterize tillage practices as they are applied within a management sequence (e.g., crop rotation). This is particularly true for area estimates of cropland under no-till, which include a relatively high proportion of “intermittent” no-till, where no-till in one year may be followed by tillage in a subsequent year. For example, a common practice in maize-soybean rotations is to use tillage in the maize crop while no-till is used for soybean, such that no-till practices are not continuous in time. Estimates of the area under continuous no-till are provided by experts at CTIC to account for intermittent tillage activity and its impact on soil C (Towery 2001).

Tillage practices are grouped into three categories: full, reduced, and no-tillage. Full tillage is defined as multiple tillage operations every year, including significant soil inversion (e.g., plowing, deep disking) and low surface-residue coverage. This definition corresponds to the intensive tillage and “reduced” tillage systems as defined by CTIC (2004). No-till is defined as not disturbing the soil except through the use of fertilizer and seed drills and where no-till is applied to all crops in the rotation. Reduced tillage made up the remainder of the cultivated area, including mulch tillage and ridge tillage as defined by CTIC and intermittent no-till. The specific tillage implements and applications used for different crops, rotations, and regions to represent the three tillage classes are derived from the 1995 Cropping Practices Survey by the Economic Research Service (USDA 1997a).

Daily maximum/minimum temperature and precipitation data are based on gridded weather data from the North America Regional Reanalysis Product (NARR) (Mesinger et al. 2006). It is necessary to use computer-generated weather data because weather station data do not exist near all NRI points and, moreover, weather station data are for a point in space. The NARR product uses this information with interpolation algorithms to derive weather patterns for areas between these stations. NARR weather data are available for the United States from 1980 through 2007 at a 32 km resolution. Each NRI point is assigned the NARR weather data for the grid cell containing the point.

Soil texture and natural drainage capacity (i.e., hydric versus non-hydric soil characterization) are the main soil variables used as input to the DayCent model. Texture is one of the main controls on soil processes in the DayCent model, which uses particle-size fractions of sand (50-2,000 µm), silt (2-50 µm), and clay (< 2 µm) as inputs. Hydric soils are poorly-drained and hence prone to have a high water table for part of the year in their native (pre-cultivation) condition. Non-hydric soils are moderately to well drained.[2] Poorly drained soils can be subject to anaerobic (lack of oxygen) conditions if water inputs (precipitation and irrigation) exceed water losses from drainage and evapotranspiration. Depending on moisture conditions, hydric soils can range from being fully aerobic to completely anaerobic, varying over the year. Other soil characteristics needed for simulations, such as field capacity and wilting-point water contents, are estimated from soil texture data using a standardized hydraulic properties calculator (Saxton et al. 1986). Soil input data are derived from Soil Survey Geographic Database (SSURGO) (Soil Survey Staff 2011). The data are based on field measurements collected as part of soil survey and mapping. Each NRI point is assigned the dominant soil component in the polygon containing the point from the SSURGO data product.

3.3.2 IPCC Tier 1 Methodology for Cropped Land Not Simulated by DayCent

3.3.2.1 Mineral Soils

For mineral agricultural soils not simulated by DayCent, the Tier 1 IPCC methodology was used to estimate direct N_2O emissions. Estimates of direct N_2O emissions from N applications to non-major crop types were based on the annual increase in mineral soil N from the following practices: (1) the application of synthetic commercial fertilizers,

(2) the retention of crop residues, and (3) and non-manure organic fertilizers.

Annual synthetic fertilizer nitrogen additions to cropped land not simulated by DayCent are calculated by process of elimination. For each year, fertilizer applied to cropped and grazed lands simulated by DayCent was subtracted from total fertilizer used on farms in the United States. The difference was assumed to be applied to cropped land not simulated by DayCent. Residue nitrogen for these crops was derived from information on crop production yields, residue management (retained versus burned or removed), mass ratios of aboveground residue to crop product, dry matter fractions, and nitrogen contents of the residues (IPCC 2006). The activity data for these practices were obtained from the following sources:

- Annual production statistics for crops whose residues are left on the field: USDA (2014), Schueneman (1997, 1999a- 2001), Deren (2002), Kirstein (2003- 2004, 2006), Gonzalez (2007-2014), Cantens (2004- 2005), Lee (2003 -2007), Slaton (1999- 2001), Wilson (2002- 2007, 2009-2012), Hardke (2013, 2014), Linscombe (1999, 2001-2014), Anderson (2008- 2014), Klosterboer (1997, 1999- 2003), Stansel (2004- 2005), Texas Agricultural Experiment Station (2006, 2007-2014).

[2] Artificial drainage (e.g., ditch- or tile-drainage) is simulated as a management variable.

- Crop residue N was derived by combining amounts of above- and below-ground biomass, which were determined based on crop production yield statistics (USDA 2014), dry matter fractions (IPCC 2006), linear equations to estimate above-ground biomass given dry matter crop yields (IPCC 2006), ratios of below-to-above-ground biomass (IPCC 2006), and N contents of the residues (IPCC 2006).

Estimates of total national annual N additions from land application of other organic fertilizers were derived from organic fertilizer statistics (TVA 1991-1994, AAPFCO 1995- 2014). The organic fertilizer data, which are recorded in mass units of fertilizer, had to be converted to mass units of N by multiplying by the average organic fertilizer N contents provided in the annual fertilizer publications. These N contents are weighted average values and vary from year-to-year (ranging from 2.3 percent to 3.9 percent over the period 1990 through 2004). Annual on-farm use of these organic fertilizers is very small, less than 0.03 MMT N.

IPCC Tier 1 methodology for emissions from mineral soils is based on nitrogen inputs. Nitrogen inputs from synthetic and organic fertilizer and above- and below-ground crop residues were added together. This sum was multiplied by the default Tier 1 emission factor (1.0 percent) to derive an estimate of cropland direct N_2O emissions from non-major crop types. Nitrate leached or runoff and N volatilized from non-major crop types are calculated by multiplying N fertilizer applied by the Tier 1 default factors (30 percent and 10 percent, respectively).

3.3.2.2 Cultivation of Histosols

The IPCC Tier 1 method was used to estimate direct N_2O emissions from the drainage and cultivation of organic cropland soils. Estimates of the total U.S. acreage of drained organic soils cultivated annually for temperate and sub-tropical climate regions was obtained for 1982, 1992, and 1997 from the NRI (USDA 2000, as extracted by Eve 2001 and amended by Ogle 2002), using temperature and precipitation data from Daly et al. (1998, 1994). To estimate annual N_2O emissions from histosol cultivation, the temperate histosol area is multiplied by the IPCC default emission factor for temperate soils (8 kg N_2O-N/ha cultivated; IPCC 2006), and the sub-tropical histosol area is multiplied by the average of the temperate and tropical IPCC default emission factors (12 kg N_2O-N/ha cultivated; IPCC 2006).

3.3.2.3 Total N_2O Emissions

Total direct emissions were obtained by summing DayCent-generated emissions from most crops on mineral soils, Tier 1-generated estimates for crops on mineral soils not simulated by DayCent, and Tier 1 estimates of emissions from organic soils. Total indirect emissions from NO_3 leaching or runoff in landscapes where annual water inputs from precipitation and irrigation exceed potential evaporation rates were obtained by adding DayCent estimates for most crops on mineral soils to Tier 1 default estimates for crops on mineral soils not simulated by DayCent and multiplying by the default emission factor (0.75 percent of N leached/runoff). Total indirect emissions from nitrogen volatilization were obtained by adding DayCent estimates for most crops on mineral soils to Tier 1 estimates for crops on mineral soils not simulated by DayCent and multiplying by the default emission factor (1 percent of N volatilized). Indirect emissions from NO_3 leaching or runoff were added to those from nitrogen volatilization to get total indirect emissions. Total direct and indirect emissions were then summed to get total N_2O emissions from cropped soils.

3.3.3 Uncertainty in N_2O Emissions

Uncertainty was combined for direct emissions from crop rotations simulated by DayCent, croplands not calculated by DayCent, and indirect emissions from all cropped lands. Section 3.3.2.2 describes uncertainty for direct emissions calculated using DayCent. Uncertainty for direct emissions from cropped lands not simulated by DayCent was estimated using simple error propagation (IPCC 2006). Uncertainty in indirect emissions for most crops combined uncertainty in DayCent estimates of nitrate leaching and N gas volatilization based on the Monte Carlo simulations with uncertainty in the IPCC Tier 1 emissions factors used to convert these N loss vectors to N_2O emissions. Uncertainty in indirect emissions for crops not simulated by DayCent combined uncertainty in IPCC Tier 1 emissions factors for nitrate leaching and N gas volatilization with uncertainty in the IPCC Tier 1 emissions factors used to convert these N loss vectors to N_2O emissions. Error propagation was used to combine uncertainties in the various components by taking the square root of the sum of the squares of the standard deviations of the components (IPCC 2006). The 95-percent confidence interval in N_2O emissions was estimated to lie between 153 and 281 MMT CO_2 eq. (Table 3-1).

3.3.4 Changes Compared to the 3rd edition of the USDA GHG Report

There were several changes compared to the previous edition of the inventory. The most important was using NRI for land use information. In previous inventories, land cover was based on USDA-NASS statistics for areas of major crops (corn, soybeans, wheat, alfalfa hay, other hay, sorghum, and cotton) at the county level and region-specific assumptions regarding common cropping practices. For example, in the north central United States, corn and soybean were assumed to alternate every other year in a 2-year rotation cycle and were not irrigated while corn grown in Western States was assumed to be irrigated and grown continuously instead of being rotated with other crops. In contrast to these region-specific assumptions for land use, NRI data represent actual land use during any particular year. For example, a given NRI point could have irrigated corn grown for 3 years, followed by 2 years of irrigated soybean, followed by a year of non-irrigated wheat.

Another improvement relates to land area considered eligible to contribute to indirect N_2O from NO_3 leached or runoff from cropped fields. Instead of assuming that nitrate leaching and runoff can occur anywhere, a criterion was used to designate lands where nitrate is susceptible to be leached or runoff into waterways, as suggested by IPCC (2006). This is based on observations that in semi-arid and arid areas, nitrate can be leached below the rooting zone, but it does not enter waterways because water tables in dry areas are low or non-existent.

Other changes are related to improvements in the DayCent model and uncertainty estimation. The most noteworthy of these changes relates to expanding the number of study sites used to quantify model uncertainty for direct N_2O emissions and bias correction. There were also various changes to the DayCent model, including modifying algorithms to more realistically represent plant and soil processes and modifying parameters to improve model outputs. For example, the temperature algorithm used to simulate crop production as well as soil carbon inputs was modified. These changes resulted in an increase in N_2O emissions of approximately 4 percent, relative to the previous inventory.

3.3.5 Mitigation of N_2O Emissions

Mitigation of N_2O emissions is based on optimizing the amount and timing of nitrogen fertilizer additions. Excess fertilizer applied to crops increases the nitrogen available for N_2O, N oxide, NH_3 emissions and NO_3 leaching. Using enhanced efficiency fertilizers designed to release N slowly or formulated with nitrification inhibitors and applying fertilizer in multiple applications should improve the synchrony between nitrogen supply and plant nitrogen demand. However, multiple applications of fertilizer require increased time and equipment usage by farmers and enhanced efficiency fertilizers are more expensive than conventional fertilizers. Use of nitrification inhibitors and slow-release fertilizers has been shown to decrease N_2O emissions in some systems (Migliorati et al. 2015, Halvorson et al. 2014, Akiyama et al. 2010, Weiske et al. 2001, McTaggert et al. 1997). However, use of these improved fertilizers does not always result in N_2O mitigation (Parkin and Hatfield 2014, Dell et al. 2014, Sistani et al. 2011), and there is some evidence that these fertilizers are more effective in irrigated systems and when rainfed systems receive consistent precipitation (Hatfield and Venterea 2014). Climate-specific scaling factors have been developed to represent the expected direct N_2O reduction for enhanced efficiency fertilizers and are reported in a recent USDA publication (Ogle et al. 2014). Ogle et al. (2014) also includes scaling factors for the expected reductions in NO_3 leaching (which contributes to indirect N_2O emissions) for leguminous and non-leguminous cover crops.

3.4 Methane Emissions From Rice Cultivation

Methane emissions from rice cultivation[3] are limited to seven U.S. States (Figure 3-3). In four States (Arkansas, Florida, Louisiana, and Texas), the climate allows for cultivation of two rice crops per season, the second of which is referred to as a ratoon crop (EPA 2015). Methane emissions from primary and ratoon crops are accounted for separately because emissions from ratoon crops tend to be higher (EPA 2015). Overall, rice cultivation is a small source of CH_4 in the United States. In 2013, CH_4 emissions totaled 8.3 MMT CO_2 eq., of which 5.8 MMT CO_2 eq. were from primary crops in all seven States and 2.5 MMT CO_2 was from ratoon crops in four States (Table 3-5).

[3] This source focuses on CH_4 emissions resulting from anaerobic decomposition and does not include emissions from burning of rice residues. The latter is covered in section 3.5.

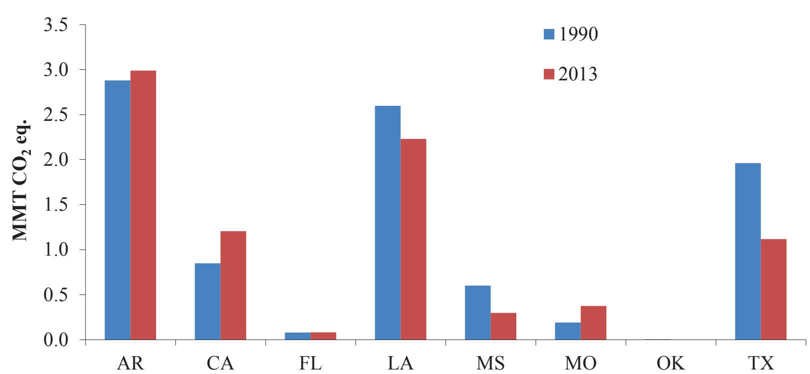


Figure 3-3 Methane from Rice Cultivation by State, 1990 & 2013
(MMT CO_2 eq. is million metric tons of carbon dioxide equivalent)

Table 3-5 Methane from Rice Cultivation from Primary and Ratoon Operations by State, 1990, 1995, 2000, 2005-2013

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013
Source						*MMT CO_2 eq.*						
Primary	6.7	7.4	7.2	6.7	5.6	5.5	5.9	6.2	7.2	5.2	5.3	5.8
Arkansas	2.9	3.2	3.4	3.3	2.8	2.7	2.8	3.0	3.6	2.3	2.6	2.6
California	0.8	1.0	1.2	0.9	0.9	1.0	0.9	1.0	1.0	1.0	1.0	1.2
Florida	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Louisiana	1.3	1.4	1.2	1.1	0.7	0.8	0.9	0.9	1.1	0.8	0.8	1.0
Mississippi	0.6	0.7	0.5	0.5	0.4	0.4	0.5	0.5	0.6	0.3	0.3	0.3
Missouri	0.2	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.3	0.4	0.4
Texas	0.8	0.8	0.5	0.4	0.3	0.3	0.3	0.3	0.4	0.4	0.3	0.3
Ratoon	**2.5**	**2.4**	**2.4**	**0.8**	**0.9**	**1.3**	**1.9**	**1.8**	**2.1**	**1.9**	**2.1**	**2.5**
Arkansas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4
Florida	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Louisiana	1.3	1.3	1.5	0.5	0.5	0.9	1.2	1.1	1.4	1.0	1.1	1.2
Texas	1.1	1.0	0.8	0.4	0.4	0.3	0.6	0.7	0.7	0.9	0.5	0.8
Total	**9.2**	**9.8**	**9.6**	**7.5**	**6.5**	**6.7**	**7.8**	**7.9**	**9.3**	**7.1**	**7.4**	**8.3**

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent.

Arkansas and California had the highest CH_4 emissions (2.6 MMT CO_2 eq. and 1.2 MMT CO_2 eq. respectively) from rice cultivation in 2013, followed by Louisiana and Missouri. Mississippi, Texas, and Florida each had emissions less than or equal to 0.4 MMT CO_2 eq. (Table 3-5). State-level shifts in CH_4 emissions are positively correlated with changes in area of rice cultivation (Appendix Table B-5). For example, since 1990, CH_4 emissions from rice cultivation have decreased by nearly 10 percent, while total area of rice cultivation has decreased by 11 percent. The State of Texas accounts for most of the overall reduction, with a decline of 43 percent (Table 3-6). Appendix Table B-5 provides a complete time series of areas harvested for rice by State with primary versus ratoon crops from 1990-2013.

Table 3-6 Change in Methane Emissions from Rice Cultivation, 1990-2013

	1990	2013	1990-2013
State	*MMT CO_2 eq.*		*% Change*
Arkansas	2.88	2.99	4
California	0.85	1.21	42
Florida	0.08	0.08	5
Louisiana	2.60	2.23	-14
Mississippi	0.60	0.30	-50
Missouri	0.19	0.37	95
Texas	1.96	1.12	-43
Total	**9.16**	**8.30**	**-9**

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent.

3.4.1 Methods for Estimating CH_4 Emissions From Rice Cultivation

The EPA provided estimates for CH_4 emissions from rice cultivation for this report. Details on the methods are provided below and are excerpted, with permission from EPA, from Chapter 6 of the U.S. GHG Inventory report (EPA 2015). The method used by EPA applies area-based seasonally integrated emission factors (i.e., amount of CH_4 emitted over a growing season per unit harvested area) to harvested rice areas to estimate annual CH_4 emissions from rice cultivation. The EPA derives specific CH_4 emission factors from published studies containing rice field measurements in the United States, with separate emissions factors for ratoon and primary crops to account for higher seasonal emissions in ratoon crops.

A review of published experiments was used to develop emissions factors for primary and ratoon crops (EPA 2015). Experiments where nitrate or sulfate fertilizers or other substances believed to suppress CH_4 formation were applied, and experiments where measurements were not made over an entire flooding season or where floodwaters were drained mid-season were excluded from the analysis. The remaining experimental results were then sorted by season (i.e., primary and ratoon) and type of fertilizer amendment (i.e., no fertilizer added, organic fertilizer added, and synthetic and organic fertilizer added). The experimental results from primary crops with synthetic and organic fertilizer added (Bossio et al. 1999, Cicerone et al. 1992, Sass et al. 1991a and 1991b) were averaged to derive an emission factor for the primary crop, and the experimental results from ratoon crops with synthetic fertilizer added (Lindau et al. 1995, Lindau & Bollich 1993) were averaged to derive an emission factor for the ratoon crop. The resultant emission factor for the primary crop is 237 kg CH_4/ha per season, and the resultant emission factor for the ratoon crop is 780 kg CH_4/ha per season (EPA 2015).

3.4.2 Uncertainty in Estimating Methane Emissions From Rice Cultivation

The following discussion of uncertainty in estimating GHG emissions from rice cultivation is modified from information provided in the U.S. GHG Inventory (EPA 2015). The information is reproduced here with permissions from the EPA.

Methane emission factors are the largest source of uncertainty in estimates for rice cultivation. Seasonal emissions, derived from field measurements in the United States, vary by more than an order of magnitude resulting from a variation in cultivation practices, fertilizer applications, cultivar types, soil, and climatic conditions. Some variability is accounted for by separating primary from ratoon areas. However, even within a cropping season, measured emissions vary significantly. Of the experiments that were used to derive the emission factors used here, primary emissions ranged from 61 to 500 kg CH_4/ha per season and ratoon emissions ranged from 481 to 1,490 kg CH_4/ha per season (EPA 2015). Other sources of uncertainty include the primary rice-cropped area for each State, percent of rice-cropped area that is ratooned, the length of the growing season, and the extent to which flooding outside of the normal rice season is practiced. Uncertainties in primary and ratooned areas were based on expert judgement and estimates of the portion of ratooned areas by State. Uncertainty regarding flooding outside the normal growing season was estimated for California (+/- 20 percent), but insufficient data were available to estimate this uncertainty source for other States.

To quantify the uncertainties for emissions from rice cultivation, a Monte Carlo (Tier 2) uncertainty analysis was performed using the information provided above. The results of the Tier 2 quantitative uncertainty analysis are summarized in Table 3-1. Rice cultivation CH_4 emissions in 2013 were estimated to be between 4 and 16 MMT CO_2 eq. at a 95-percent confidence level, which indicates a range of 50 percent below to 91 percent above the actual 2013 emission estimate of 8 MMT CO_2 eq.

3.5 Residue Burning

Greenhouse gas emissions from field burning of crop residues are a function of the amount and type of residues burned. In the United States, crop residues burned include wheat, rice, sugarcane, corn, cotton, soybeans, and lentils and often occur in the Southeastern States, the Great Plains, and the Pacific Northwest (EPA 2015). For most crops, a small portion of residues are burned each year, but a higher portion of rice residues are burned annually (EPA 2015). Consequently, emissions from residue burning are a small source of overall crop-related emissions in the United States. One-fourth of GHG emissions from residue burning, across all crop types, consisted of CH_4 in 2013; the remaining emissions were N_2O (Table 3-7, Figure 3-4). The highest GHG

Table 3-7 Greenhouse Gas Emissions from Agriculture Burning by Crop, 1990, 1995, 2000, 2005–2013

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013
Source						*MMT CO_2 eq.*						
CH_4	**0.32**	**0.28**	**0.31**	**0.22**	**0.28**	**0.28**	**0.32**	**0.29**	**0.29**	**0.30**	**0.30**	**0.31**
Wheat	0.16	0.13	0.14	0.10	0.10	0.12	0.16	0.12	0.12	0.14	0.13	0.13
Rice	0.05	0.05	0.05	0.04	0.05	0.07	0.05	0.06	0.06	0.05	0.05	0.05
Sugarcane	0.07	0.06	0.06	0.03	0.07	0.03	0.04	0.05	0.04	0.05	0.05	0.05
Corn	0.02	0.02	0.03	0.02	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05
Cotton	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Soybeans	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Lentils	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
N_2O	**0.10**	**0.09**	**0.10**	**0.08**	**0.09**	**0.10**	**0.11**	**0.10**	**0.10**	**0.10**	**0.10**	**0.10**
Wheat	0.04	0.04	0.04	0.03	0.03	0.03	0.04	0.03	0.03	0.04	0.04	0.04
Rice	0.02	0.02	0.02	0.01	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Sugarcane	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Corn	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cotton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Soybeans	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Lentils	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	**0.42**	**0.37**	**0.41**	**0.30**	**0.37**	**0.38**	**0.43**	**0.39**	**0.38**	**0.40**	**0.40**	**0.42**

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent. CH_4 is methane; N_2O is nitrous oxide; CO_2 is carbon dioxide.

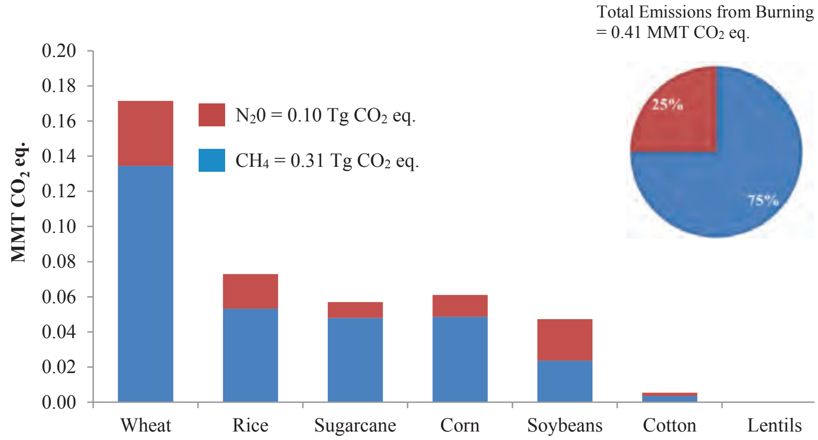


Figure 3-4 Greenhouse Gas Emissions from Field Burning by Crop Type, 2013
(CH_4 is methane; N_2O is nitrous oxide; CO_2 is carbon dioxide. MMT CO_2 eq. is million metric tons of carbon dioxide equivalent.)

emissions were from burning of wheat crop residues, at 42 percent. Burning of rice, sugarcane, corn, and soybean crop residues each contributed 20 percent or less to overall GHG emissions. Burning of lentil crop residues contributed almost nothing to this source of GHG due to the relatively small amount of land area planted with this crop. This is also why a small increase in land area (Figure 3-5) for lentil crops from 1990 to 2013 exhibits such a dramatic proportional increase (Figure 3-6).

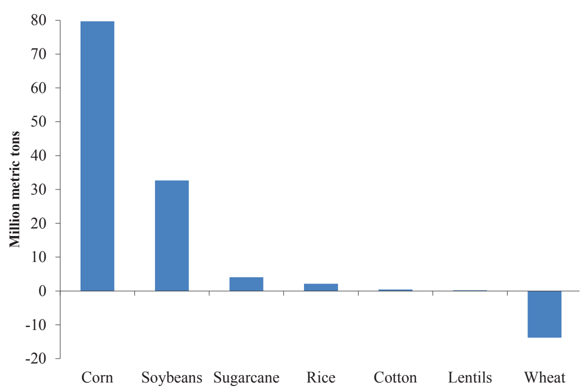


Figure 3-5 Change in Commodity Production, 1990-2013

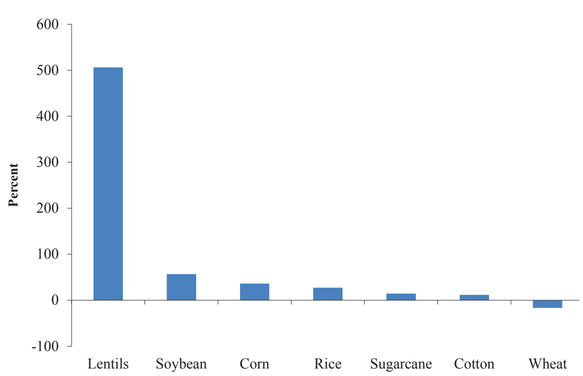


Figure 3-6 Percent Change in Commodity Production, 1990-2013

Total GHG emissions from residue burning decreased 8 percent from 1990 to 2013. Trends in relative GHG emissions were similar across crop types in 1990 compared to 2013, with a few exceptions. In both 1990 and 2013, burning of wheat residues contributed the most to GHG emissions from residue burning, while rice burning was the second-largest source. Between 1990 and 2013, soybean and corn for grain production (excluding corn for silage) both increased in absolute amounts, while GHG emissions from burning decreased in wheat (Figure 3-5). Proportionally, soybean production increased slightly more than corn but still not near the level of increase for lentil production (Figure 3-6). Despite the higher nitrogen content in soybeans relative to corn, corn production was still greater than soybean production in 2013 (Table 3-8), thus resulting in higher GHG emissions from corn residue burning.

Appendix Table B-6 provides the complete time series of crop production from 1990 to 2013 for crop types that contribute to GHG emissions from burning. Appendix Table B-7 provides nationwide data for crop production managed with burning by year. Production of crops such as corn and soybeans has been slowly increasing since 1990, with other crops like wheat, rice, and sugarcane remaining relatively constant or decreasing. Wheat production has declined since the mid-1990s. The State-level rice harvest estimates were provided directly by EPA based on State production data.

3.5.1 Methods for Estimating CH_4 and N_2O Emissions from Residue Burning

A Tier 2 method (EPA 2015) was used to estimate greenhouse gas emissions from field burning of agricultural residues. The methodology described below is summarized with permission from EPA.

Table 3-8 Agricultural Crop Production

Crop	1990	2005	2006	2007	2008	2009	2010	2011	2012	2013
					MMT of product					
Corn[1]	222.2	311.1	294.9	365.1	338.6	366.6	348.5	346.1	301.8	351.3
Cotton	3.7	5.7	5.2	4.6	3.1	2.9	4.3	3.7	4.2	2.8
Legumes[2]	0.0	0.3	0.2	0.2	0.1	0.3	0.4	0.2	0.3	2.1
Rice	7.8	11.2	9.7	10.0	10.2	11.0	12.2	9.2	10.0	8.6
Soybeans	57.8	92.1	95.9	80.3	89.0	100.8	99.9	92.8	90.4	91.4
Sugarcane	28.1	26.6	29.6	30.0	27.6	30.4	27.4	29.2	32.2	27.9
Wheat	81.9	63.1	54.3	61.5	75.0	66.5	66.2	60.0	68.1	58.1

Note: MMT is million metric tons.
Source: USDA, NASS Crop Production 2014 Summary
[1] Corn for grain (i.e., excludes corn for silage).
[2] Legumes are dry beans, peas, and lentils

The equation below was used to estimate the amounts of carbon and nitrogen released during burning.

C or N released = Σ for all crop types and State:

AB/(CAH x CP x RCR x DMF x BE x CE x (FC or FN))

where, Area Burned (AB) = Total area of crop burned, by State; Crop Area Harvested (CAH) = Total area of crop harvested, by State; Crop Production (CP) = Annual production of crop in Gg, by State; Residue/Crop Ratio (RCR) = Amount of residue produced per unit of crop production, by State; Dry Matter Fraction (DMF) = Amount of dry matter per unit of biomass for a crop; Fraction of C or N (FC or FN) = Amount of C or N per unit of dry matter for a crop; Burning Efficiency (BE) = The proportion of pre-fire fuel biomass consumed; and Combustion Efficiency (CE) = The proportion of C or N released with respect to the total amount of C or N available in the burned material, respectively.

Crop production and area harvested were available by State and year from USDA (2014) for all crops (except rice in Florida and Oklahoma, as detailed below). The amount C or N released was used in the following equation to determine the CH_4 and N_2O emissions from the field burning of agricultural residues:

CH_4 or N_2O Emissions from Field Burning of Agricultural Residues = C or N Released × ER for C or N × CF

where, Emissions Ratio (ER) = g CH_4-C released, or g N_2O-N /g N released, and Conversion Factor (CF) = conversion, by molecular weight ratio, of CH_4-C to C (16/12), or N_2O-N to N (44/28).

National and State-level crop production statistics are provided in Appendix Table B-6 and Appendix Table B-7. The sources for developing these input data are described for each parameter below. Values used in the equation above to estimate emissions from residue burning are summarized in Appendix Tables B-8(a-c).

Annual Crop Production:
Crop production data for all crops except rice in Florida and Oklahoma were taken from the USDA's Field Crops, Final Estimates 1987–1992, 1992–1997, 1997–2002 (USDA 1994, 1998, 2003), and Crop Production Summary (USDA 2005-2014). Rice production data for Florida and Oklahoma, which are not collected by USDA, were estimated separately. Average primary and ratoon crop yields for Florida (Schueneman & Deren 2002) were applied to Florida acreages (Schueneman 1999b, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007-2014), and crop yields for Arkansas (USDA 1994, 1998, 2003, 2005- 2009) were applied to Oklahoma acreages (Lee 2003- 2006; Anderson 2008, 2009).

Residue-to-Crop Product Mass Ratios:
All residue:crop product mass ratios except sugarcane and cotton were obtained from Strehler and Stützle (1987). The ratio for sugarcane is from Kinoshita (1988) and the ratio for cotton is from Huang et al. (2007). The residue:crop ratio for lentils was assumed to be equal to the average of the values for peas and beans. Residue dry matter fractions for all crops except soybeans, lentils, and cotton were obtained from Turn et al. (1997). Soybean and lentil dry-matter fractions were obtained from Strehler and Stützle (1987); the value for lentil residue was assumed to equal the value for bean straw. The cotton dry-matter fraction was taken from Huang et al. (2007). The residue C contents and N contents for all crops except soybeans and cotton are from Turn et al. (1997). The residue C content for soybeans is the IPCC default (IPCC/UNEP/OECD/IEA 1997). The N content of soybeans is from Barnard and Kristoferson (1985). The C and N contents of lentils were assumed to equal those of soybeans. The C and N contents

of cotton are from Lachnicht et al. (2004). These data are listed in Table 5-27. The burning efficiency was assumed to be 93 percent, and the combustion efficiency was assumed to be 88 percent for all crop types except sugarcane (EPA 1994). For sugarcane, the burning efficiency was assumed to be 81 percent (Kinoshita 1988) and the combustion efficiency was assumed to be 68 percent (Turn et al. 1997). Emission ratios and conversion factors for all gases (see Table 5-28) were taken from the Revised 1996 IPCC Guidelines (IPCC/UNEP/OECD/IEA 1997).

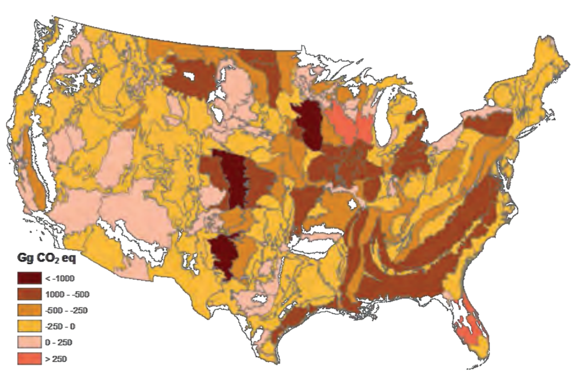
Fraction of Residues Burned:
The fraction of crop area burned was calculated using data on area burned by crop type and State from McCarty (2010) for corn, cotton, lentils, rice, soybeans, sugarcane, and wheat. McCarty (2010) used remote sensing data from Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate area burned by crop. State-level area burned data were divided by State-level crop-area-harvested data to estimate the percent of crop area burned by crop type for each State. As described above, all crop-area-harvested data were from USDA (2014) except for rice acreage in Florida and Oklahoma, which is not measured by USDA (Schueneman 1999, 2000, 2001; Deren 2002; Kirstein 2003, 2004; Cantens 2004, 2005; Gonzalez 2007-2014; Lee 2003- 2007; Anderson 2008- 2014). Data on crop area burned were only available from McCarty (2010) for the years 2003 through 2007. For other years in the time series, the percent area burned was set equal to the average 5-year percent area burned, based on data availability and interannual variability. This average was taken at the crop and State level. Table 5-26 shows these percent-area estimates aggregated for the United States as a whole, at the crop level. State-level estimates based on State-level crop-area-harvested and area burned data were also prepared, but are not presented here.

3.5.2 Uncertainty in Estimating Methane and Nitrous Oxide Emissions from Residue Burning

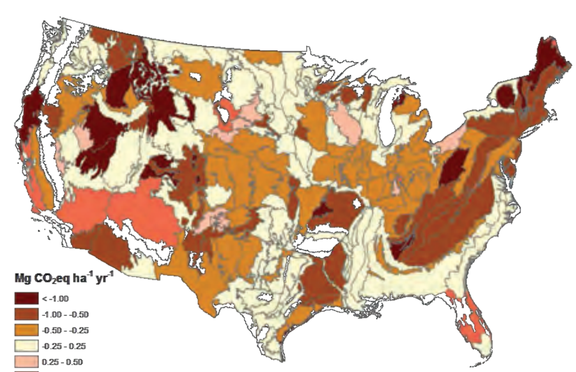
Calculations for crop-specific burned areas, residue-to-crop harvest ratios, burning/combustion efficiencies, and other factors contribute to overall uncertainty. A Monte Carlo analysis was performed to quantify these uncertainties. The calculated 95-percent confidence interval was 0.07 to 0.14 MMT CO_2 eq. for N_2O emissions from residue burning, or 30 percent below and 32 percent above the estimate of 0.1 MMT CO_2 eq. and 0.15 to 0.36 MMT CO_2 eq. for CH_4 emissions from residue burning, or 41 percent below and 42 percent above the estimate of 0.31 MMT CO_2 eq. (Table 3-1).

3.5.3 Changes Compared to the 3rd edition of the USDA GHG Report

The methodology was revised relative to the previous inventory to incorporate more recent State- and crop-level data on area burned from McCarty (2010). Cotton and lentils were added as crops, and peanuts and barley were removed because McCarty (2009) found that their residues are not burned in significant quantities in the United States. Fraction of residue burned was calculated at the State and crop level based on McCarty (2010) and USDA (2010) data, rather than assuming a 3-percent burn rate for all crops except rice and sugarcane, as was used in the previous inventory. Because the percent area burned was lower than previously assumed for almost all crops, these changes resulted in an average decrease in CH_4 emissions of about 66 percent and an average decrease in N_2O emissions of about 80 percent across the time series, compared to the previous inventory.



Map 3-3a Soil Carbon Changes for Major Land Resource Areas, Tier 3 Crops, Annual Means 2003-2007 *(Gg CO_2 eq. is gigagrams carbon dioxide equivalent.)*



Map 3-3b Unit Area Soil Carbon Changes for Major Land Resource Areas, Tier 3 Crops, Annual Means 2003–2007 *(Mg CO_2 eq. ha^{-1} yr^{-1} is megagrams carbon dioxide equivalent per hectare per year.)*

3.6 Carbon Stock Changes in Cropped Soils

Except for cultivated organic soils and liming practices, cropped soils in the United States were estimated to accumulate about 34 MMT CO_2 eq. in 2013 (Table 3-1)[4]. Much of the carbon change is attributable to the land enrolled in the CRP and land used to grow hay (Figure 3-7). Practices such as the adoption of conservation tillage, including no-till, which have taken place over the past two decades, and reduced frequency of summer fallow are important drivers of carbon stock changes. Manure applications to cropland also impact the estimated soil carbon stock.

In contrast, the small area of cultivated organic soils (less than 1 million hectares) concentrated in Florida, California, the Gulf and Southeastern coastal region and parts of the upper Midwest was a net source of CO_2 emissions for all years covered by the inventory (1990-2013). In 2013, about 27 MMT CO_2 eq. was emitted from cultivation of these soils (Table 3-1). Liming of agricultural soils resulted in emissions of about 6 MMT CO_2 eq. per year. Total net carbon sequestration in 2013 equaled ~1 MMT CO_2 eq. when all of the above components were taken into consideration. Carbon uptake on agricultural soils varied between 1990 and 2013 (Table 3-2), driven largely by land use changes and weather fluctuations.

Many regions in the Corn Belt, Great Plains, and Eastern United States are storing C in cropped mineral soils due to adoption of reduced tillage and other practices (see Map 3-3a for total emissions and Maps 3-3b and 3-4 for emissions per unit area). On average, conventional till soils used for annual cropping were a source of about 0.25 MT CO_2 eq. ha-1 yr-1, reduced till soils were roughly carbon neutral, and no-till soils stored about 0.68 MT CO_2 eq. ha-1 yr-1. Note that the maps in this chapter only show C stock changes for mineral soils and, as stated above, emissions from cropped organic soils are significant in some regions.

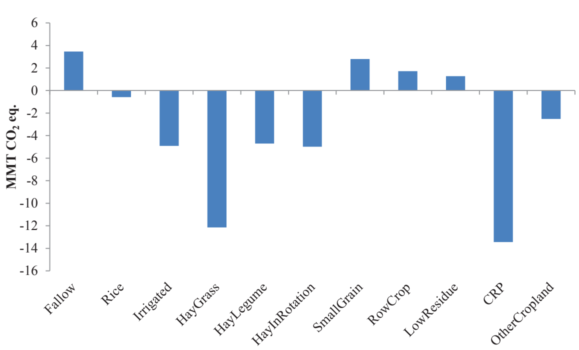
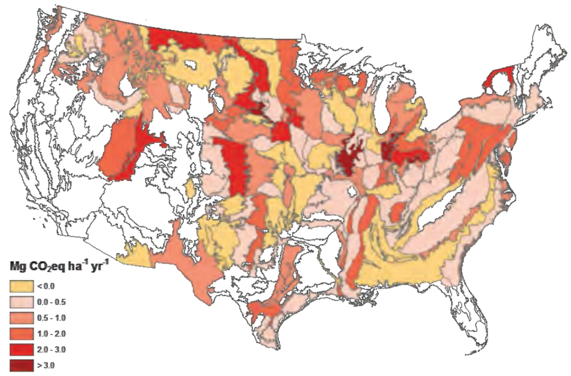
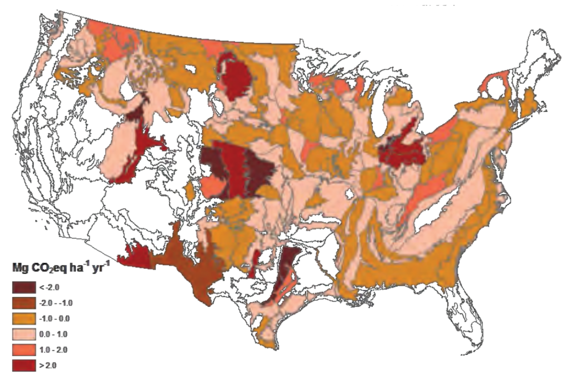


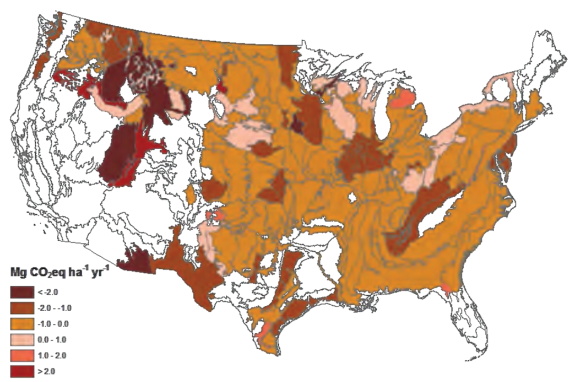
Figure 3-7 CO2 Emissions and Sequestration Sources from Cropland Soils, 2003-2007 *(MMT CO_2 eq. is million metric tons of carbon dioxide equivalent. CRP is USDA Conservation Reserve Program)*



Map 3-4a Soil Carbon Changes for Major Land Resource Areas, Tier 3 Crops Conventional Till, Annual Means 2003-2007 *(Mg CO_2 eq. ha^{-1} yr^{-1} is megagrams carbon dioxide equivalent per hectare per year.)*



Map 3-4b Soil Carbon Changes for Major Land Resource Areas, Tier 3 Crops Reduced Till, Annual Means 2003-2007 *(Mg CO_2 eq. ha^{-1} yr^{-1} is megagrams carbon dioxide equivalent per hectare per year.)*



Map 3-4c Soil Carbon Changes for Major Land Resource Areas, Tier 3 Crops No Till, Annual Means 2003-2007 *(Mg CO_2 eq. ha^{-1} yr^{-1} is megagrams carbon dioxide equivalent per hectare per year.)*

[4] Emissions and sinks of carbon in agricultural soils are expressed in terms of CO2 equivalents; carbon sequestration is a result of changes in stocks of carbon in soils, from which CO2 fluxes are inferred. Units of CO2 equivalent can be converted to carbon using a multiplier of 0.272.

3.6.1 Methods for Estimating Carbon Stock Changes in Agricultural Soils

Two broad categories of cropland were considered: cropland remaining cropland and land converted to cropland. Within both of these categories, Tier 2 and Tier 3 methodologies were used. The Tier 2 approach is based on relatively simple equations used in IPCC (2003) methodology that have been modified to better represent nations or regions within nations. The Tier 3 approach (DayCent model) uses a more complex ecosystem model to simulate carbon fluxes for cropped systems. Both tiers used land use and management data based primarily on the NRI (USDA 2009). The NRI represents a robust statistical sampling of land use and management on all non-Federal land in the United States, and more than 400,000 NRI survey points occurred in agricultural lands and were used in the inventory analysis. The methodology summarized below is described in detail in the U.S. GHG Inventory (EPA 2015).

3.6.2 Tier 3 DayCent Model Simulations for Most Cropped Mineral Soils

In this section, we highlight aspects of the DayCent model relevant to soil C stocks because the simulations described in detail in section 3.3.2 apply here except for the quantification of model structural uncertainty. Namely, soil C stock changes generated by DayCent were compared with measurements from 84 long-term field plots to quantify structural uncertainty for this GHG source. Soil C stock change estimates from DayCent reflect the balance between C additions from plant residues that are not removed during harvest operations and manure amendments and C losses from decomposition of plant residues and soil organic matter. Note that the model does not account for C losses from erosion nor gains from deposition of soil or organic matter.

3.6.3 Tier 2 Approach for Remaining Cropped Mineral Soils, Organic Soils, and Liming

A Tier 2 approach was used to estimate soil carbon stock changes for crop rotations not simulated by the DayCent model, for non-agricultural lands that were converted to cropland, and for organic soils. Data on climate, soil type, and land use were used to classify land area and apply appropriate stock change factors. U.S.-specific carbon stock change factors were derived from published literature to estimate the impact of management practices (e.g., changes in tillage or crop rotation) on soil carbon fluxes (Ogle et al. 2003, 2006b). Cultivated histosol areas are listed in Appendix Table B-9, carbon loss rates from organic soils under agricultural management in the United States are listed in Appendix Table B-10, MLRA-level estimates of annual soil carbon stock changes by major land use and management type

are listed in Appendix Table B-11, and State-level estimates of mineral soil carbon changes on cropland by major activity are listed in Appendix Table B-12.

Stock change factors and reference carbon stocks can vary for different climate regimes and soil types. The IPCC method defines eight climate types according to mean annual temperature, precipitation, and potential evapotranspiration. Six of these occur in the continental United States. The PRISM long-term monthly climate data set (Daly et al. 1998) was used to classify each of the 180 MLRAs in the United States into climate zones. Reference soil carbon stocks were stratified by climate region and categorized into six major groupings, based on taxonomic orders that relate to soil development and physical characteristics that influence soil carbon contents. Estimates for carbon stocks under conventionally managed cropland (defined as the reference land use) were derived from the National Soil Survey Characterization Database (USDA 1997b).

Based on the NRI, crop management systems were aggregated into 22 different categories. Tillage practices are not included in the NRI. Thus, supplemental data were used from the Conservation Technology Information Center (CTIC 1998), which provides spatial information on tillage practices. Data for wetland restoration under CRP were obtained from Euliss and Gleason (2002). Organic soils (i.e., peat, mucks) that have been drained and converted to cropland or pasture are subject to potentially high rates of carbon loss. Annual C losses were estimated using IPCC (1997, 2006) methodology except that U.S.-specific carbon loss rates were used in the calculations instead of the default IPCC rates (Ogle et al. 2003). Manure N amendments over the inventory time period were based on application rates and areas amended with manure N from Edmonds et al. (2003).

Limestone and dolomite are often applied to acidic soils to raise the pH. However, CO_2 is emitted when these materials degrade. Emissions were estimated using a Tier 2 approach. Application rates were derived from estimates and industry sources (Minerals Yearbook, published by the U.S. Bureau of Mines through 1994 and by the U.S. Geological Survey from 1994 to present). The emission factors used, 0.059 ton CO_2-C/1 ton limestone and 0.064 ton CO_2-C/1 ton dolomite, are lower than the default IPCC emission factors because they account for a portion of limestone that may leach through soils and travel through waterways to the ocean (West & McBride 2005). The methodology summarized above is described in detail in Chapter 7 of the U.S. GHG Inventory (EPA 2015).

3.6.4 Uncertainty in Estimating Carbon Stock Changes in Agricultural Soils

Uncertainty was calculated separately for the Tier 3 and Tier 2 approaches used to estimate soil CO_2 fluxes. The methodologies summarized below are described in detail in Chapter 7 and Annex 3.13 of the U.S. GHG Inventory (EPA 2015). Uncertainty was combined for soil C stock changes on mineral soils for crop rotations simulated by DayCent, mineral soils for crop rotations not calculated by DayCent, cropped organic soils, and emissions from liming. Section 3.3.2.2 describes uncertainty for crop rotations calculated using DayCent. Uncertainty for the remaining sources was estimated using simple error propagation (IPCC 2006). Error propagation was used to combine uncertainties in the various components by taking the square root of the sum of the squares of the standard deviations of the components (IPCC 2006). The combined 95-percent confidence interval for C stock change in cropped soils in 2013 ranged from -39 to 38 MMT CO_2 eq. around the estimate of -1 MMT CO_2 eq. (Table 3-1). Because the estimate (-1 MMT CO_2 eq.) is close to 0 (i.e., C neutral) the uncertainty bounds in Table 3-1 stated as percentages are very wide.

There were important changes in land classification data that affected C stock change estimates. More recent annual data from the USDA NRI were used to classify land use and management practices in this edition. In previous inventories, NRI data were collected in 5-year increments, and the last available year was 1997. Availability of new annual data extended the time series of activity data beyond 1997 to 2007. In addition, annual C flux estimates for mineral soils between 1990 and 20013 were adjusted to account for additional C stock changes associated with sewage sludge amendments using a Tier 2 method provided in IPCC (2003, 2006), which utilizes U.S.-specific C loss rates (Ogle et al. 2003) rather than default IPCC rates. Overall, these methodological changes resulted in an average decline in mineral soil C sequestration of about 14 percent during 1990-2008. The smaller average C sequestration estimated with the current methodology results mainly from smaller estimates during the latter part of the time series. This is due to using updated NRI data instead of assuming that land use was constant after 1997.

3.7 Mitigation of CO_2 Emissions

Currently, cropped mineral soils in the United States are estimated to be storing carbon at a rate of approximately 34 MMT CO_2 per year, but this is largely nullified when emissions from cropped organic soils and liming are accounted. Taking organic soils out of production provides an opportunity to mitigate emissions because they make up less than 1 percent of total cropped land in the United States, but are a source of 27 MMT CO_2 per year (Table 3-1). Other strategies to increase carbon storage and decrease net C emissions include increasing cropping intensity, conversion to CRP, reducing tillage intensity, and amending soils with organic matter. Increasing cropping intensity by growing cover crops and minimizing fallow periods can sequester C because carbon inputs to soil are increased. When soils are fallow, particularly during summer, carbon levels tend to decrease because plants are not present to provide carbon inputs but decomposition of soil carbon by microbes continues. Growing-season length limits where fall-spring cover crops can be grown, while soil moisture availability precludes growing summer crops every year in some arid areas of the United States. Cropped land converted to CRP stores carbon because the land is not cultivated and trees or grasses are planted to provide carbon inputs that typically exceed those of annual crops. However, increases in demand, particular for grains supplied by row crops, have led to conversion of CRP back to cropping in recent years. Including hay or pasture in rotations also increases carbon inputs, and carbon losses are lower because the land is not tilled during the hay or pasture phase of the rotation. Further reductions in tillage intensity should also store C, but this is not feasible in all regions. Additions of organic matter (manure and compost) and biochar also typically promote C sequestration in soil, but transportation and other costs associated with these amendments limit their widespread use.

Agroforestry practices such as establishing windbreaks and riparian forest buffers represent another potential carbon sink in cropland agriculture. Comprehensive data on agroforestry practices are not available to estimate the current national levels of carbon sequestration from such practices. However, published research studies have estimated the potential agroforestry carbon sink in the United States. In temperate systems, agroforestry practices store large amounts of carbon (Kort & Turlock 1999, Schroeder 1994), with the potential ranging from 15 to 198 metric tons of carbon per hectare (modal value of 34 metric tons of carbon per hectare) (Dixon 1995). Nair and Nair (2003) estimated that by the year 2025, the potential carbon sequestration of agroforestry in the United States will be 90 million metric tons of carbon per year.

3.8 Planned Improvements

There are many updates currently being made to the methodology to calculate GHG emissions from croplands. Land cover/use activity data are being improved by accounting for USDA NRI time series and land use/management data through 2010. Improvements to the DayCent crop phenology sub-model are anticipated to better represent senescence, particularly following grain filling in crops. In addition, the effects of temperature on plant production will be improved by continued calibration of DayCent. The number of experimental study sites used for testing will be expanded to more accurately assess model structural uncertainty, and studies measuring daily N_2O fluxes frequently will be given higher priority because they provide more robust estimates of annual emissions than do studies that measure emissions less frequently. Another planned improvement is to account for the use of slow-release fertilizers and nitrification inhibitors. Field investigations suggest that the use of these types of N sources often contribute to reductions in the rate of N_2O emissions, and although the DayCent model is capable of simulating use of nitrification inhibitors, validation requires that simulated data be compared with data from a sufficient number of in situ studies. Currently there is a mismatch between the amount of residue DayCent simulates for burning and the amount of residue burned according to the Field Burning of Agricultural Residues source category (EPA 2015). Significant updates have been made to this source category based on new spatial data, and ideally, future DayCent simulations will account for the same amount of residue available for burning. Hawaii and Alaska are not currently included in the inventory for agricultural soil management, except for N_2O emissions from drained organic soils (croplands and grasslands) in Hawaii. In addition to more fully including Alaska and Hawaii in the subsequent inventory, it is also expected that more crop types will be incorporated to the DayCent model simulations and removed from the Tier 1 analyses. Soil C stock changes with land use conversion from forest land to cropland are undergoing further evaluation to ensure consistency in the land-representation time series. Different methods are used to estimate soil C stock changes in forest land and croplands, and while the areas have been reconciled between these land uses, there has been limited evaluation of the consistency in C stock changes with conversion from forest land to cropland.

SUGGESTED CITATION

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3.10 Appendix B

B-1 MLRA-Level Area Estimates by Major Crop Rotation, 2003-2007

B-2 MLRA-Level Estimates of Total Annual Direct N_2O Emissions by Major Crop Rotation, 2003-2007

B-3 MLRA-Level Estimates of Total Annual Indirect N_2O Emissions from Ammonia, Nitric Oxide and Nitrogen Dioxide Volatilization by Major Crop Rotation, 2003-2007

B-4 MLRA-Level Estimates of Total Annual Indirect N_2O Emissions for Nitrate Leaching by Major Crop Rotation, 2003-2007

B-5 Rice Harvested Area, 1990, 1995, 2000-2013

B-6 Total U.S. Production of Crops Managed With Burning, 1990, 1995, 2000-2013

B-7 Production of Crops Managed With Burning

B-8 Information Used in Estimating Methane and Nitrous Oxide Emissions from Crop Residue Burning

B-9 Cultivated Histosol (Organic Soils) Area

B-10 Carbon Loss Rates from Organic Soils Under Agricultural Management in the United States

B-11 MLRA-Level Estimates of Annual Soil Carbon Stock Changes by Major Crop Rotation, 2003-2007

B-12 State-Level Estimates of Mineral Soil Carbon Changes on Cropland by Major Activity, 2013

Appendix Table B-1 MLRA-Level Area Estimates by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*hectares*					
2	-	-	23,715	21,480	25,374	91,821	-	-	-	-	189,942
5	-	-	-	-	-	20,334	-	-	-	-	-
7	32,780	68,351	-	-	-	370,458	-	-	-	-	-
8	516,582	1,187,268	-	-	-	147,229	-	28,449	-	-	220,109
9	135,571	231,521	-	-	29,866	48,548	-	-	-	-	584,542
10	-	15,781	-	-	16,511	139,697	-	-	-	-	-
11	-	44,733	-	-	-	959,877	-	-	-	-	-
12	-	-	-	-	-	95,053	-	-	-	-	-
13	222,575	63,126	-	16,026	17,442	132,510	-	-	-	-	76,018
14	-	-	16,026	-	-	63,813	-	-	-	-	-
15	-	-	-	-	-	46,607	-	34,115	-	-	-
16	-	-	-	-	-	34,217	-	-	-	-	-
17	-	24,079	-	-	-	721,579	-	77,255	205,024	-	-
21	-	-	-	-	-	174,120	-	-	-	-	-
23	-	-	-	-	-	113,689	-	-	-	-	-
24	-	-	-	-	-	82,208	-	-	-	-	-
25	-	-	-	-	-	42,909	-	-	-	-	-
26	-	-	-	-	-	7,917	-	-	-	-	-
27	-	-	-	-	-	66,271	-	2,266	-	-	-
29	-	-	-	-	-	9,264	-	-	-	-	-
30	-	-	-	-	-	23,254	-	-	-	-	-
31	-	21,408	-	-	-	179,357	-	10,158	-	-	-
32	-	-	-	-	-	131,672	-	-	-	-	-
35	-	-	-	-	-	35,565	-	-	-	-	-
36	19,830	34,317	-	-	-	70,638	-	-	-	-	19,708
40	-	-	-	-	-	121,208	-	13,152	-	-	-
41	-	-	-	-	-	20,437	-	-	-	-	-
42	-	-	-	-	-	171,981	-	52,569	-	-	-
44	-	112,083	7,608	-	49,412	361,826	-	-	-	-	37,879
46	70,092	269,302	-	-	94,292	158,441	-	-	-	-	143,906
47	-	-	-	-	-	67,989	-	-	-	-	-
49	-	25,778	-	-	-	11,935	-	-	-	-	-
51	-	-	-	-	-	149,262	-	-	-	-	-
52	542,239	1,582,282	-	-	20,760	87,974	-	-	-	-	295,926
54	244,268	193,278	131,159	106,262	264,705	42,735	-	34,722	-	110,965	1,317,166
56	318,245	-	34,075	41,278	42,168	-	112,907	484,490	-	1,181,429	629,530
57	-	-	-	61,269	80,087	-	-	-	-	154,125	-
61	-	-	-	-	20,315	-	-	-	-	-	-
64	30,311	193,480	-	-	46,498	107,067	-	-	-	35,491	56,575
65	-	-	-	-	11,938	124,481	-	-	-	-	-
66	-	-	16,592	38,838	72,884	113,548	-	-	-	99,553	32,618
69	150,098	58,194	-	-	-	115,950	-	-	-	-	-
71	12,424	-	15,095	-	50,586	683,436	-	-	-	145,606	-
72	695,557	2,113,497	-	-	18,494	1,074,751	-	369,681	-	381,133	551,870
73	288,130	959,834	20,275	67,973	91,135	356,913	-	458,752	-	493,029	865,745
74	82,632	18,899	21,974	41,157	47,227	56,211	-	28,692	-	326,501	577,123

Continued - Appendix Table B-1 MLRA-Level Area Estimates by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*hectares*					
75	19,263	31,727	-	-	16,349	877,138	-	-	-	479,715	69,646
76	13,193	-	56,251	20,720	19,708	-	-	-	-	145,197	105,623
79	161,385	91,945	-	-	18,170	208,535	-	37,636	-	103,896	571,766
85	-	18,049	-	-	-	-	-	-	-	43,625	169,760
89	-	-	-	19,263	15,257	34,398	-	-	-	40,469	-
92	-	-	-	-	12,667	-	-	-	-	-	-
96	-	-	6,232	-	8,620	-	-	-	-	-	-
97	-	-	-	-	24,322	15,124	-	-	-	138,160	-
98	39,455	-	62,524	58,027	142,126	164,778	-	45,730	-	1,264,292	16,875
99	26,588	-	-	20,286	46,417	-	12,141	52,043	-	1,268,131	10,805
101	-	-	79,238	140,361	201,615	-	-	50,869	-	249,624	18,899
103	108,530	-	21,367	55,482	68,028	-	-	19,951	-	5,022,610	-
104	52,417	-	13,233	48,382	33,670	-	-	35,572	-	2,233,534	-
105	250,318	-	56,089	330,595	208,413	22,619	-	105,583	-	1,409,838	-
106	136,258	-	55,118	34,830	43,666	88,141	-	15,661	-	1,200,584	55,280
109	480,654	-	177,010	78,132	195,140	-	-	15,014	-	1,143,162	-
110	-	-	-	7,972	-	-	-	9,874	-	1,217,948	-
112	82,663	-	222,173	35,702	99,634	37,696	-	38,567	-	950,411	362,369
113	159,562	-	60,460	55,740	64,183	11,614	-	17,928	-	1,722,294	25,576
121	-	-	114,405	35,254	156,937	-	-	-	-	102,335	-
122	33,076	-	170,858	52,208	190,809	-	23,310	-	-	425,580	23,917
123	-	-	37,433	-	46,296	-	-	-	-	41,235	-
124	-	-	77,983	47,987	98,055	-	-	13,152	-	162,039	-
125	-	-	26,750	-	17,240	-	-	-	-	21,003	-
126	-	-	183,606	40,478	72,317	-	-	-	-	72,603	-
127	-	-	95,465	46,590	54,187	-	-	12,748	-	57,004	-
128	-	-	107,525	30,191	100,119	-	68,716	13,314	-	116,409	-
129	-	-	21,772	-	-	-	-	-	-	42,439	-
134	231,640	26,993	113,838	-	-	196,075	320,269	82,961	217,516	755,810	50,707
136	36,098	-	308,614	63,694	29,097	-	19,223	42,856	-	209,545	46,440
137	-	-	22,501	-	-	-	26,386	12,626	-	27,216	-
138	-	-	-	-	-	12,096	-	-	-	-	-
139	-	-	53,702	83,733	156,168	-	-	26,305	-	369,536	-
140	-	-	243,904	165,009	236,782	-	-	24,443	-	142,569	-
142	-	-	84,134	62,367	140,912	-	-	-	-	53,336	-
143	-	-	34,520	-	20,639	-	-	-	-	-	-
145	-	-	15,459	-	-	-	-	-	-	13,993	-
146	-	-	-	-	-	-	19,546	-	-	-	-
147	-	-	161,672	131,700	119,585	-	-	40,307	-	353,730	21,570
148	-	-	83,163	86,885	77,133	-	-	34,277	-	302,066	21,655
155	-	-	-	-	-	110,784	-	-	-	-	-
102A	231,606	-	41,318	71,225	94,575	50,748	-	54,268	-	1,880,376	135,813
102B	-	-	-	-	23,674	-	-	-	-	373,886	-
102C	88,339	-	23,593	60,662	71,994	507,355	-	-	-	1,359,543	-
107A	-	-	-	-	-	-	-	15,014	-	926,590	-
107B	86,927	-	52,650	26,752	40,307	109,994	-	-	-	2,213,355	14,261
108A	-	-	-	-	14,528	-	-	-	-	1,916,475	-

Continued - Appendix Table B-1 MLRA-Level Area Estimates by Major Crop Rotation, 2003-2007

MLRA[2]	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
						hectares					
108B	16,514	-	-	-	26,628	27,715	-	-	-	1,904,706	-
108C	118,856	-	19,830	37,960	30,392	-	-	28,045	-	1,177,787	-
108D	111,469	-	21,813	44,973	66,692	-	-	-	-	683,944	-
111A	-	-	15,459	-	32,011	-	-	-	-	1,610,775	-
111B	100,628	-	17,806	40,745	67,947	9,712	-	17,604	-	1,904,787	12,383
111C	-	-	-	-	-	-	-	-	-	575,028	-
111D	-	-	-	-	11,979	-	-	-	-	828,783	-
111E	-	-	-	16,147	16,633	-	-	9,348	-	339,457	-
114A	-	-	23,148	15,321	34,075	-	-	-	-	384,282	-
114B	21,246	-	15,216	27,999	19,546	-	-	-	-	812,550	16,592
115A	-	-	-	-	14,973	17,968	-	-	-	627,496	24,888
115B	22,743	-	64,143	-	30,999	-	-	20,639	-	375,613	16,552
115C	97,497	-	48,805	44,070	66,045	61,431	-	22,986	-	1,545,842	-
116A	-	-	178,426	-	65,802	-	-	-	-	83,047	-
116B	-	-	104,854	-	29,380	-	-	-	-	22,161	15,621
118A	-	-	14,285	-	-	-	-	-	-	21,974	27,814
120A	80,472	-	37,110	27,511	68,554	-	-	-	-	385,636	-
120B	-	-	13,112	-	-	-	-	-	-	97,961	-
120C	-	-	-	-	-	-	-	-	-	19,061	-
130A	-	-	-	-	-	-	-	-	-	5,382	-
130B	-	-	25,131	-	22,541	-	-	-	-	-	-
131A	68,554	49,169	17,685	-	-	1,118,667	532,162	122,660	722,280	1,316,008	81,301
131B	-	20,315	-	-	-	306,643	27,761	-	205,338	60,946	-
131C	-	-	-	-	-	25,455	31,039	-	30,149	115,740	-
131D	-	-	-	-	-	94,697	-	-	158,354	-	-
133A	376,047	74,278	180,895	58,728	16,997	301,787	880,685	216,467	-	536,764	81,423
133B	-	-	46,134	-	-	-	-	-	-	47,429	20,826
135A	145,627	-	60,784	-	-	-	70,780	10,360	-	149,410	-
144A	-	-	118,533	40,647	61,108	-	6,596	9,955	-	49,940	-
144B	-	-	92,997	10,687	32,253	-	-	-	-	13,476	-
149A	-	-	7,608	-	-	14,812	-	-	-	74,336	-
150A	-	-	-	-	-	242,060	173,408	258,554	280,439	319,500	-
150B	-	-	-	-	-	-	-	-	10,279	-	-
152B	-	-	-	-	-	-	-	20,922	16,673	-	-
153A	-	-	-	-	-	18,345	133,936	34,924	-	181,828	-
153B	-	-	-	-	-	8,158	35,208	11,048	-	139,549	5,666
153C	-	-	-	-	-	11,007	-	-	-	165,759	-
153D	-	-	-	-	-	44,904	-	-	-	122,932	-
156A	-	-	-	-	-	23,512	-	-	-	-	-
28A	93,685	42,613	-	-	-	391,900	-	-	-	-	15,174
28B	-	-	-	-	-	15,083	-	-	-	-	-
34A	-	15,580	-	-	-	193,445	-	-	-	-	-
34B	-	-	-	-	-	128,932	-	-	-	-	-
43A	26,871	-	-	-	16,754	-	-	-	-	-	72,803
43B	30,473	-	-	-	24,848	100,708	-	-	-	-	-
48A	-	-	-	-	-	65,288	-	-	-	-	-
48B	-	-	-	-	-	24,442	-	-	-	-	-

Continued - Appendix Table B-1 MLRA-Level Area Estimates by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*hectares*					
53A	299,063	297,727	17,563	-	16,754	15,459	-	54,956	-	-	742,396
53B	412,172	106,999	74,017	83,350	115,133	-	-	107,646	-	604,601	1,199,004
53C	19,627	-	-	-	15,297	16,552	-	-	-	205,742	172,801
55A	250,501	-	25,333	-	19,668	-	26,628	176,484	-	128,488	1,502,113
55B	378,783	-	57,465	71,920	63,495	31,889	21,610	219,664	-	1,458,407	666,545
55C	57,101	-	21,772	64,426	103,316	46,370	-	47,955	-	1,178,071	75,312
58A	360,171	488,335	85,389	123,762	164,667	171,904	-	60,339	-	-	191,174
58B	-	-	-	-	15,540	56,996	-	-	-	-	-
60A	-	61,147	-	-	38,728	27,761	-	-	-	-	53,540
63A	66,166	62,160	29,259	-	20,518	-	-	-	-	89,274	241,719
63B	-	-	9,105	16,511	53,661	-	-	17,847	-	89,881	39,700
67A	141,964	89,593	-	-	17,037	235,975	-	-	-	11,048	17,078
67B	578,903	873,526	-	-	-	302,986	-	81,544	-	195,221	122,863
70A	-	-	-	-	-	10,141	-	-	-	-	-
70B	-	-	-	-	-	30,311	-	-	-	-	-
70C	-	-	-	-	-	7,163	-	-	-	-	-
77A	226,988	120,354	-	-	-	498,043	-	21,610	-	113,393	392,019
77B	23,472	-	-	-	-	128,680	-	-	-	-	-
77C	1,121,627	137,985	-	-	-	1,353,623	810,106	49,776	-	57,749	463,285
77D	163,898	-	-	-	-	62,259	-	-	-	-	35,929
77E	229,295	25,171	-	-	-	36,870	-	-	-	-	114,966
78A	-	-	-	-	-	-	-	-	-	-	119,802
78B	302,019	-	-	-	-	52,189	289,818	-	-	-	407,644
78C	195,359	37,231	-	-	20,679	103,737	184,438	31,768	-	18,696	1,203,236
80A	36,058	-	25,900	-	65,519	56,101	-	-	-	38,000	1,711,492
80B	-	-	-	-	-	-	-	-	-	-	121,120
81A	-	-	-	-	-	89,193	51,759	69,201	-	-	36,426
81B	-	-	-	-	-	-	-	-	-	-	40,766
81C	-	-	-	-	-	-	-	-	-	-	26,669
82B	-	-	-	-	-	-	-	-	-	-	37,396
83A	-	-	-	-	-	87,203	-	17,280	-	97,853	69,140
83C	-	-	-	-	-	-	-	-	-	23,836	-
83D	-	-	-	-	-	167,773	43,504	-	-	129,095	-
83E	-	-	-	-	-	-	-	-	-	39,295	-
84A	-	-	25,252	-	-	-	-	-	-	-	74,299
84B	-	-	-	-	-	32,495	-	-	-	-	91,358
86A	-	-	24,403	-	-	-	32,577	76,769	-	411,602	323,225
87A	-	-	-	-	-	-	-	-	-	55,887	22,674
87B	-	-	-	-	-	-	-	-	-	-	32,529
90A	-	-	67,218	107,074	114,202	-	-	-	-	129,816	-
90B	13,881	-	51,719	158,888	95,304	-	-	41,723	-	351,542	-
91A	44,371	-	-	23,259	35,734	91,861	-	-	-	120,634	-
91B	-	-	-	-	13,152	-	-	-	-	38,526	-
94A	-	-	-	-	67,987	-	-	-	-	55,578	-
94B	-	-	-	-	25,212	-	-	-	-	-	-
95A	29,137	-	15,864	163,384	75,514	-	-	37,717	-	353,169	12,060
95B	37,838	-	21,125	141,795	73,936	23,876	-	45,122	-	959,343	-

[1] CRP = Conservation Reserve Program
[2] MLRA = Major Land Resource Area

Appendix Table B-2 MLRA-Level Estimates of Total Annual Direct N_2O Emissions by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq.*[3]					
2	-	-	34.28	26.08	22.21	78.26	-	-	-	-	140.14
5	-	-	-	-	-	25.13	-	-	-	-	-
7	7.09	29.75	-	-	-	304.47	-	-	-	-	-
8	111.01	482.06	-	-	-	167.32	-	15.61	-	-	112.93
9	40.84	124.56	-	-	27.31	55.69	-	-	-	-	448.83
10	-	10.55	-	-	16.82	159.65	-	-	-	-	-
11	-	30.61	-	-	-	963.09	-	-	-	-	-
12	-	-	-	-	-	94.63	-	-	-	-	-
13	63.71	36.29	-	11.83	11.54	150.35	-	-	-	-	71.76
14	-	-	11.91	-	-	32.47	-	-	-	-	-
15	-	-	-	-	-	22.84	-	8.52	-	-	-
16	-	-	-	-	-	27.38	-	-	-	-	-
17	-	26.57	-	-	-	759.82	-	21.68	623.93	-	-
21	-	-	-	-	-	204.76	-	-	-	-	-
23	-	-	-	-	-	103.71	-	-	-	-	-
24	-	-	-	-	-	67.19	-	-	-	-	-
25	-	-	-	-	-	54.51	-	-	-	-	-
26	-	-	-	-	-	10.59	-	-	-	-	-
27	-	-	-	-	-	51.26	-	0.67	-	-	-
29	-	-	-	-	-	5.04	-	-	-	-	-
30	-	-	-	-	-	13.46	-	-	-	-	-
31	-	15.86	-	-	-	277.41	-	4.97	-	-	-
32	-	-	-	-	-	98.71	-	-	-	-	-
35	-	-	-	-	-	33.96	-	-	-	-	-
36	5.21	16.35	-	-	-	67.88	-	-	-	-	7.99
40	-	-	-	-	-	106.61	-	5.96	-	-	-
41	-	-	-	-	-	22.90	-	-	-	-	-
42	-	-	-	-	-	159.16	-	25.78	-	-	-
44	-	63.09	12.04	-	49.57	402.75	-	-	-	-	33.74
46	8.90	99.43	-	-	45.33	123.50	-	-	-	-	72.69
47	-	-	-	-	-	63.70	-	-	-	-	-
49	-	7.49	-	-	-	11.06	-	-	-	-	-
51	-	-	-	-	-	130.99	-	-	-	-	-
52	64.40	420.76	-	-	6.70	73.58	-	-	-	-	94.43
54	25.78	57.71	59.20	32.64	63.65	31.47	-	14.39	-	70.42	521.07
56	58.36	-	20.37	37.41	20.84	-	82.47	331.07	-	923.89	400.35
57	-	-	-	38.17	45.24	-	-	-	-	119.39	-
61	-	-	-	-	7.45	-	-	-	-	-	-
64	2.37	55.79	-	-	13.86	81.29	-	-	-	19.94	19.71
65	-	-	-	-	3.15	103.41	-	-	-	-	-
66	-	-	14.36	23.24	25.86	93.34	-	-	-	92.20	18.35
69	24.40	32.45	-	-	-	134.79	-	-	-	-	-
71	2.15	-	15.90	-	15.75	659.43	-	-	-	128.31	-
72	117.05	744.00	-	-	4.11	984.92	-	154.54	-	268.80	197.26
73	39.33	326.59	17.19	41.28	23.84	346.89	-	182.38	-	275.36	344.05

Continued - Appendix Table B-2 MLRA-Level Estimates of Total Annual Direct N_2O Emissions by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq.[3]*					
74	19.79	6.80	28.62	26.34	18.19	37.57	-	11.73	-	197.40	288.44
75	3.98	18.26	-	-	6.06	821.47	-	-	-	365.71	41.01
76	3.19	-	67.69	19.00	8.33	-	-	-	-	102.74	58.03
79	21.66	29.22	-	-	4.98	133.57	-	15.03	-	56.69	216.01
85	-	8.50	-	-	-	-	-	-	-	46.49	100.41
89	-	-	-	16.46	11.23	28.79	-	-	-	36.52	-
92	-	-	-	-	13.07	-	-	-	-	-	-
96	-	-	8.89	-	9.11	-	-	-	-	-	-
97	-	-	-	-	22.76	14.94	-	-	-	152.68	-
98	12.74	-	74.90	56.73	128.06	154.18	-	33.93	-	1,190.01	14.66
99	8.05	-	-	16.40	37.86	-	12.77	42.56	-	1,199.86	9.53
101	-	-	127.69	195.30	220.33	-	-	58.03	-	366.69	22.19
103	27.08	-	16.25	42.79	41.78	-	-	16.12	-	4,494.84	-
104	14.42	-	11.94	40.73	25.28	-	-	33.48	-	2,221.85	-
105	78.41	-	54.58	289.00	156.02	22.63	-	97.11	-	1,462.65	-
106	32.31	-	40.70	21.92	24.45	78.69	-	8.86	-	1,005.43	38.23
109	131.20	-	137.93	60.31	133.51	-	-	11.04	-	994.19	-
110	-	-	-	7.26	-	-	-	6.74	-	1,303.22	-
112	19.81	-	144.26	25.57	67.21	29.02	-	25.18	-	707.90	223.41
113	42.24	-	45.85	41.75	49.40	11.44	-	12.92	-	1,416.53	17.98
121	-	-	100.79	32.27	149.06	-	-	-	-	94.45	-
122	8.86	-	111.56	34.03	152.57	-	12.22	-	-	326.93	16.15
123	-	-	22.87	-	32.37	-	-	-	-	26.13	-
124	-	-	72.46	50.06	96.91	-	-	12.92	-	176.59	-
125	-	-	16.30	-	12.56	-	-	-	-	14.14	-
126	-	-	155.09	37.61	69.71	-	-	-	-	77.60	-
127	-	-	109.92	53.21	58.89	-	-	15.28	-	79.38	-
128	-	-	63.81	19.86	77.98	-	35.65	4.29	-	72.44	-
129	-	-	9.70	-	-	-	-	-	-	23.55	-
134	44.73	12.74	67.03	-	-	128.30	177.00	36.58	391.30	449.92	32.12
136	6.95	-	230.41	37.87	16.52	-	9.05	15.20	-	133.18	24.56
137	-	-	12.80	-	-	-	11.50	3.42	-	13.90	-
138	-	-	-	-	-	5.43	-	-	-	-	-
139	-	-	101.13	102.47	168.49	-	-	23.22	-	417.03	-
140	-	-	653.17	343.96	304.35	-	-	39.81	-	259.51	-
142	-	-	323.98	163.95	236.50	-	-	-	-	134.96	-
143	-	-	113.19	-	29.51	-	-	-	-	-	-
145	-	-	43.81	-	-	-	-	-	-	21.79	-
146	-	-	-	-	-	-	25.40	-	-	-	-
147	-	-	270.67	175.96	119.70	-	-	49.14	-	474.71	24.30
148	-	-	121.08	95.64	71.58	-	-	37.57	-	332.97	22.10
155	-	-	-	-	-	48.92	-	-	-	-	-
102A	38.93	-	28.37	40.04	41.29	37.13	-	29.27	-	1,396.38	76.37
102B	-	-	-	-	11.19	-	-	-	-	298.10	-
102C	17.56	-	14.82	40.57	35.49	479.53	-	-	-	1,173.53	-
107A	-	-	-	-	-	-	-	14.29	-	1,077.88	-
107B	21.96	-	35.20	18.50	24.13	162.56	-	-	-	2,016.77	11.97

Continued - Appendix Table B-2 MLRA-Level Estimates of Total Annual Direct N_2O Emissions by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq.[3]*					
108A	-	-	-	-	10.82	-	-	-	-	1,926.14	-
108B	6.05	-	-	-	19.34	28.08	-	-	-	1,925.11	-
108C	34.32	-	17.90	31.59	23.02	-	-	26.37	-	1,183.03	-
108D	29.43	-	15.66	36.55	44.32	-	-	-	-	647.46	-
111A	-	-	10.95	-	25.44	-	-	-	-	1,502.43	-
111B	32.75	-	16.34	34.62	55.64	9.37	-	12.96	-	1,813.91	11.44
111C	-	-	-	-	-	-	-	-	-	539.66	-
111D	-	-	-	-	9.44	-	-	-	-	788.44	-
111E	-	-	-	13.82	13.57	-	-	6.53	-	328.99	-
114A	-	-	19.48	13.26	29.14	-	-	-	-	353.10	-
114B	5.75	-	12.02	25.19	16.75	-	-	-	-	719.42	12.85
115A	-	-	-	-	12.07	14.52	-	-	-	551.41	19.04
115B	6.25	-	44.61	-	24.00	-	-	16.07	-	333.44	12.66
115C	28.59	-	36.45	35.42	50.20	54.60	-	18.81	-	1,470.60	-
116A	-	-	135.18	-	55.01	-	-	-	-	73.06	-
116B	-	-	75.59	-	24.20	-	-	-	-	17.34	11.46
118A	-	-	7.91	-	-	-	-	-	-	12.53	12.77
120A	25.44	-	28.70	18.84	57.00	-	-	-	-	333.39	-
120B	-	-	11.10	-	-	-	-	-	-	95.81	-
120C	-	-	-	-	-	-	-	-	-	18.60	-
130A	-	-	-	-	-	-	-	-	-	5.55	-
130B	-	-	17.92	-	18.10	-	-	-	-	-	-
131A	17.06	36.74	12.59	-	-	1,024.69	496.79	83.95	1,311.68	1,064.17	55.37
131B	-	15.76	-	-	-	324.37	23.68	-	351.43	50.33	-
131C	-	-	-	-	-	37.53	26.17	-	59.85	95.38	-
131D	-	-	-	-	-	69.05	-	-	223.46	-	-
133A	56.63	26.53	94.44	25.42	8.30	99.75	361.19	67.91	-	275.66	37.07
133B	-	-	28.41	-	-	-	-	-	-	44.41	13.20
135A	31.74	-	41.93	-	-	-	50.15	3.48	-	95.91	-
144A	-	-	303.48	78.20	80.06	-	9.55	14.50	-	80.04	-
144B	-	-	321.08	21.72	46.73	-	-	-	-	31.57	-
149A	-	-	9.04	-	-	11.47	-	-	-	59.65	-
150A	-	-	-	-	-	193.82	179.67	98.79	676.85	311.64	-
150B	-	-	-	-	-	-	-	-	30.40	-	-
152B	-	-	-	-	-	-	-	8.38	40.11	-	-
153A	-	-	-	-	-	8.30	59.70	12.59	-	83.13	-
153B	-	-	-	-	-	3.96	17.76	4.84	-	72.82	3.01
153C	-	-	-	-	-	9.63	-	-	-	139.87	-
153D	-	-	-	-	-	40.27	-	-	-	102.98	-
156A	-	-	-	-	-	4.84	-	-	-	-	-
28A	22.89	27.14	-	-	-	334.09	-	-	-	-	9.18
28B	-	-	-	-	-	13.19	-	-	-	-	-
34A	-	8.58	-	-	-	219.45	-	-	-	-	-
34B	-	-	-	-	-	144.76	-	-	-	-	-
43A	10.75	-	-	-	18.49	-	-	-	-	-	66.56
43B	5.94	-	-	-	20.31	122.52	-	-	-	-	-
48A	-	-	-	-	-	78.56	-	-	-	-	-

Continued - Appendix Table B-2 MLRA-Level Estimates of Total Annual Direct N_2O Emissions by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq.[3]*					
48B	-	-	-	-	-	41.38	-	-	-	-	-
53A	21.07	73.90	9.41	-	4.83	8.71	-	15.65	-	-	236.38
53B	48.76	33.21	36.98	32.67	31.14	-	-	47.75	-	360.58	496.51
53C	3.40	-	-	-	5.36	9.60	-	-	-	135.37	86.03
55A	33.47	-	13.26	-	6.90	-	15.38	81.75	-	74.47	674.62
55B	55.37	-	27.40	33.02	19.63	20.35	11.23	95.06	-	898.33	284.56
55C	9.71	-	12.59	31.06	37.59	33.13	-	28.82	-	880.07	43.87
58A	70.80	180.91	56.94	48.28	42.39	151.71	-	26.64	-	-	69.75
58B	-	-	-	-	5.41	44.87	-	-	-	-	-
60A	-	32.50	-	-	15.03	62.91	-	-	-	-	25.51
63A	12.31	54.94	50.67	-	10.07	-	-	-	-	72.50	145.53
63B	-	-	12.66	12.10	20.87	-	-	14.28	-	95.52	26.14
67A	18.93	27.10	-	-	3.76	198.75	-	-	-	8.26	6.09
67B	82.12	290.78	-	-	-	299.07	-	37.68	-	136.21	45.93
70A	-	-	-	-	-	9.42	-	-	-	-	-
70B	-	-	-	-	-	13.32	-	-	-	-	-
70C	-	-	-	-	-	5.74	-	-	-	-	-
77A	39.01	53.05	-	-	-	440.68	-	12.21	-	84.68	205.48
77B	3.79	-	-	-	-	101.07	-	-	-	-	-
77C	179.25	63.43	-	-	-	728.78	423.78	26.59	-	39.00	249.87
77D	24.07	-	-	-	-	24.14	-	-	-	-	17.00
77E	40.99	8.75	-	-	-	25.83	-	-	-	-	64.81
78A	-	-	-	-	-	-	-	-	-	-	67.64
78B	42.10	-	-	-	-	18.19	145.65	-	-	-	218.02
78C	33.32	14.42	-	-	5.96	43.64	100.43	16.25	-	13.68	603.55
80A	8.40	-	27.05	-	22.64	22.27	-	-	-	22.56	765.81
80B	-	-	-	-	-	-	-	-	-	-	52.24
81A	-	-	-	-	-	45.92	27.56	37.41	-	-	22.54
81B	-	-	-	-	-	-	-	-	-	-	20.74
81C	-	-	-	-	-	-	-	-	-	-	14.29
82B	-	-	-	-	-	-	-	-	-	-	19.51
83A	-	-	-	-	-	56.87	-	10.66	-	77.71	34.58
83C	-	-	-	-	-	-	-	-	-	14.75	-
83D	-	-	-	-	-	134.23	27.78	-	-	84.73	-
83E	-	-	-	-	-	-	-	-	-	23.22	-
84A	-	-	27.81	-	-	-	-	-	-	-	36.13
84B	-	-	-	-	-	8.17	-	-	-	-	38.00
86A	-	-	49.22	-	-	-	33.58	42.83	-	488.92	190.60
87A	-	-	-	-	-	-	-	-	-	64.79	25.28
87B	-	-	-	-	-	-	-	-	-	-	16.14
90A	-	-	66.98	87.67	90.75	-	-	-	-	121.72	-
90B	3.69	-	49.11	126.69	69.12	-	-	33.79	-	304.98	-
91A	8.35	-	-	15.48	17.82	74.98	-	-	-	95.00	-
91B	-	-	-	-	10.10	-	-	-	-	31.10	-
94A	-	-	-	-	59.97	-	-	-	-	64.25	-
94B	-	-	-	-	28.80	-	-	-	-	-	-
95A	9.07	-	17.26	152.13	64.10	-	-	36.21	-	378.44	11.26
95B	11.11	-	20.33	125.89	59.13	20.72	-	40.08	-	924.96	-

[1] CRP = Conservation Reserve Program
[2] MLRA = Major Land Resource Area
[3] Gg CO_2 eq. = Gigagrams carbon dioxide equivalent

Appendix Table B-3 MLRA-Level Estimates of Total Annual Indirect N_2O Emissions from Ammonia, Nitric Oxide, and Nitrogen Dioxide Volatilization, by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq*[3]					
2	-	-	2.87	2.39	1.51	7.68	-	-	-	-	10.00
5	-	-	-	-	-	2.44	-	-	-	-	-
7	0.43	1.81	-	-	-	23.14	-	-	-	-	-
8	7.53	18.96	-	-	-	8.51	-	0.83	-	-	6.04
9	2.37	5.69	-	-	0.93	2.09	-	-	-	-	20.10
10	-	0.76	-	-	0.45	10.05	-	-	-	-	-
11	-	1.66	-	-	-	57.62	-	-	-	-	-
12	-	-	-	-	-	5.04	-	-	-	-	-
13	3.63	1.26	-	0.35	0.23	6.50	-	-	-	-	2.62
14	-	-	0.53	-	-	3.70	-	-	-	-	-
15	-	-	-	-	-	3.75	-	0.93	-	-	-
16	-	-	-	-	-	1.74	-	-	-	-	-
17	-	1.54	-	-	-	53.44	-	2.85	19.26	-	-
21	-	-	-	-	-	12.04	-	-	-	-	-
23	-	-	-	-	-	7.25	-	-	-	-	-
24	-	-	-	-	-	6.75	-	-	-	-	-
25	-	-	-	-	-	5.29	-	-	-	-	-
26	-	-	-	-	-	0.65	-	-	-	-	-
27	-	-	-	-	-	3.78	-	0.05	-	-	-
29	-	-	-	-	-	0.28	-	-	-	-	-
30	-	-	-	-	-	1.81	-	-	-	-	-
31	-	1.16	-	-	-	12.57	-	0.38	-	-	-
32	-	-	-	-	-	8.41	-	-	-	-	-
35	-	-	-	-	-	2.69	-	-	-	-	-
36	0.50	1.36	-	-	-	6.95	-	-	-	-	1.01
40	-	-	-	-	-	11.86	-	0.65	-	-	-
41	-	-	-	-	-	2.59	-	-	-	-	-
42	-	-	-	-	-	12.57	-	1.84	-	-	-
44	-	4.13	0.68	-	1.21	22.16	-	-	-	-	1.41
46	1.08	8.06	-	-	1.59	9.82	-	-	-	-	6.45
47	-	-	-	-	-	3.48	-	-	-	-	-
49	-	0.78	-	-	-	1.56	-	-	-	-	-
51	-	-	-	-	-	14.66	-	-	-	-	-
52	11.18	42.08	-	-	0.38	4.71	-	-	-	-	10.53
54	4.36	4.78	5.46	2.90	3.75	2.67	-	1.33	-	6.50	47.60
56	9.47	-	1.74	1.76	0.83	-	3.22	29.41	-	114.43	36.79
57	-	-	-	3.10	2.44	-	-	-	-	16.24	-
61	-	-	-	-	0.53	-	-	-	-	-	-
64	0.50	5.67	-	-	0.96	7.83	-	-	-	2.01	2.14
65	-	-	-	-	0.28	14.68	-	-	-	-	-
66	-	-	1.76	2.37	1.86	14.13	-	-	-	8.26	1.86
69	3.78	2.29	-	-	-	9.17	-	-	-	-	-
71	0.48	-	0.88	-	0.88	78.04	-	-	-	14.83	-
72	25.48	74.04	-	-	0.28	105.14	-	17.35	-	27.60	22.36

Continued - Appendix Table B-3 MLRA-Level Estimates of Total Annual Indirect N_2O Emissions from Ammonia, Nitric Oxide, and Nitrogen Dioxide Volatilization, by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]					*Gg CO_2 eq*[3]						
73	10.05	33.59	1.41	3.32	1.26	34.42	-	22.92	-	35.28	40.54
74	3.78	0.55	1.26	1.31	0.63	4.48	-	1.56	-	31.38	31.35
75	0.83	1.99	-	-	0.23	110.83	-	-	-	49.71	4.48
76	0.58	-	3.37	0.63	0.28	-	-	-	-	16.17	6.77
79	6.02	3.73	-	-	0.33	19.49	-	2.14	-	8.59	28.53
85	-	0.65	-	-	-	-	-	-	-	2.87	9.04
89	-	-	-	0.78	0.43	2.54	-	-	-	4.16	-
92	-	-	-	-	0.43	-	-	-	-	-	-
96	-	-	0.48	-	0.40	-	-	-	-	-	-
97	-	-	-	-	0.83	1.36	-	-	-	16.32	-
98	1.59	-	4.56	3.10	4.84	19.42	-	3.07	-	146.79	1.26
99	0.98	-	-	0.86	1.21	-	0.65	3.35	-	139.84	0.83
101	-	-	5.79	7.86	6.14	-	-	3.05	-	21.96	1.31
103	4.53	-	0.86	2.52	1.39	-	-	1.44	-	594.64	-
104	2.22	-	0.43	2.19	0.63	-	-	2.14	-	271.62	-
105	11.66	-	1.99	14.15	3.85	2.27	-	6.30	-	151.17	-
106	5.39	-	2.69	1.54	0.83	10.85	-	1.08	-	135.26	4.03
109	19.87	-	9.85	3.70	5.31	-	-	1.11	-	137.17	-
110	-	-	-	0.38	-	-	-	0.65	-	148.15	-
112	3.48	-	11.71	2.17	2.49	4.10	-	2.64	-	115.64	23.82
113	6.35	-	3.27	3.32	1.71	1.41	-	1.46	-	209.67	2.01
121	-	-	9.97	3.05	9.09	-	-	-	-	12.67	-
122	1.59	-	16.12	5.52	12.82	-	1.41	-	-	55.30	1.66
123	-	-	3.65	-	2.47	-	-	-	-	5.82	-
124	-	-	6.32	3.88	4.99	-	-	0.88	-	19.54	-
125	-	-	2.57	-	1.01	-	-	-	-	2.87	-
126	-	-	16.07	3.25	4.41	-	-	-	-	7.50	-
127	-	-	8.31	3.45	3.27	-	-	0.88	-	5.57	-
128	-	-	10.85	2.39	7.83	-	4.41	0.76	-	14.20	-
129	-	-	2.19	-	-	-	-	-	-	5.06	-
134	9.27	1.36	8.34	-	-	20.35	18.79	5.84	27.20	87.74	3.35
136	1.54	-	39.18	6.75	1.56	-	1.51	3.10	-	29.79	3.35
137	-	-	3.00	-	-	-	1.99	0.76	-	4.33	-
138	-	-	-	-	-	0.98	-	-	-	-	-
139	-	-	4.21	4.84	5.99	-	-	1.86	-	41.00	-
140	-	-	26.32	14.23	13.57	-	-	2.19	-	13.30	-
142	-	-	9.34	4.13	6.22	-	-	-	-	3.42	-
143	-	-	3.80	-	1.13	-	-	-	-	-	-
145	-	-	1.99	-	-	-	-	-	-	0.55	-
146	-	-	-	-	-	-	1.13	-	-	-	-
147	-	-	19.67	11.13	7.08	-	-	3.53	-	38.53	1.84
148	-	-	9.49	6.85	3.93	-	-	3.32	-	35.08	2.12
155	-	-	-	-	-	9.22	-	-	-	-	-
102A	7.61	-	1.51	2.97	1.94	6.35	-	3.50	-	196.43	10.02
102B	-	-	-	-	0.40	-	-	-	-	38.81	-
102C	3.27	-	1.11	2.82	1.28	62.05	-	-	-	156.76	-
107A	-	-	-	-	-	-	-	1.11	-	115.34	-

Continued - Appendix Table B-3 MLRA-Level Estimates of Total Annual Indirect N_2O Emissions from Ammonia, Nitric Oxide, and Nitrogen Dioxide Volatilization, by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq[3]*					
107B	4.18	-	2.44	1.54	0.96	13.40	-	-	-	273.66	1.06
108A	-	-	-	-	0.35	-	-	-	-	239.36	-
108B	0.93	-	-	-	0.53	3.48	-	-	-	232.71	-
108C	5.62	-	0.68	1.71	0.55	-	-	1.71	-	152.03	-
108D	5.39	-	0.98	2.04	1.26	-	-	-	-	84.89	-
111A	-	-	0.63	-	0.63	-	-	-	-	200.00	-
111B	4.26	-	0.76	1.99	1.59	1.11	-	1.46	-	228.33	1.13
111C	-	-	-	-	-	-	-	-	-	73.06	-
111D	-	-	-	-	0.33	-	-	-	-	105.21	-
111E	-	-	-	0.88	0.38	-	-	0.73	-	41.45	-
114A	-	-	1.46	1.16	1.28	-	-	-	-	49.99	-
114B	0.86	-	0.91	1.91	0.58	-	-	-	-	98.54	1.46
115A	-	-	-	-	0.63	2.44	-	-	-	77.06	1.71
115B	1.03	-	3.45	-	0.88	-	-	1.84	-	47.27	1.28
115C	4.41	-	2.37	1.81	1.46	7.68	-	1.74	-	190.46	-
116A	-	-	18.18	-	5.19	-	-	-	-	9.42	-
116B	-	-	11.11	-	2.42	-	-	-	-	2.52	1.18
118A	-	-	1.54	-	-	-	-	-	-	2.90	1.31
120A	4.16	-	3.00	2.24	2.97	-	-	-	-	48.05	-
120B	-	-	1.21	-	-	-	-	-	-	12.92	-
120C	-	-	-	-	-	-	-	-	-	2.44	-
130A	-	-	-	-	-	-	-	-	-	0.76	-
130B	-	-	2.72	-	1.99	-	-	-	-	-	-
131A	2.59	2.32	1.36	-	-	114.35	35.10	9.59	86.53	153.74	5.64
131B	-	1.06	-	-	-	30.77	1.94	-	24.60	7.15	-
131C	-	-	-	-	-	2.44	2.82	-	3.10	13.60	-
131D	-	-	-	-	-	11.26	-	-	20.83	-	-
133A	15.19	4.36	20.15	6.90	0.55	18.53	54.57	13.75	-	68.42	4.66
133B	-	-	6.12	-	-	-	-	-	-	4.16	1.44
135A	5.69	-	5.31	-	-	-	4.63	0.50	-	20.57	-
144A	-	-	13.72	2.80	2.82	-	0.38	0.86	-	3.27	-
144B	-	-	10.68	0.86	1.74	-	-	-	-	0.73	-
149A	-	-	0.86	-	-	1.26	-	-	-	8.97	-
150A	-	-	-	-	-	21.93	11.58	15.26	31.23	24.68	-
150B	-	-	-	-	-	-	-	-	1.21	-	-
152B	-	-	-	-	-	-	-	1.28	1.84	-	-
153A	-	-	-	-	-	1.79	9.70	2.49	-	25.74	-
153B	-	-	-	-	-	0.68	2.47	0.83	-	16.75	0.35
153C	-	-	-	-	-	1.08	-	-	-	18.79	-
153D	-	-	-	-	-	4.68	-	-	-	15.34	-
156A	-	-	-	-	-	0.55	-	-	-	-	-
28A	1.54	1.28	-	-	-	18.11	-	-	-	-	0.53
28B	-	-	-	-	-	1.74	-	-	-	-	-
34A	-	0.53	-	-	-	14.35	-	-	-	-	-
34B	-	-	-	-	-	12.69	-	-	-	-	-
43A	0.55	-	-	-	0.33	-	-	-	-	-	2.57
43B	0.45	-	-	-	0.43	6.37	-	-	-	-	-

Continued - Appendix Table B-3 MLRA-Level Estimates of Total Annual Indirect N_2O Emissions from Ammonia, Nitric Oxide, and Nitrogen Dioxide Volatilization, by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq[3]*					
48A	-	-	-	-	-	6.09	-	-	-	-	-
48B	-	-	-	-	-	2.64	-	-	-	-	-
53A	4.91	7.81	0.65	-	0.23	0.88	-	1.59	-	-	25.36
53B	8.84	3.20	3.32	3.30	2.12	-	-	4.99	-	47.55	51.93
53C	0.53	-	-	-	0.40	1.03	-	-	-	13.85	7.96
55A	5.59	-	1.16	-	0.38	-	0.78	9.02	-	10.83	67.72
55B	9.09	-	2.39	3.37	1.26	3.10	0.81	13.37	-	135.94	36.31
55C	1.79	-	1.26	2.77	2.34	5.21	-	3.22	-	115.16	4.31
58A	9.44	13.32	5.29	3.60	2.34	11.28	-	1.99	-	-	6.77
58B	-	-	-	-	0.33	3.70	-	-	-	-	-
60A	-	2.14	-	-	1.03	1.49	-	-	-	-	2.22
63A	1.11	1.79	1.44	-	0.33	-	-	-	-	3.02	7.50
63B	-	-	0.60	0.58	0.55	-	-	0.55	-	4.26	1.69
67A	3.37	2.80	-	-	0.38	18.79	-	-	-	0.86	0.71
67B	15.08	28.96	-	-	-	24.93	-	4.00	-	12.47	5.24
70A	-	-	-	-	-	1.11	-	-	-	-	-
70B	-	-	-	-	-	2.39	-	-	-	-	-
70C	-	-	-	-	-	0.55	-	-	-	-	-
77A	8.49	5.59	-	-	-	42.86	-	1.13	-	9.34	16.90
77B	0.86	-	-	-	-	14.00	-	-	-	-	-
77C	40.52	6.40	-	-	-	94.64	54.85	2.69	-	3.42	20.62
77D	6.27	-	-	-	-	3.83	-	-	-	-	1.94
77E	10.27	0.91	-	-	-	3.25	-	-	-	-	5.74
78A	-	-	-	-	-	-	-	-	-	-	6.42
78B	11.48	-	-	-	-	2.97	18.71	-	-	-	20.55
78C	8.41	1.33	-	-	0.38	6.19	10.78	1.76	-	1.74	58.40
80A	1.61	-	1.81	-	1.33	2.74	-	-	-	2.54	80.38
80B	-	-	-	-	-	-	-	-	-	-	6.77
81A	-	-	-	-	-	5.94	3.10	3.27	-	-	1.66
81B	-	-	-	-	-	-	-	-	-	-	1.74
81C	-	-	-	-	-	-	-	-	-	-	1.11
82B	-	-	-	-	-	-	-	-	-	-	1.86
83A	-	-	-	-	-	6.57	-	1.11	-	8.41	3.58
83C	-	-	-	-	-	-	-	-	-	2.12	-
83D	-	-	-	-	-	14.08	3.10	-	-	10.45	-
83E	-	-	-	-	-	-	-	-	-	3.60	-
84A	-	-	2.24	-	-	-	-	-	-	-	3.73
84B	-	-	-	-	-	1.61	-	-	-	-	5.36
86A	-	-	2.06	-	-	-	1.69	3.70	-	29.41	16.24
87A	-	-	-	-	-	-	-	-	-	4.58	1.08
87B	-	-	-	-	-	-	-	-	-	-	1.99
90A	-	-	2.62	4.46	2.92	-	-	-	-	11.76	-
90B	0.60	-	1.69	7.00	2.14	-	-	2.34	-	34.45	-
91A	1.64	-	-	1.18	0.88	9.95	-	-	-	12.77	-
91B	-	-	-	-	0.43	-	-	-	-	3.98	-
94A	-	-	-	-	2.37	-	-	-	-	5.36	-
94B	-	-	-	-	0.93	-	-	-	-	-	-
95A	1.13	-	0.96	7.98	2.39	-	-	2.37	-	31.73	0.88
95B	1.54	-	1.13	6.98	1.79	2.19	-	2.95	-	100.28	-

Note: N_2O is nitrous oxide.

[1] CRP = Conservation Reserve Program

[2] MLRA = Major Land Resource Area

[3] Gg CO_2 eq. = Gigagrams carbon dioxide equivalent

Appendix Table B-4 MLRA-Level Estimates of Total Annual Indirect N_2O Emissions for Nitrate Leaching by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq[3]*					
2	-	-	4.14	5.33	6.61	26.68	-	-	-	-	61.8
5	-	-	-	-	-	3.97	-	-	-	-	-
7	0	3.58	-	-	-	58.46	-	-	-	-	-
8	0.12	13.07	-	-	-	30.04	-	0	-	-	1.09
9	0.27	5.78	-	-	0.38	2.25	-	-	-	-	35.99
10	-	2.21	-	-	0.16	7.15	-	-	-	-	-
11	-	15.27	-	-	-	205.46	-	-	-	-	-
12	-	-	-	-	-	4.46	-	-	-	-	-
13	0.01	2.05	-	0.17	0.15	24.77	-	-	-	-	7.4
14	-	-	3.4	-	-	9.47	-	-	-	-	-
15	-	-	-	-	-	7.23	-	1.39	-	-	-
16	-	-	-	-	-	2.91	-	-	-	-	-
17	-	4.52	-	-	-	97.01	-	0.51	13.81	-	-
21	-	-	-	-	-	11.92	-	-	-	-	-
23	-	-	-	-	-	6.28	-	-	-	-	-
24	-	-	-	-	-	7.61	-	-	-	-	-
25	-	-	-	-	-	0.9	-	-	-	-	-
26	-	-	-	-	-	1.43	-	-	-	-	-
27	-	-	-	-	-	2.83	-	0	-	-	-
29	-	-	-	-	-	0.22	-	-	-	-	-
30	-	-	-	-	-	1.72	-	-	-	-	-
31	-	0	-	-	-	0.56	-	0	-	-	-
32	-	-	-	-	-	25.29	-	-	-	-	-
35	-	-	-	-	-	29.4	-	-	-	-	-
36	0	0.46	-	-	-	12.18	-	-	-	-	0
40	-	-	-	-	-	34.67	-	0.01	-	-	-
41	-	-	-	-	-	2.13	-	-	-	-	-
42	-	-	-	-	-	247.13	-	0	-	-	-
44	-	4.95	0.98	-	1.02	11.73	-	-	-	-	2.3
46	0.01	1.57	-	-	0.27	3.45	-	-	-	-	1.7
47	-	-	-	-	-	3.15	-	-	-	-	-
49	-	0.3	-	-	-	0.74	-	-	-	-	-
51	-	-	-	-	-	74.83	-	-	-	-	-
52	0	1.11	-	-	0	12.3	-	-	-	-	0
54	0	0	0	0	0	3.2	-	0	-	0	0
56	0.47	-	0.58	0.47	0.07	-	0.03	3.25	-	8.23	6.78
57	-	-	-	2.65	2.25	-	-	-	-	16.08	-
61	-	-	-	-	0.01	-	-	-	-	-	-
64	0	2.14	-	-	0	7.12	-	-	-	0	0
65	-	-	-	-	0	37.67	-	-	-	-	-
66	-	-	0	0	0	23.85	-	-	-	0.06	0
69	0	17.03	-	-	-	37.29	-	-	-	-	-
71	0.02	-	0.17	-	0.07	100.12	-	-	-	3.71	-
72	0	26.78	-	-	0	197.64	-	0	-	0	0
73	0	7.93	0	0	0	48.88	-	0.05	-	0.75	2.7

Continued - Appendix Table B-4 MLRA-Level Estimates of Total Annual Indirect N_2O Emissions for Nitrate Leaching by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq[3]*					
74	0.41	0.34	7.67	2.13	0.13	4.92	-	0.47	-	13.12	14.76
75	0.1	1.35	-	-	0.04	69.38	-	-	-	13.65	1.63
76	0.07	-	21.66	2.74	0.09	-	-	-	-	10	5.82
79	0.1	1.39	-	-	0.01	37.21	-	0.26	-	0.76	5.96
85	-	0	-	-	-	-	-	-	-	0.14	1.64
89	-	-	-	1.19	0.79	7.67	-	-	-	4.71	-
92	-	-	-	-	0.26	-	-	-	-	-	-
96	-	-	0.22	-	0.5	-	-	-	-	-	-
97	-	-	-	-	1.6	2.67	-	-	-	19.93	-
98	0.42	-	2.02	4.22	7.81	29.04	-	3.26	-	144.3	1.65
99	0.24	-	-	1	2.21	-	1.35	4.01	-	93.76	1.18
101	-	-	3.66	17.43	10.24	-	-	7.48	-	65.01	3.5
103	0.43	-	0.37	1.83	1.07	-	-	1.31	-	411.02	-
104	0.25	-	0.16	2.23	0.86	-	-	2.36	-	206.26	-
105	1.16	-	1.66	15.61	5.89	4.87	-	6.02	-	119.12	-
106	0.18	-	0.73	0.27	0.23	5.15	-	0.39	-	39.85	2.36
109	3.54	-	4.28	2.98	6.51	-	-	1.18	-	97.46	-
110	-	-	-	0.32	-	-	-	0.4	-	103.26	-
112	0.41	-	3.3	2.03	3.31	3.98	-	3.08	-	78.98	29.11
113	1.28	-	1.1	2.48	2.86	0.86	-	0.81	-	144.67	1.91
121	-	-	5.61	3.26	20.21	-	-	-	-	14.82	-
122	0.48	-	8.75	4.11	25.61	-	3.64	-	-	54.14	3.17
123	-	-	1.75	-	5.28	-	-	-	-	5.5	-
124	-	-	3.9	3.75	10.43	-	-	1.47	-	24.22	-
125	-	-	1.67	-	2.4	-	-	-	-	3.3	-
126	-	-	8.38	3.59	7.43	-	-	-	-	10.49	-
127	-	-	5.17	4.39	5.94	-	-	1.56	-	15.79	-
128	-	-	5.5	2.59	11.33	-	9.98	0.95	-	16.53	-
129	-	-	1.58	-	-	-	-	-	-	7.68	-
134	3.57	5.93	7.18	-	-	28.4	63.09	8.5	35.93	105.34	10.07
136	0.75	-	33.14	7.01	3.57	-	3.62	3.12	-	31.9	7.6
137	-	-	4.04	-	-	-	5.79	1.03	-	5.26	-
138	-	-	-	-	-	2.65	-	-	-	-	-
139	-	-	9.46	13.09	14.3	-	-	3.18	-	60.85	-
140	-	-	39.48	33.36	22.69	-	-	8.92	-	57.48	-
142	-	-	17.54	18.47	12.99	-	-	-	-	25.8	-
143	-	-	11.11	-	2.97	-	-	-	-	-	-
145	-	-	5.16	-	-	-	-	-	-	4.33	-
146	-	-	-	-	-	-	4.91	-	-	-	-
147	-	-	33.68	25.13	15.9	-	-	10.42	-	103.97	5.24
148	-	-	17.18	15.57	9.57	-	-	8.09	-	63.33	5.66
155	-	-	-	-	-	35.28	-	-	-	-	-
102A	0.2	-	0.13	0.75	0.44	4.2	-	1.15	-	43.26	4.4
102B	-	-	-	-	0	-	-	-	-	0.83	-
102C	0.17	-	0.22	0.76	0.31	60.73	-	-	-	37.66	-
107A	-	-	-	-	-	-	-	0.32	-	43.14	-
107B	0.25	-	0.26	0.29	0.46	4.8	-	-	-	84.04	0.52

Continued - Appendix Table B-4 MLRA-Level Estimates of Total Annual Indirect N_2O Emissions for Nitrate Leaching by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq[3]*					
108A	-	-	-	-	0.66	-	-	-	-	109.02	-
108B	0.15	-	-	-	0.56	3.34	-	-	-	87.05	-
108C	0.51	-	0.45	0.63	0.34	-	-	0.83	-	48.65	-
108D	0.53	-	0.26	1.52	1.13	-	-	-	-	43.68	-
111A	-	-	0.41	-	2.18	-	-	-	-	175.63	-
111B	0.94	-	0.64	2.75	3.62	1.57	-	1.61	-	219.36	1.53
111C	-	-	-	-	-	-	-	-	-	83.03	-
111D	-	-	-	-	0.7	-	-	-	-	81.58	-
111E	-	-	-	1.18	0.94	-	-	0.56	-	36.07	-
114A	-	-	1.1	1.16	2.85	-	-	-	-	39.97	-
114B	0.17	-	0.62	1.86	1.71	-	-	-	-	72.44	1.46
115A	-	-	-	-	1.45	2.53	-	-	-	62.06	2.14
115B	0.18	-	1.08	-	1.5	-	-	1.44	-	28.76	1.81
115C	0.68	-	0.45	0.94	1.3	7.98	-	0.83	-	70.74	-
116A	-	-	7.42	-	7.24	-	-	-	-	11.49	-
116B	-	-	3.94	-	3.61	-	-	-	-	3.02	1.95
118A	-	-	0.97	-	-	-	-	-	-	2.95	3.15
120A	1.6	-	2.06	2.37	8.37	-	-	-	-	51.06	-
120B	-	-	0.83	-	-	-	-	-	-	14.58	-
120C	-	-	-	-	-	-	-	-	-	2.19	-
130A	-	-	-	-	-	-	-	-	-	0.95	-
130B	-	-	2.15	-	3.01	-	-	-	-	-	-
131A	0.75	9.28	0.79	-	-	152.94	80.35	14.83	110.32	116.32	12.72
131B	-	3.25	-	-	-	28.1	4.12	-	11.66	4.16	-
131C	-	-	-	-	-	2.28	6.37	-	2.87	8.86	-
131D	-	-	-	-	-	14.36	-	-	21.64	-	-
133A	7.91	14.54	24.16	6.83	1.81	40.25	165.85	22.55	-	86.12	15.22
133B	-	-	6.01	-	-	-	-	-	-	3.97	2
135A	2.04	-	4.1	-	-	-	14.76	0.61	-	17.05	-
144A	-	-	30.65	10.21	6.92	-	3.56	3.23	-	16.66	-
144B	-	-	28.47	3.21	5.6	-	-	-	-	8.94	-
149A	-	-	2.5	-	-	3.15	-	-	-	11.11	-
150A	-	-	-	-	-	25.43	10.42	5.69	26.23	12.64	-
150B	-	-	-	-	-	-	-	-	0.36	-	-
152B	-	-	-	-	-	-	-	0.44	1.58	-	-
153A	-	-	-	-	-	3.75	28.31	4.09	-	30.28	-
153B	-	-	-	-	-	1.72	8.21	1.61	-	19.26	0.68
153C	-	-	-	-	-	2.97	-	-	-	29.18	-
153D	-	-	-	-	-	15.11	-	-	-	29.99	-
156A	-	-	-	-	-	3.35	-	-	-	-	-
28A	0.01	2.13	-	-	-	22.49	-	-	-	-	0
28B	-	-	-	-	-	0.57	-	-	-	-	-
34A	-	0.73	-	-	-	41.81	-	-	-	-	-
34B	-	-	-	-	-	36.51	-	-	-	-	-
43A	0.37	-	-	-	0.41	-	-	-	-	-	6.66
43B	0.02	-	-	-	0.27	2.1	-	-	-	-	-
48A	-	-	-	-	-	8.88	-	-	-	-	-

Continued - Appendix Table B-4 MLRA-Level Estimates of Total Annual Indirect N_2O Emissions for Nitrate Leaching by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay In Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq[3]*					
48B	-	-	-	-	-	4.16	-	-	-	-	-
53A	0	0.01	0	-	0	0.91	-	0	-	-	0
53B	0	0.2	0	0	0	-	-	0	-	0	0
53C	0	-	-	-	0	0.85	-	-	-	0	0
55A	0	-	0	-	0	-	0	0	-	0	0
55B	0	-	0	0	0	3.06	0	0.06	-	0.25	0.01
55C	0	-	0	0.07	0	2.47	-	0	-	0.16	0
58A	0	6.32	0	0	0	121.36	-	0	-	-	0
58B	-	-	-	-	0.01	2.36	-	-	-	-	-
60A	-	2.02	-	-	0	0.08	-	-	-	-	0
63A	0	0	0	-	0	-	-	-	-	0	0
63B	-	-	0	0.01	0	-	-	0	-	0	0
67A	0	15.64	-	-	0	81.01	-	-	-	0	0
67B	0	68.02	-	-	-	137.28	-	6.95	-	0	0
70A	-	-	-	-	-	7.18	-	-	-	-	-
70B	-	-	-	-	-	2.17	-	-	-	-	-
70C	-	-	-	-	-	2.09	-	-	-	-	-
77A	0	5.07	-	-	-	68.25	-	0.06	-	0	0.01
77B	0	-	-	-	-	11.32	-	-	-	-	-
77C	0	4.4	-	-	-	123.35	0.01	0.15	-	0	0.18
77D	0	-	-	-	-	5.09	-	-	-	-	0
77E	0	0.08	-	-	-	5.63	-	-	-	-	0.03
78A	-	-	-	-	-	-	-	-	-	-	0
78B	0	-	-	-	-	1.96	0	-	-	-	0
78C	0	0.48	-	-	0	5.31	0.37	0	-	0	0.05
80A	0.02	-	9.49	-	0.23	2.82	-	-	-	3.7	47.01
80B	-	-	-	-	-	-	-	-	-	-	0
81A	-	-	-	-	-	51.98	0	0	-	-	0
81B	-	-	-	-	-	-	-	-	-	-	0
81C	-	-	-	-	-	-	-	-	-	-	0
82B	-	-	-	-	-	-	-	-	-	-	0
83A	-	-	-	-	-	8.33	-	0	-	0	0
83C	-	-	-	-	-	-	-	-	-	0	-
83D	-	-	-	-	-	8.62	0.75	-	-	1.71	-
83E	-	-	-	-	-	-	-	-	-	0	-
84A	-	-	7.77	-	-	-	-	-	-	-	4.06
84B	-	-	-	-	-	1.85	-	-	-	-	1.51
86A	-	-	7.4	-	-	-	2.21	1.4	-	3.76	8.98
87A	-	-	-	-	-	-	-	-	-	4.43	0
87B	-	-	-	-	-	-	-	-	-	-	1.94
90A	-	-	1.43	4.68	3.54	-	-	-	-	13.67	-
90B	0.04	-	1.17	5.78	2.89	-	-	1.72	-	21.84	-
91A	0.18	-	-	1.5	0.96	14.08	-	-	-	15.06	-
91B	-	-	-	-	0.74	-	-	-	-	5.79	-
94A	-	-	-	-	4.13	-	-	-	-	8.51	-
94B	-	-	-	-	1.07	-	-	-	-	-	-
95A	0.13	-	0.64	13.18	3.69	-	-	2.91	-	43.96	1.53
95B	0.25	-	0.6	9.76	3.11	3.18	-	2.92	-	62.1	-

Note: N_2O is nitrous oxide.
[1] CRP = Conservation Reserve Program
[2] MLRA = Major Land Resource Area
[3] Gg CO_2 eq. = Gigagrams carbon dioxide equivalent

Appendix Table B-5 Rice Harvested Area, 1990, 1995, 2000-2013

State and Crop	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
	1,000 hectares															
Arkansas	**1,200**	**1,340**	**1,410**	**1,621**	**608**	**589**	**629**	**1637**	**1400**	**1325**	**1395**	**1470**	**1785**	**1154**	**1414**	**1124**
Primary	1,200	1,340	1,410	1,621	1,503	1,455	1,555	1,635	1,400	1,325	1,395	1,470	1,785	1,154	1,285	1,070
Ratoon	0	0	0	0	0	0	0	2	0	0	0	0	0	0	129	54
California	**395**	**465**	**548**	**471**	**528**	**507**	**590**	**526**	**523**	**533**	**517**	**556**	**553**	**580**	**557**	**561**
Florida	**18**	**36**	**27**	**18**	**19**	**12**	**16**	**11**	**15**	**20**	**18**	**20**	**19**	**26**	**22**	**22**
Primary	12	24	19	11	13	6	9	11	11	15	13	14	13	20	15	17
Ratoon	6	12	8	7	7	6	7	0	3	5	4	6	6	6	7	5
Louisiana	**709**	**741**	**672**	**710**	**615**	**608**	**693**	**593**	**414**	**510**	**650**	**626**	**749**	**564**	**556**	**570**
Primary	545	570	480	546	535	450	533	525	345	378	464	464	535	418	397	413
Ratoon	164	171	192	164	80	158	160	68	69	132	186	162	214	146	159	157
Mississippi	**250**	**288**	**218**	**253**	**253**	**234**	**234**	**263**	**189**	**189**	**229**	**243**	**303**	**157**	**129**	**124**
Missouri	**80**	**112**	**169**	**207**	**182**	**171**	**195**	**214**	**214**	**178**	**199**	**200**	**251**	**128**	**177**	**156**
Texas	**494**	**445**	**321**	**302**	**282**	**248**	**294**	**255**	**209**	**197**	**263**	**269**	**290**	**319**	**216**	**242**
Primary	353	318	214	216	206	180	218	201	150	145	172	170	188	180	134	144
Ratoon	141	127	107	86	76	68	76	54	59	52	91	99	102	139	82	98
Total	**3,146**	**3,427**	**3,365**	**3,582**	**2,488**	**2,368**	**2,652**	**3,499**	**2,963**	**2,953**	**3,270**	**3,384**	**3,949**	**2,928**	**3,070**	**2,798**

Appendix Table B-6 Total U.S. Production of Crops Managed with Burning, 1990, 1995, 2000-2013

	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Crop	*1,000 Metric tons*															
Wheat	2,200	1,788	1,949	1,666	1,425	1,615	1,482	1,405	1,316	1,598	2,210	1,664	1,607	1,865	1,807	1,841
Rice	723	783	830	844	857	751	904	607	744	1,097	813	889	922	823	825	804
Sugarcane	15,040	12,971	13,017	12,190	13,068	16,631	10,638	6,234	14,951	7,153	9,776	10,207	9,428	10,631	10,914	10,481
Corn	412	406	554	514	488	552	465	361	691	630	661	703	693	710	693	875
Cotton	43	50	48	58	47	63	74	70	43	35	39	35	49	51	53	41
Soybeans	129	128	146	154	147	93	128	192	182	189	187	217	198	180	187	210
Lentil	1	2	2	2	2	0	0	1	2	2	1	2	2	1	1	2
Total	**18,548**	**16,128**	**16,547**	**15,428**	**16,034**	**19,705**	**13,692**	**8,870**	**17,929**	**10,703**	**13,688**	**13,717**	**12,899**	**14,261**	**14,481**	**14,253**

Appendix Table B-7 Production of Crops Managed with Burning

	Corn	Soybeans	Cotton	Wheat	Lentils	Rice	Sugarcane
Year	*1,000 bushels*				*1,000 cwt*		*1,000 tons*
1990	16,227	4,725	195	80,847	23	15,937	16,578
1991	15,867	4,779	229	53,075	41	16,488	16,185
1992	19,388	5,552	214	68,820	0	17,740	15,414
1993	13,867	4,523	207	71,653	47	16,088	15,703
1994	20,809	5,943	250	67,555	39	19,773	15,354
1995	15,987	4,689	230	65,713	44	17,259	14,298
1996	21,705	5,519	250	79,415	27	17,472	13,434
1997	21,489	6,211	248	72,633	45	17,613	13,983
1998	21,801	5,701	174	74,146	34	16,771	14,965
1999	20,587	5,515	224	68,424	40	18,234	14,118
2000	21,810	5,379	219	71,629	51	18,290	14,348
2001	20,222	5,676	264	61,199	50	18,609	13,437
2002	19,230	5,398	217	52,342	45	18,902	14,404
2003	21,747	3,402	291	59,323	0	16,555	18,333
2004	18,308	4,716	341	54,453	10	19,928	11,726
2005	14,213	7,048	320	51,631	20	13,390	6,872
2006	27,211	6,688	199	48,348	49	16,394	16,481
2007	24,791	6,942	160	58,702	45	24,194	7,884
2008	26,033	6,867	180	81,195	24	17,933	10,776
2009	27,662	7,975	162	61,150	41	19,601	11,251
2010	27,292	7,266	227	59,057	34	20,320	10,393
2011	27,944	6,601	232	68,532	32	18,150	11,718
2012	27,291	6,882	241	66,412	32	18,179	12,031
2013	34,442	7,733	186	67,653	35	17,716	11,553

Appendix Table B-8(a) Crop Assumptions and Coefficients

Assumption/Coefficient	Corn	Cotton	Lentils	Rice	Soybean	Sugarcane	Wheat
Residue/Crop Ratio	1.0	1.6	2.0	1.4	2.1	0.2	1.3
Fraction Residue Burned	0.00	0.01	0.01	0.09	0.00	0.37	0.03
Fraction Dry Matter	0.91	0.90	0.85	0.91	0.45	0.62	0.93
Burning Efficiency	0.93	0.93	0.93	0.93	0.93	0.81	0.93
Combustion Efficiency	0.88	0.88	0.88	0.88	0.88	0.68	0.88
Fraction Carbon	0.45	0.45	0.45	0.38	0.45	0.42	0.44
Fraction Nitrogen	0.006	0.012	0.023	0.007	0.023	0.004	0.006

Appendix Table B-8(b) Emissions Factors and Global Warming Potentials

GHG	Factor & GWP
Emissions Factor	
Methane	0.005
Nitrous Oxide	0.007
Global Warming Potential	
Methane	25
Nitrous Oxide	298

Appendix Table B-8(c) Rice Area Burned by State

State	% Burned
Arkansas	6
California	16
Florida	84
Louisiana	2
Mississippi	2
Missouri	3
Oklahoma	100
Texas	26

Appendix Table B-9 Cultivated Histosol (Organic Soils) Area

	Cold Temperate	Warm Temperate	Sub-Tropical
Year	*Million hectares*		
1990	0.72	0.17	0.30
1991	0.72	0.17	0.30
1992	0.71	0.17	0.30
1993	0.70	0.16	0.30
1994	0.70	0.17	0.30
1995	0.69	0.17	0.29
1996	0.69	0.17	0.29
1997	0.68	0.16	0.28
1998	0.68	0.17	0.28
1999	0.67	0.17	0.28
2000	0.67	0.17	0.28
2001	0.65	0.16	0.28
2002	0.64	0.16	0.28
2003	0.63	0.16	0.26
2004	0.63	0.17	0.26
2005	0.63	0.17	0.26
2006	0.62	0.16	0.26
2007	0.62	0.16	0.26
2008	0.62	0.16	0.26
2009	0.62	0.16	0.26
2010	0.62	0.16	0.26
2011	0.62	0.16	0.26
2012	0.62	0.16	0.26
2013	0.62	0.16	0.26

Appendix Table B-10 Carbon Loss Rates from Organic Soils Under Agricultural Management in the United States

	Cropland	Grassland[1]
Climate Regions	*Metric Tons C/ha-yr*[2]	
CTD & CTM	11.2 ± 2.5	2.8 ± 0.51
WTD & WTM	14.0 ± 2.5	3.5 ± 0.81
STD & STM	14.0 ± 3.3	3.5 ± 0.81

[1] There is not enough data available to estimate values for C losses from grasslands. Estimates are 25% of the values for cropland (the IPCC default organic soil C losses on grasslands).
[2] Metric Tons C/ha-yr is metric tons carbon per hectare per year
Climate regions: Cold temperate dry (CTD), cold temperate moist (CTM), warm temperate dry (WTD), warm temperate moist (WTM), subtropical temperate dry (STD), and subtropical temperate moist (STM).

Appendix Table B-11 MLRA-Level Estimates of Annual Soil Carbon Stock Changes by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay in Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq[3]*					
2	-	-	-70.12	-51.24	-8.29	-26.48	-	-	-	-	138.63
5	-	-	-	-	-	-20.86	-	-	-	-	-
7	-28.27	22.35	-	-	-	-108.18	-	-	-	-	-
8	-475.31	451.85	-	-	-	26.86	-	-8.69	-	-	39.80
9	-114.61	45.01	-	-	-30.13	-27.99	-	-	-	-	-5.09
10	-	34.36	-	-	2.26	-104.39	-	-	-	-	-
11	-	68.57	-	-	-	-301.58	-	-	-	-	-
12	-	-	-	-	-	-26.00	-	-	-	-	-
13	-229.48	25.07	-	-28.04	-32.45	-32.14	-	-	-	-	20.15
14	-	-	6.07	-	-	-8.43	-	-	-	-	-
15	-	-	-	-	-	45.11	-	11.81	-	-	-
16	-	-	-	-	-	3.40	-	-	-	-	-
17	-	-36.65	-	-	-	-204.68	-	-83.22	-45.45	-	-
21	-	-	-	-	-	-151.58	-	-	-	-	-
23	-	-	-	-	-	-52.73	-	-	-	-	-
24	-	-	-	-	-	28.77	-	-	-	-	-
25	-	-	-	-	-	-62.43	-	-	-	-	-
26	-	-	-	-	-	2.79	-	-	-	-	-
27	-	-	-	-	-	15.22	-	1.52	-	-	-
29	-	-	-	-	-	-1.22	-	-	-	-	-
30	-	-	-	-	-	42.72	-	-	-	-	-
31	-	9.77	-	-	-	-178.61	-	-11.16	-	-	-
32	-	-	-	-	-	9.25	-	-	-	-	-
35	-	-	-	-	-	21.75	-	-	-	-	-
36	-21.25	45.04	-	-	-	-67.94	-	-	-	-	11.49
40	-	-	-	-	-	-68.82	-	-12.77	-	-	-
41	-	-	-	-	-	3.16	-	-	-	-	-
42	-	-	-	-	-	-59.03	-	-33.71	-	-	-
44	-	393.32	-12.05	-	-49.58	-258.94	-	-	-	-	6.42
46	-111.35	125.28	-	-	-132.05	-136.05	-	-	-	-	101.95
47	-	-	-	-	-	-10.42	-	-	-	-	-
49	-	-3.14	-	-	-	-9.77	-	-	-	-	-
51	-	-	-	-	-	-61.89	-	-	-	-	-
52	-779.05	605.59	-	-	-6.52	-91.50	-	-	-	-	8.81
54	-301.28	62.66	-68.94	-72.72	-182.95	-10.54	-	-19.34	-	156.46	624.19
56	-393.54	-	-50.30	-31.54	-66.27	-	59.18	-91.94	-	52.14	188.52
57	-	-	-	-27.91	-45.85	-	-	-	-	139.63	-
61	-	-	-	-	-16.91	-	-	-	-	-	-
64	-33.96	54.68	-	-	15.97	46.81	-	-	-	8.35	29.18
65	-	-	-	-	0.96	-36.55	-	-	-	-	-
66	-	-	-25.82	-36.18	-45.11	-8.35	-	-	-	73.04	73.46
69	-29.23	67.57	-	-	-	-11.02	-	-	-	-	-
71	-20.62	-	-43.96	-	2.83	-202.00	-	-	-	35.88	-
72	-836.33	94.11	-	-	2.42	-397.37	-	-157.74	-	-102.42	-38.35
73	-374.53	85.94	-36.66	-51.24	-105.80	-190.42	-	-139.99	-	-287.90	102.64

Continued - Appendix Table B-11 MLRA-Level Estimates of Annual Soil Carbon Stock Changes by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay in Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]					*Gg CO_2 eq[3]*						
74	-106.62	3.42	-34.08	-43.80	-69.67	-34.28	-	-1.35	-	-135.07	-50.70
75	-24.67	27.78	-	-	-26.06	-292.06	-	-	-	-105.09	31.51
76	-11.55	-	-90.58	-43.21	0.76	-	-	-	-	-68.35	-17.90
79	-158.58	21.20	-	-	-13.71	-89.44	-	-36.66	-	11.47	36.63
85	-	-7.59	-	-	-	-	-	-	-	-6.13	41.48
89	-	-	-	-7.26	-17.43	-4.25	-	-	-	34.16	-
92	-	-	-	-	-5.64	-	-	-	-	-	-
96	-	-	-10.17	-	-5.02	-	-	-	-	-	-
97	-	-	-	-	-25.50	0.43	-	-	-	33.05	-
98	-25.60	-	-149.12	-71.61	-117.86	-29.92	-	-43.76	-	254.51	-0.34
99	-59.30	-	-	-8.47	-69.85	-	8.93	-42.31	-	-341.12	0.66
101	-	-	-208.72	-151.89	-132.42	-	-	-12.25	-	564.32	31.34
103	-261.57	-	-79.35	-141.55	-204.04	-	-	-46.74	-	-1330.07	-
104	-48.86	-	-26.46	-70.52	-52.20	-	-	-57.57	-	-148.27	-
105	-76.07	-	-145.52	-251.91	-218.28	-5.18	-	-77.80	-	1765.92	-
106	-166.86	-	-142.90	-70.08	-36.34	-37.82	-	-24.39	-	107.31	34.50
109	-381.42	-	-398.82	-109.29	-92.63	-	-	-2.28	-	381.66	-
110	-	-	-	-25.35	-	-	-	-17.17	-	-170.01	-
112	-76.11	-	-509.05	-77.42	-62.64	-29.33	-	-56.58	-	-5.98	162.67
113	-197.14	-	-176.22	-109.78	-36.61	-7.48	-	-45.43	-	-371.09	-5.06
121	-	-	-254.48	-25.46	-7.84	-	-	-	-	161.04	-
122	0.97	-	-365.21	-76.30	-52.51	-	16.13	-	-	74.76	10.64
123	-	-	-97.60	-	-9.77	-	-	-	-	16.04	-
124	-	-	-201.73	-116.53	-62.73	-	-	-8.10	-	224.54	-
125	-	-	-44.28	-	-14.88	-	-	-	-	3.57	-
126	-	-	-382.31	-54.04	-34.99	-	-	-	-	89.01	-
127	-	-	-223.34	-25.43	-4.00	-	-	-2.89	-	123.64	-
128	-	-	-237.27	-53.72	-1.28	-	-27.85	-15.25	-	-52.55	-
129	-	-	-71.76	-	-	-	-	-	-	-28.63	-
134	-166.05	3.18	-400.19	-	-	-43.20	112.47	-56.42	-63.30	97.66	57.89
136	-2.21	-	-598.39	-95.46	-4.84	-	-5.88	-32.00	-	26.17	-17.77
137	-	-	-43.19	-	-	-	11.00	-9.23	-	0.06	-
138	-	-	-	-	-	16.47	-	-	-	-	-
139	-	-	-170.99	25.09	-85.79	-	-	-4.14	-	452.66	-
140	-	-	-797.59	-141.40	-100.87	-	-	41.43	-	389.66	-
142	-	-	-263.65	43.18	-23.10	-	-	-	-	190.71	-
143	-	-	-60.88	-	3.91	-	-	-	-	-	-
145	-	-	-28.93	-	-	-	-	-	-	6.09	-
146	-	-	-	-	-	-	10.22	-	-	-	-
147	-	-	-473.16	-117.76	-99.80	-	-	-20.37	-	211.03	12.86
148	-	-	-246.28	-115.53	-73.11	-	-	-16.10	-	157.62	12.23
155	-	-	-	-	-	257.16	-	-	-	-	-
102A	-271.08	-	-157.73	-113.15	-145.54	-11.37	-	-43.49	-	585.51	86.65
102B	-	-	-	-	-53.30	-	-	-	-	19.51	-
102C	-96.36	-	-60.82	-264.58	-134.97	-161.97	-	-	-	263.53	-
107A	-	-	-	-	-	-	-	-59.66	-	-588.16	-
107B	-112.86	-	-194.55	-73.20	11.66	-70.96	-	-	-	81.59	10.08

Continued - Appendix Table B-11 MLRA-Level Estimates of Annual Soil Carbon Stock Changes by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay in Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq[3]*					
108A	-	-	-	-	-27.37	-	-	-	-	-684.44	-
108B	-22.83	-	-	-	-48.00	-14.05	-	-	-	-664.44	-
108C	-108.02	-	-82.35	-109.41	-60.60	-	-	-64.58	-	-76.91	-
108D	-135.78	-	-54.02	-63.29	-78.07	-	-	-	-	160.50	-
111A	-	-	-49.79	-	-38.49	-	-	-	-	-604.97	-
111B	-139.76	-	-41.53	-95.91	-115.07	-3.48	-	-23.36	-	-337.17	2.26
111C	-	-	-	-	-	-	-	-	-	-166.24	-
111D	-	-	-	-	-11.34	-	-	-	-	-305.93	-
111E	-	-	-	-28.22	-12.70	-	-	-15.78	-	-19.53	-
114A	-	-	-45.41	-29.87	-40.78	-	-	-	-	-5.10	-
114B	-28.18	-	-50.38	-64.39	-23.50	-	-	-	-	-93.95	8.67
115A	-	-	-	-	-25.24	-10.19	-	-	-	-150.93	-1.53
115B	-5.73	-	-137.00	-	-8.37	-	-	-17.45	-	188.33	2.78
115C	-141.68	-	-161.42	-124.31	-63.79	-33.52	-	-29.00	-	-236.21	-
116A	-	-	-389.87	-	-3.71	-	-	-	-	72.85	-
116B	-	-	-204.67	-	-2.14	-	-	-	-	-14.52	10.69
118A	-	-	-34.22	-	-	-	-	-	-	13.67	25.30
120A	-77.78	-	-88.49	-15.90	-61.84	-	-	-	-	86.66	-
120B	-	-	-28.33	-	-	-	-	-	-	74.72	-
120C	-	-	-	-	-	-	-	-	-	20.07	-
130A	-	-	-	-	-	-	-	-	-	7.02	-
130B	-	-	-36.60	-	-2.47	-	-	-	-	-	-
131A	-143.64	31.50	-50.70	-	-	-169.09	-51.44	-94.58	-147.92	-157.84	2.52
131B	-	24.63	-	-	-	-74.56	0.84	-	8.74	-4.21	-
131C	-	-	-	-	-	-1.63	20.45	-	-24.87	-31.29	-
131D	-	-	-	-	-	-20.51	-	-	-32.12	-	-
133A	-255.83	3.07	-381.70	-19.18	-5.18	-61.68	511.97	-116.96	-	-220.33	34.95
133B	-	-	-84.70	-	-	-	-	-	-	6.71	-8.40
135A	-113.56	-	-152.23	-	-	-	64.28	-8.68	-	37.88	-
144A	-	-	-286.27	-18.80	-9.27	-	22.36	17.96	-	66.03	-
144B	-	-	-209.49	-6.96	13.30	-	-	-	-	57.60	-
149A	-	-	-20.38	-	-	3.22	-	-	-	-14.48	-
150A	-	-	-	-	-	-74.64	40.85	-230.29	-274.07	8.79	-
150B	-	-	-	-	-	-	-	-	-13.89	-	-
152B	-	-	-	-	-	-	-	-9.24	-18.58	-	-
153A	-	-	-	-	-	6.39	46.57	-18.92	-	-57.92	-
153B	-	-	-	-	-	-2.75	19.33	-2.79	-	-51.59	-2.21
153C	-	-	-	-	-	-5.00	-	-	-	-103.18	-
153D	-	-	-	-	-	-16.18	-	-	-	-89.81	-
156A	-	-	-	-	-	-4.73	-	-	-	-	-
28A	-144.74	68.02	-	-	-	86.86	-	-	-	-	-3.94
28B	-	-	-	-	-	-24.73	-	-	-	-	-
34A	-	6.98	-	-	-	-44.60	-	-	-	-	-
34B	-	-	-	-	-	-166.44	-	-	-	-	-
43A	-32.45	-	-	-	-18.89	-	-	-	-	-	-7.99
43B	-44.82	-	-	-	-33.34	-84.18	-	-	-	-	-
48A	-	-	-	-	-	-42.60	-	-	-	-	-

Continued - Appendix Table B-11 MLRA-Level Estimates of Annual Soil Carbon Stock Changes by Major Crop Rotation, 2003-2007

	CRP[1]	Fallow	Hay Grass	Hay in Rotation	Hay Legume	Irrigated	Low Residue	Other Cropland	Rice	Row Crop	Small Grain
MLRA[2]						*Gg CO_2 eq[3]*					
48B	-	-	-	-	-	-30.46	-	-	-	-	-
53A	-261.68	48.12	-22.89	-	-9.27	10.27	-	-54.07	-	-	35.87
53B	-490.83	48.86	-57.97	-51.31	-58.63	-	-	-24.26	-	-48.40	306.94
53C	-42.62	-	-	-	-8.54	-12.67	-	-	-	0.80	4.48
55A	-395.12	-	-28.37	-	-12.58	-	10.60	-109.10	-	-36.38	-238.89
55B	-555.38	-	-81.86	-121.22	-68.73	-2.91	11.72	-118.28	-	139.71	124.65
55C	-67.77	-	-38.23	-126.31	-131.55	5.32	-	12.07	-	332.56	-13.41
58A	-636.19	253.83	-77.55	-103.82	-145.15	-117.02	-	17.25	-	-	27.75
58B	-	-	-	-	-1.80	-12.88	-	-	-	-	-
60A	-	104.77	-	-	-10.78	-0.51	-	-	-	-	25.50
63A	-111.53	250.41	-65.13	-	-15.81	-	-	-	-	33.68	80.83
63B	-	-	-39.74	-29.38	-102.88	-	-	24.92	-	-11.30	-5.73
67A	-84.50	19.56	-	-	-6.43	-133.51	-	-	-	2.66	1.54
67B	-471.14	167.05	-	-	-	-165.70	-	-8.13	-	-59.18	-5.61
70A	-	-	-	-	-	4.50	-	-	-	-	-
70B	-	-	-	-	-	-24.81	-	-	-	-	-
70C	-	-	-	-	-	-6.25	-	-	-	-	-
77A	-285.26	-36.94	-	-	-	-94.78	-	-7.82	-	-62.84	87.54
77B	-4.20	-	-	-	-	65.74	-	-	-	-	-
77C	-1117.36	-8.72	-	-	-	-226.05	-146.43	-14.83	-	-12.06	69.76
77D	-120.01	-	-	-	-	14.44	-	-	-	-	12.30
77E	-342.86	8.80	-	-	-	-0.45	-	-	-	-	19.19
78A	-	-	-	-	-	-	-	-	-	-	-18.50
78B	-366.82	-	-	-	-	4.45	-26.34	-	-	-	91.79
78C	-168.58	-24.60	-	-	0.74	-36.84	-4.65	15.37	-	-13.46	44.24
80A	-37.84	-	-47.28	-	-65.41	-38.49	-	-	-	-16.85	6.57
80B	-	-	-	-	-	-	-	-	-	-	28.13
81A	-	-	-	-	-	14.19	-9.94	-47.43	-	-	1.23
81B	-	-	-	-	-	-	-	-	-	-	5.65
81C	-	-	-	-	-	-	-	-	-	-	4.64
82B	-	-	-	-	-	-	-	-	-	-	11.69
83A	-	-	-	-	-	-21.46	-	-3.68	-	-12.17	8.67
83C	-	-	-	-	-	-	-	-	-	2.13	-
83D	-	-	-	-	-	-55.22	8.36	-	-	-7.22	-
83E	-	-	-	-	-	-	-	-	-	-6.38	-
84A	-	-	-23.20	-	-	-	-	-	-	-	13.40
84B	-	-	-	-	-	-45.17	-	-	-	-	-12.01
86A	-	-	-18.69	-	-	-	25.09	-79.26	-	-60.68	27.65
87A	-	-	-	-	-	-	-	-	-	-8.27	4.49
87B	-	-	-	-	-	-	-	-	-	-	-7.61
90A	-	-	-142.03	-101.24	-109.63	-	-	-	-	96.73	-
90B	-8.03	-	-123.42	-28.69	-88.23	-	-	-16.46	-	381.13	-
91A	-21.23	-	-	-19.96	-8.14	20.55	-	-	-	74.26	-
91B	-	-	-	-	-11.73	-	-	-	-	12.44	-
94A	-	-	-	-	-76.98	-	-	-	-	33.63	-
94B	-	-	-	-	-6.22	-	-	-	-	-	-
95A	-8.95	-	-27.50	-75.70	-78.03	-	-	-23.08	-	348.63	4.39
95B	-33.80	-	-64.40	-166.83	-106.40	7.94	-	-46.76	-	694.39	-

[1] CRP = Conservation Reserve Program
[2] MLRA = Major Land Resource Area
[3] Gg CO_2 eq. = Gigagrams carbon dioxide equivalent

Appendix Table B-12 State-Level Estimates of Mineral Soil Carbon Changes on Cropland[1] by Major Activity, 2013

State	Cropland Remaining Cropland	Land Converted to Cropland[2]	Grassland Remaining Grassland	Land Converted to Grassland	***Net Total***
			Tg CO_2 eq.		
Alabama	(0.63)	(0.08)	(0.33)	(1.38)	**(2.41)**
Alaska	ND	ND	ND	ND	**ND**
Arizona	(0.05)	(0.01)	(0.65)	(0.73)	**(1.43)**
Arkansas	(0.69)	0.14	(0.23)	(0.84)	**(1.61)**
California	(0.46)	0.28	(0.57)	(0.93)	**(1.67)**
Colorado	(0.43)	0.17	1.08	(0.31)	**0.50**
Connecticut	(0.01)	(0.01)	(0.02)	(0.00)	**(0.03)**
Delaware	(0.09)	0.00	(0.00)	(0.01)	**(0.11)**
Florida	0.04	0.73	(0.27)	(0.09)	**0.41**
Georgia	(0.31)	(0.00)	(0.40)	(0.19)	**(0.90)**
Hawaii	0.00	0.00	0.00	0.00	**0.00**
Idaho	(5.35)	0.98	(1.90)	(0.18)	**(6.45)**
Illinois	(1.00)	0.14	0.19	(0.12)	**(0.80)**
Indiana	(6.15)	0.76	(0.46)	(0.26)	**(6.12)**
Iowa	(2.52)	0.34	(0.17)	(0.12)	**(2.46)**
Kansas	(4.20)	0.48	0.83	(0.28)	**(3.17)**
Kentucky	(0.76)	(0.06)	(0.67)	(0.26)	**(1.75)**
Louisiana	(0.86)	(0.05)	(0.14)	(0.28)	**(1.33)**
Maine	(0.06)	0.00	(0.01)	0.00	**(0.07)**
Maryland	(0.35)	0.03	(0.02)	(0.04)	**(0.37)**
Massachusetts	(0.12)	(0.02)	0.01	(0.00)	**(0.14)**
Michigan	(0.82)	0.03	(0.15)	(0.13)	**(1.07)**
Minnesota	(2.91)	0.62	(1.14)	(0.46)	**(3.89)**
Mississippi	(2.55)	0.80	(1.06)	(0.33)	**(3.14)**
Missouri	(0.57)	0.14	(0.42)	(0.28)	**(1.13)**
Montana	(2.26)	0.44	5.63	(0.34)	**3.46**
Nebraska	(0.78)	0.01	(0.24)	(0.14)	**(1.15)**
Nevada	(0.90)	0.71	0.36	0.05	**0.22**
New Hampshire	(2.39)	0.58	1.37	(0.11)	**(0.54)**
New Jersey	(0.05)	(0.01)	0.00	(0.00)	**(0.06)**
New Mexico	(0.13)	0.00	(0.01)	(0.03)	**(0.18)**
New York	(0.28)	(0.05)	1.19	(0.05)	**0.81**
North Carolina	(0.02)	(0.00)	0.08	(0.01)	**0.05**
North Dakota	(1.05)	0.08	(0.13)	(0.07)	**(1.18)**
Ohio	(2.00)	0.12	(0.14)	(0.17)	**(2.19)**
Oklahoma	(1.46)	0.19	1.01	(0.33)	**(0.58)**
Oregon	(0.26)	(0.15)	0.25	(0.22)	**(0.39)**
Pennsylvania	(0.54)	(0.03)	(0.17)	(0.08)	**(0.82)**
Rhode Island	(0.00)	0.01	(0.01)	0.00	**(0.00)**
South Carolina	(0.39)	(0.05)	(0.19)	(0.05)	**(0.68)**
South Dakota	(1.02)	1.33	0.30	(0.10)	**0.50**
Tennessee	(0.98)	0.08	(0.79)	(0.32)	**(2.01)**
Texas	(2.97)	0.50	4.67	(0.72)	**1.48**
Utah	(0.01)	0.07	2.38	(0.08)	**2.36**
Vermont	(0.91)	(0.10)	(0.43)	(0.11)	**(1.55)**
Virginia	0.00	0.00	0.02	(0.01)	**0.02**
Washington	(0.04)	0.15	(0.29)	(0.10)	**(0.28)**
West Virginia	0.74	0.31	(0.36)	(0.32)	**0.36**
Wisconsin	(0.34)	(0.06)	(0.07)	(0.02)	**(0.49)**
Wyoming	(0.44)	0.23	2.44	(0.04)	**2.19**
Total	(49.33)	**9.79**	**10.34**	**(10.60)**	**(39.80)**

Note: Parentheses indicate a net sequestration. Tg CO_2 eq is teragrams carbon dioxide equivalent. ND= No data.

[1] Data from mineral soils used; includes soil C sequestration on CRP lands.[2] Losses from annual cropping systems due to plow-out of pastures, rangeland, hayland, set-aside lands, and perennial/horticultural cropland.

Chapter 4

Download data: http://dx.doi.org/10.15482/USDA.ADC/1264247

Carbon Stocks and Stock Changes in U.S. Forests

4.1 Summary

This chapter includes summary updates of inventories and carbon estimations relative to the national forest carbon budgets reported in the previous edition of the USDA Greenhouse Gas Inventory, Chapter 4 (Smith and Heath 2011). We present estimates of stocks and net annual stock change for carbon on forest lands and in harvested wood products for the United States that correspond to values reported for forest lands in the recent U.S. GHG Inventory, specifically Chapter 6: Land Use, Land-Use Change, and Forestry of EPA (2015). Results are generally consistent with reporting recommendations of the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance for Land Use, Land-Use Change, and Forestry (Penman et al. 2003).

Chapter 6 (Land Use, Land-Use Change, and Forestry) of the U.S. GHG Inventory reported that carbon sequestered, or stored, in U.S. forest ecosystems and harvested wood products offset approximately 11.6 percent of total U.S. greenhouse gas emissions in 2013 (EPA 2015). The U.S. GHG Inventory also found that forests in the United States stored an estimated 705 and 71 MMT CO_2 eq. in 2013 (MMT ≡ million metric tons, where 1 metric ton = 106g) for forest ecosystems and harvested wood products, respectively. These numbers represent the amount of carbon sequestered in 2013 alone, adding to carbon stocks built up over past years. Total sequestration in 2013 was estimated to be 776 MMT CO_2 eq. with a 95-percent confidence interval from 973 to 576 MMT CO_2 eq. (Table 4-1). Forest ecosystems plus harvested wood products sequestered about 21 percent more CO_2 eq. in 2013 than in 1990 (Table 4-2). The forest ecosystems included in the report are in the conterminous United States and south central and southeastern coastal Alaska (Map 4-1). Estimated total carbon stocks of forest ecosystems are 146,600 MMT CO_2 eq.

Forest lands of the United States constitute approximately one-third of total land area (Oswalt et al. 2014). Recently summarized data indicate that forest land area in the conterminous United States has increased by 5 percent over the interval from 1987 to 2012, increasing from 243 to 257 million hectares (Oswalt et al. 2014). Table 4-2 shows the overall increase in forest land since 1990, based on the U.S. GHG Inventory. Carbon stocks in forest ecosystems and harvested wood products have also increased since 1990. Overall, the increased forest carbon sequestration between 1990 and 2013 is due to both increased forest area and increased carbon density (MT C per hectare of forest, where MT ≡ metric ton). The apparent increased carbon density from Table 4-2 is based on dividing total carbon stock by forest area, and this national-scale effect is influenced by more localized factors including management, disturbances, climate, and land use. The general trend of increased forest area and carbon stocks of Table 4-2 does not hold for all regions and ownerships (Tables 4-4 and 4-5); both area and carbon stocks have decreased in privately owned forest lands in the Rocky Mountains. In contrast, privately owned forests in the South generally decreased in forest area since the year 2000, while total carbon stocks increased over that same time interval.

Stock change sequences as calculated for the carbon pools are sometimes large and variable over time; this is particularly apparent with the larger pools such as aboveground biomass and soil organic carbon – as in Table 4-2 between 2000 and 2005. Because change over an interval here is based on all forestland at time one relative to all forestland at time two, carbon pools on land entering or leaving "forest land" relative to other sectors is retained in this change

Table 4-1 Forest Carbon Stock Change Annualized Estimates and Uncertainty Intervals, 2013

	Estimate	95% Confidence Interval
Source	*MMT CO_2 eq.*	
Forest	(705)	(901) to (506)
Harvested Wood	(71)	(90) to (54)
Total	**(776)**	**(973) to (576)**

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent.
Forest ecosystem carbon stock change is based on annualized estimates for 2013 from the shaded area in Map 4-1.
Parentheses (i.e., negative net annual change) indicate net forest ecosystem or wood products sequestration, by convention.
Source: EPA 2015

Table 4-2 Forest Carbon Stock/Stock Change and Area Annualized Estimates, 1990, 1995, 2000, 2005, 2010, and 2013

	1990	1995	2000	2005	2010	2013
Annual Change			*MMT CO_2 eq. yr^{-1}*			
Forest	(507.7)	(542.5)	(376.4)	(704.4)	(704.9)	(704.9)
Aboveground Biomass	(324.6)	(372.5)	(329.9)	(402.8)	(433.7)	(433.7)
Belowground Biomass	(63.2)	(73.2)	(65.0)	(79.3)	(87.4)	(87.4)
Dead Wood	(45.9)	(47.3)	(70.2)	(66.8)	(95.0)	(95.0)
Litter	(26.8)	(18.2)	0.7	(11.8)	(10.9)	(10.9)
Soil Organic Carbon	(47.2)	(31.2)	88.0	(143.8)	(77.9)	(77.9)
Harvested Wood	(131.8)	(118.4)	(113.0)	(102.7)	(60.5)	(70.8)
Wood Products	(64.8)	(55.2)	(47.1)	(44.0)	3.7	(11.0)
SWDS	(67.0)	(63.2)	(65.9)	(58.7)	(62.3)	(62.3)
Total	(639.4)	(660.9)	(489.4)	(807.1)	(765.4)	(775.7)
Carbon Stock			*MMT CO_2 eq.*			
Forest	133,134	135,686	138,082	140,905	144,496	146,611
Aboveground Biomass	44,974	46,661	48,470	50,331	52,457	53,758
Belowground Biomass	8,911	9,241	9,597	9,963	10,387	10,650
Dead Wood	7,838	8,077	8,380	8,743	9,153	9,438
Litter	10,080	10,204	10,254	10,276	10,336	10,369
Soil Organic Carbon	61,330	61,503	61,380	61,592	62,163	62,397
Harvested Wood	6,817	7,440	8,021	8,525	8,969	9,167
Wood Products	4,514	4,807	5,069	5,262	5,397	5,408
SWDS	2,303	2,633	2,952	3,263	3,571	3,758
Total	139,951	143,125	146,103	149,430	153,465	155,777
			1,000 ha			
Forest Area	265,938	267,565	267,987	268,334	269,536	269,911

Notes: Forest ecosystem carbon stocks and stock changes as well as forest area are based on annualized estimates for the shaded area in Map 4-1. Parentheses (i.e., negative net annual change) indicate net forest ecosystem or wood products sequestration, by convention. SWDS is Solid Waste Disposal Site. MMT CO_2 eq. is million metric tons carbon dioxide equivalent. MMT CO_2 eq. yr^{-1} is million metric tons carbon dioxide equivalent per year.
Source: EPA 2015

accounting as stock gains or losses, respectively. These apparent highly variable change estimates can be partitioned to individual States and specific inventories within those States (Smith and Heath 2015); however, such an extension of the analysis is beyond the scope of this chapter.

Tables 4-1 and 4-2 do not include woody biomass burned for energy production and carbon sequestered by trees in urban areas, though these affect net GHG emissions. An additional 209 MMT CO_2 eq. was harvested and burned to produce energy in 2013. This quantity of emitted CO_2 eq. is not included in this chapter (or the Land Use, Land-Use Change, and Forestry portion of the national GHG inventory) because it is a part of energy accounting; see Chapter 3 (Energy) of EPA (2015). Trees in urban areas also sequestered about 90 MMT CO_2 eq. in 2013. This quantity is reported in Chapter 6, Land Use, Land-Use Change, and Forestry of EPA (2015) but is reported separately from forest land because urban lands fall within the settlements land use category.

4.2 Background Concepts and Conventions for Reporting Forest Carbon

This chapter summarizes carbon stocks and stock changes on the approximately 270 million hectares located in the conterminous 48 States and coastal Alaska that are considered managed (EPA 2015). Land designated as managed aligns with IPCC guidance for greenhouse gas inventories. The IPCC defines managed forests as those under human influence and with a potential to affect anthropogenic carbon emissions. All forest land of the conterminous United States is considered managed under IPCC guidance due to explicit timber and fire management (e.g., fire suppression in wilderness areas). A large proportion of conterminous U.S. forests, 80 percent, are classified as timberland, meaning they meet minimum levels of productivity and are administratively available for timber harvest. We do not distinguish between the effects of management and land use change, such as afforestation, increased

Table 4-3 Carbon Stocks by Ownership and Forest Type and Groups by Region, 2013

Region:	Pacific Coast			Rocky Mountain			North			South		
	Federal	*Other Public*	*Private*	*Federal*	*Other Public*	*Private*	*Federal*	*Other Public*	*Private*	*Federal*	*Other Public*	*Private*
Forest Type Group	*MMT CO_2 eq. yr^{-1}*											
White/Red/Jack Pine							407	636	1,602	43	6	72
Spruce/Fir	111	34	26				793	1,833	3,013	6	5	3
Longleaf/Slash Pine										526	359	2,326
Loblolly/Shortleaf Pine							47	126	207	1,040	309	9,784
Other Eastern Softwoods							3	5	138	12	8	192
Pinyon/Juniper	94	4	10	1,874	160	880	11	2	10	15	21	517
Douglas-fir	4,663	869	3,145	2,499	142	648		0	1			
Ponderosa Pine	1,091	60	636	969	83	553	128	10	63			
Western White Pine	43			4	1	5						
Fir/Spruce/Mountain Hemlock	4,238	127	393	4,312	126	346			9			
Lodgepole Pine	659	21	115	1,855	28	133						
Hemlock/Sitka Spruce	3,683	653	1,046	234	26	68						
Western Larch	114	9	22	178	25	41						
Redwood	53	87	263									
Other Western Softwoods	511	18	200	301	14	29						
California Mixed Conifer	2,005	32	553									
Exotic Softwoods								26	124			
Other Softwoods									1			
Oak/Pine							123	229	984	470	193	3,425
Oak/Hickory			1	4		7	881	2,140	11,871	1,903	618	13,463
Oak/Gum/Cypress							18	57	143	801	734	5,480
Elm/Ash/Cottonwood	53	46	66	22	10	66	253	705	3,386	134	144	1,814
Maple/Beech/Birch							1,132	2,282	9,289	90	17	320
Aspen/Birch	74	16	55	1,077	43	281	682	1,370	2,630	1		2
Alder/Maple	156	217	707	2	1	1						
Western Oak	615	71	885									
Tanoak/Laurel	349	57	442									
Other Hardwoods	97	24	131	1	0	0	39	109	241	59	11	159
Woodland Hardwoods	49	3	20	432	35	227				9	38	1,455
Tropical Hardwoods										43	107	97
Exotic Hardwoods	0		0		0	1	0	6	42	3	17	171
Nonstocked	266	21	147	539	32	164	36	77	254	31	46	665

Notes:
See USDA Forest Service (2015a) for additional details on how classifications are defined.
Carbon densities are based on the most recent inventory per state for shaded area in Map 4-1.
Blank indicates that the type group does not appear within the inventory for that region and ownership, zeros are the result of rounding a small quantity.

productivity, reduced conversion to non-forest uses, lengthened rotations, and increased proportion and retention of carbon in harvested wood products in this chapter, but the effects are implicitly a part of the inventory and are thus reflected in estimates of carbon stocks and stock changes.

For reporting purposes (e.g., as in Table 4-2), we classify carbon estimates in forest ecosystems into the following pools (Penman et al. 2003):

- Aboveground biomass, which includes all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage. This category includes not only live trees but also live understory.
- Belowground biomass, which includes all living biomass of coarse living roots greater than 2 mm diameter.
- Dead wood, which includes all non-living woody biomass either standing, lying on the ground (but not including litter), or in the soil.
- Litter, which includes the litter, fumic, and humic layers, and all non-living biomass with a diameter less than 7.5 cm at transect intersection lying on the ground.
- Soil organic carbon (SOC), which includes all organic material, including fine roots, in soil to a depth of 1 meter but excluding the coarse roots of the belowground pools.

Within the carbon pool of biomass, we further separated initial carbon estimates into the categories of live trees (diameter greater than 2.5 cm) and understory (smaller live vegetation). Similarly, we separated the dead wood pool into standing dead wood and down dead wood.

The two carbon pools reported for harvested wood products are:

- Harvested wood products in use.
- Harvested wood products in solid waste disposal sites.

The U.S. GHG Inventory estimates of carbon in harvested wood products are reported at the national scale in Tables 4-1 and 4-2, and are not disaggregated to the State level.

The U.S. GHG Inventory relies on annualized estimates of forest carbon stocks within each U.S. State from 1990 to present. Many of the carbon stock summaries presented here (and some in EPA 2015) are based on the most recent per-State forest inventory data; the year of these newest data varies by State. Thus, some of our results reflect the annualized State data (EPA 2015, Smith et al. 2010), and other results are based on the most recent available forest inventory data per State. Specifically, we used the annualized model for stock and stock change as the basis for Tables 4-1, 4-2, 4-4, 4-7, 4-8, and C-2 and Figures 4-1 and 4-2. The most recent surveys per State are summarized in Tables 4-3, 4-6, C-1, C-3, and C-4.

The estimates in this chapter focus on carbon mass, but we report results as the equivalent mass of carbon dioxide by multiplying by 44/12, by convention. Also following reporting conventions, GHG inventory reporting records net ecosystem carbon gain as a negative value (i.e., CO_2 loss from the atmosphere). Therefore, numbers in parentheses (negative values) represent a net annual gain in carbon accumulated within forests or harvested wood pools (i.e., forest carbon gain as a negative net change, or flux, of carbon stocks). For example, Table 4-2 lists (706) MMT CO_2 eq. as the net amount sequestered by forest ecosystems in 2013, which from an atmosphere perspective represents CO_2 removed from the atmosphere.

The carbon stocks estimated in this chapter reflect lands identified as forest at the time field data were collected. Thus, the stock change estimates include net change in forest land area and do not separately account for land use change. Net gains or losses within the carbon pools could result in either a CO_2 exchange with the atmosphere or movement of carbon to or from non-forest lands. Future improvements in the forest carbon estimates will directly address these issues. Most live tree and dead wood carbon changes are very likely the result of forest growth, removals, or mortality rather than land use changes. However, soil organic carbon, while generally much higher in forests as compared to other ecosystems, is a relatively large pool and slow to change.

4.3 Carbon Stocks and Stock Changes by Forest Type, Region, and Ownership

Some of the results in this chapter are reprinted from EPA 2015; specifically Tables 4-1 and 4-2. The remaining tables are based on the same underlying inventory-based forest carbon data (developed by the authors and provided to EPA 2015) but are summarized according to additional classification details not included in EPA (2015) such as ownership, regions, forest types, or stand characteristics. Thus, the forest carbon estimates reported here expand on the information provided in the U.S. GHG Inventory (EPA 2015).

Table 4-3 lists total forest ecosystem carbon stocks according to forest type group, region, and ownership. Forest type groups are partitioned according to those in the forest inventory database (FIADB, USDA FS 2015a). Regions are identified in Map 4-1. There are three broad classes of land ownership. Publicly owned forest lands are divided into Federally owned lands and "other public" (i.e., those under State, city, or other local government). All privately owned forest lands are combined into the third ownership classification of "private." Table 4-3 is based on the most recent survey data per State.

Map 4-1 Geographic Regions Used for Carbon Stock and Stock Change Summaries *(The shaded area represents the extent of the forest inventories used for forest carbon estimates.)*

The majority of forest carbon in the Western United States is on public lands while the majority of forest carbon in the Eastern United States is on privately owned forest lands (Table 4-3). There are some trends apparent between public and private lands. For example, carbon stocks in the ponderosa pine and fir/spruce/mountain hemlock group tend to occur on publicly owned land, which corresponds to the type of forest. As seen in Table 4-3, the oak/hickory type group contains the largest stock of forest carbon. Appendix tables C-1a and C-1b provide forest area and carbon stocks of live trees, respectively, in the same format as Table 4-3.

The same classifications for region and ownership were applied to disaggregated annualized stock and stock change estimates. Tables 4-4 and 4-5 show the total annualized carbon stock change and annualized forest area by region. These tables also show uncertainty around the 2013 estimates using a 95-percent confidence interval. In general, the gains in total carbon stocks (negative values in Table 4-4) were accompanied by increases in forest area (Table 4-5). The trend toward continuous increase in stocks and area does not hold for all regions and ownerships; both area and carbon stocks decreased for privately owned forest lands in the Pacific Coast

Table 4-4 Total Annualized Carbon Stock Change 1990-2013, With Uncertainty Interval for 2013

		1990	1995	2000	2005	2010	2013	2013	2013
Region	Ownership group	Forest ecosystem total carbon stock change						Uncertainty LB	UB
		MMT CO_2 eq. yr^{-1}						MMT CO_2 eq. yr^{-1}	
Pacific Coast	Federal	(60)	(60)	(51)	(47)	(101)	(101)	(185)	(15)
Pacific Coast	Other Public	(26)	(26)	(16)	(16)	(12)	(12)	(65)	41
Pacific Coast	Private	(28)	(28)	12	12	(11)	(11)	(89)	70
Rocky Mountain	Federal	(59)	(58)	(22)	(22)	(34)	(35)	(93)	21
Rocky Mountain	Other Public	(4)	(4)	(3)	(1)	(2)	(2)	(14)	8
Rocky Mountain	Private	22	22	19	26	27	27	(1)	54
North	Federal	(13)	(6)	(13)	(38)	(32)	(32)	(64)	(0)
North	Other Public	(48)	(65)	(81)	(95)	(99)	(99)	(162)	(37)
North	Private	(99)	(68)	(33)	(258)	(170)	(170)	(254)	(86)
South	Federal	(61)	(96)	(101)	(47)	(42)	(42)	(110)	35
South	Other Public	(51)	(76)	(76)	(59)	(44)	(44)	(96)	12
South	Private	(69)	(66)	(12)	(161)	(191)	(191)	(304)	(79)

Notes: MMT CO_2 eq. yr^{-1} is million metric tons carbon dioxide equivalent per year. Parentheses (i.e., negative net annual change) indicate net forest ecosystem or wood products sequestration, by convention.

Table 4-5 Total Annualized Forest Land 1990-2013, with Uncertainty Interval for 2013

		1990	1995	2000	2005	2010	2013	2013	2013
Region	Ownership group	Forest land						Uncertainty LB	UB
		1,000 ha						1,000 ha	
Pacific Coast	Federal	23,610	23,663	23,672	23,492	23,250	23,096	22,629	23,553
Pacific Coast	Other Public	2,318	2,409	2,485	2,549	2,588	2,599	2,342	2,856
Pacific Coast	Private	14,596	14,583	14,497	14,215	13,861	13,638	13,130	14,142
Rocky Mountain	Federal	39,256	39,714	39,656	39,054	39,110	39,229	38,376	40,063
Rocky Mountain	Other Public	2,452	2,481	2,510	2,517	2,546	2,568	2,311	2,829
Rocky Mountain	Private	14,716	14,216	13,726	13,252	12,845	12,631	12,062	13,196
North	Federal	6,009	6,072	6,134	6,249	6,382	6,452	6,320	6,587
North	Other Public	10,987	11,383	11,919	12,485	13,050	13,405	13,153	13,650
North	Private	53,346	53,262	53,070	53,641	54,355	54,564	54,147	54,989
South	Federal	7,172	7,615	8,230	8,676	8,889	9,000	8,558	9,408
South	Other Public	2,474	2,918	3,514	4,108	4,537	4,746	4,433	5,029
South	Private	89,085	89,293	88,586	88,083	88,117	87,994	87,237	88,752

Notes:
See USDA Forest Service (2014a) for additional details on how classifications are defined.
Uncertainty bounds (LB=Lower Bounds; UB=Upper Bounds) are the 2.5th and 97.5th percentiles of the results of the Monte Carlo simulation.
Carbon stock change and forest area are based on annualized estimates for the shaded area in Map 4-1.
Parentheses (i.e., negative net annual change) indicate net forest ecosystem sequestration, by convention.

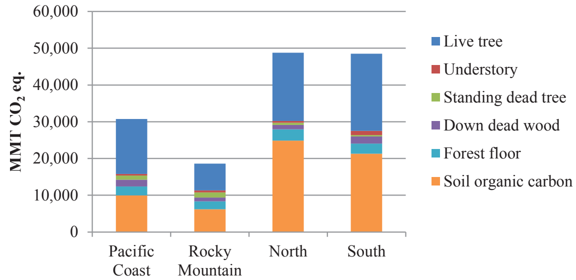

Figure 4-1 Forest Ecosystem Carbon Stocks
(MMT CO_2 eq. is million metric tons of carbon dioxide equivalent)

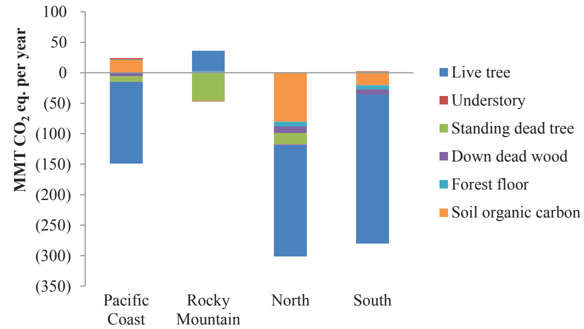

Figure 4-2 Net Annual Forest Carbon Stock Change
(MMT CO_2 eq. is million metric tons of carbon dioxide equivalent)

and Rocky Mountain regions for at least a portion of the interval. In Federally owned forest lands in the Pacific Coast region and privately owned forests in the South, forest area generally decreased since the year 2000 while total carbon stocks increased over that same interval.

Estimates of current average stocks and stock change according to ecosystem carbon pools are illustrated in Figures 4-1 and 4-2. Table 4-6 shows plot-level carbon densities for the six ecosystem pools: live trees, understory, standing dead trees, down dead wood, forest floor, and soil organic carbon by region and ownership. The densities—measured in MT CO_2 eq. per hectare—were based on the most recent survey data per State. Note that despite the sometimes much greater carbon stock per hectare in some western forests, especially along the Pacific Coast, the generally larger total area of forest land in the East places those forests as the major portion of stock and change as illustrated in Figures 4-1 and 4-2. Tables 4-7 and 4-8 disaggregate the ecosystem pools for the annualized data for 2013 for carbon stocks (MMT CO_2 eq.) and net stock change (MMT CO_2 eq. per year). As discussed above, these stock change estimates are not separately allocated according to land use change, and corresponding stock gains or losses are retained in the net annual changes provided in Tables 4-2 and 4-8, for example. See Smith and Heath (2015) for additional discussion on how aggregate change at regional or national levels can be attributed to individual State-level forest inventories.

Additional summaries are provided in the appendix tables. Annualized stock and net stock change estimates for 2013 are provided for the 49 States included in the inventory in Table C-2. In addition

Table 4-6 Mean Plot-Level Carbon Densities According to Region and Ownership for Six Carbon Pools Based on the Most Recent Inventory Per State

Region	Ownership group	Live tree	Understory	Standing dead tree	Down dead wood	Forest floor	Soil organic carbon	Forest area
					MT CO_2 eq. per ha			*1,000 ha*
Pacific Coast	Federal	400.7	11.1	37.0	47.5	66.1	247.5	23,370
Pacific Coast	Other Public	451.8	12.1	23.3	57.6	67.4	304.4	2,582
Pacific Coast	Private	272.1	12.8	11.1	40.1	48.9	251.5	14,011
Rocky Mountain	Federal	151.4	9.7	28.8	19.6	42.7	116.6	38,784
Rocky Mountain	Other Public	112.8	10.7	9.0	15.6	33.4	108.5	2,508
Rocky Mountain	Private	95.1	10.8	7.2	14.7	32.5	107.3	12,888
North	Federal	242.8	6.6	9.5	16.4	43.3	391.7	6,409
North	Other Public	244.8	6.7	8.4	16.5	45.5	409.2	13,150
North	Private	246.4	6.6	6.6	16.0	39.7	309.3	54,443
South	Federal	286.6	10.3	7.2	21.7	34.0	222.1	8,911
South	Other Public	232.6	10.4	3.9	21.9	34.2	272.9	4,570
South	Private	189.6	11.8	3.0	18.4	25.9	204.8	88,076

Note: MT CO_2 eq. per ha is metric tons carbon dioxide equivalent per hectare.

to the annualized forest area for 2013, Table C-2 allocates total forest carbon stocks into three pools: live trees, total non-soil (including live trees), and soil organic carbon. Net annualized stock change summed for each State for 2013 is also included for the live tree and total non-soil carbon classifications. The two remaining appendix tables were compiled from the most recent forest inventory data per State and organized about the four regions, but the ownership classifications were modified slightly because the emphasis in these tables is on productivity and reserved status (and multiple ownership classifications are superfluous). First, all forest lands classified as reserved (see USDA FS 2015a) were pooled, and the remaining, non-reserved, forest land was sorted according to public versus private ownership. We also disaggregated carbon density by the three pools from Table C-2, land area, and stand age class (Table C-3). Table C-3 reports the range of plot-level carbon densities from the 5th to 95th percentiles for the three pools. Similar classifications and summary values were compiled according to stand size class for Table C-4.

Table 4-7 Total Forest Ecosystem Carbon Stocks According to Region and Ownership for Six Carbon Pools Based on Annualized Estimates for 2013

Region	Ownership group	Live tree	Understory	Standing dead tree	Down dead wood	Forest floor	Soil organic carbon
				MMT CO_2 eq.			
Pacific Coast	Federal	9,840	252	905	1,128	1,553	5,739
Pacific Coast	Other Public	1,235	31	58	150	174	780
Pacific Coast	Private	3,876	173	158	570	674	3,462
Rocky Mountain	Federal	5,813	386	1,301	765	1,660	4,584
Rocky Mountain	Other Public	289	27	25	40	86	278
Rocky Mountain	Private	1,173	137	90	185	407	1,348
North	Federal	1,590	42	66	107	280	2,525
North	Other Public	3,329	90	119	224	609	5,456
North	Private	13,644	360	380	884	2,166	16,903
South	Federal	2,613	92	69	197	306	2,010
South	Other Public	1,109	49	17	103	163	1,296
South	Private	17,247	1,034	255	1,641	2,291	18,015

Note: MMT CO_2 eq. is million metric tons carbon dioxide equivalent.

Table 4-8 Net Annual Forest Ecosystem Carbon Stock Change According to Region and Ownership for Six Carbon Pools Based on Annualized Estimates for 2013

Region	Ownership group	Live tree	Understory	Standing dead tree	Down dead wood	Forest floor	Soil organic carbon
				MMT CO_2 eq. yr^{-1}			
Pacific Coast	Federal	(96)	1	(9)	(4)	(2)	8
Pacific Coast	Other Public	(13)	(0)	0	(0)	(0)	1
Pacific Coast	Private	(25)	1	(1)	(2)	2	12
Rocky Mountain	Federal	21	(2)	(45)	(0)	0	(10)
Rocky Mountain	Other Public	(1)	(0)	(0)	(0)	(0)	(0)
Rocky Mountain	Private	13	1	0	1	3	9
North	Federal	(19)	(0)	(3)	(1)	(1)	(8)
North	Other Public	(50)	(1)	(4)	(3)	(5)	(36)
North	Private	(115)	(0)	(11)	(7)	(2)	(36)
South	Federal	(24)	(0)	(1)	(1)	(2)	(14)
South	Other Public	(20)	(1)	0	(1)	(3)	(20)
South	Private	(201)	2	3	(6)	(3)	14

Notes:
MMT CO_2 eq. yr^{-1} is million metric tons carbon dioxide equivalent per year.
See USDA Forest Service (2015a) for additional details on how classifications are defined.
Summaries are based on forest inventories for the shaded area in Map 4-1.
Parentheses (i.e., negative net annual change) indicate net forest ecosystem sequestration, by convention.

4.4 Mechanisms of Carbon Transfer

Forest management can be defined as activities involving the regeneration, tending, protection, harvest, and utilization of forest resources to meet goals defined by the forest land owner. Forest management affects carbon stocks and stock changes through the control of mechanisms associated with carbon gain and loss. For example, increased tree volume per area of forest generally indicates increased carbon stocks.

Carbon sequestration results from the continuous exchange of carbon dioxide between forest ecosystems/products and the atmosphere (Figure 4-3). Note that comprehensive greenhouse gas reporting for forests would also include some non-CO_2 emissions such as methane and non-carbon emissions such as nitrous oxide, for example. However, the vast majority of exchange is in terms of CO_2, which is the focus of this chapter. Trees accumulate carbon as they grow and remove it from the atmosphere, whereas other processes such as respiration, decomposition, or combustion remove CO_2 from forests. Forests convert much of the accumulated organic carbon to wood, which stores carbon and energy. Plant death and subsequent decomposition as well as external influences such as harvest and utilization of wood play significant roles in emissions of CO_2 from forests to the atmosphere. Mortality and disturbance emit some CO_2 (e.g., from fire) and also add to the pools of down dead wood and forest floor, which decay over time. Carbon can also be removed from forest ecosystems through runoff or leaching through soil.

Wood products that are removed from the forest sequester carbon until it is eventually released. Harvested wood carbon pools can lengthen the time before that carbon returns to the atmosphere; however, expected life-spans of wood products vary considerably. Wood products emit CO_2 through either burning or decay (Figure 4-3). Net release of carbon from wood products depends on the product, its end use, and the means of disposal (Smith et al. 2006, Skog 2008). Wood can be burned for energy or without energy capture (Figure 4-3). Because of its role as an energy source, wood can displace other fuel sources. Improved management of wood products in their use and in landfills provides a number of opportunities to reduce emissions and increase sequestration, such as substituting for nonrenewable materials, for example (Perez-Garcia et al. 2005).

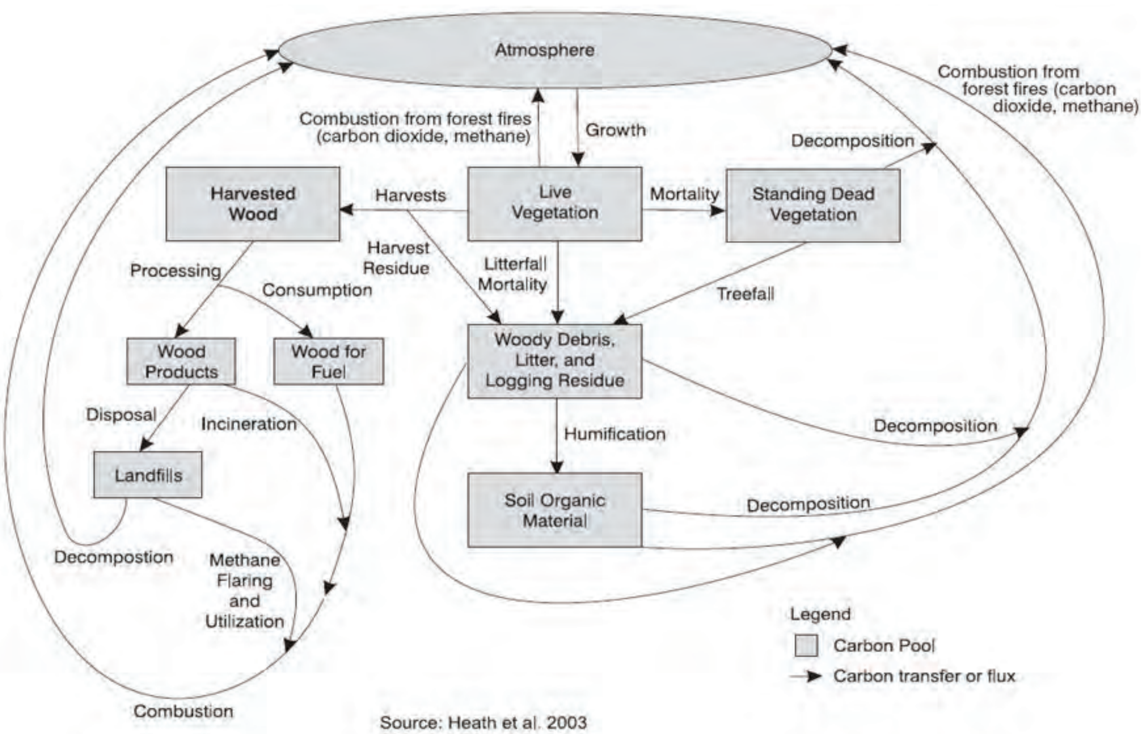

Figure 4-3 Summary Diagram of Forest Carbon Pools and Carbon Transfer Among Pools

4.5 Methods

We based estimates of forest ecosystem carbon on the stock change method, using collected forest data to produce a series of successive carbon stock estimates for an individual State (Penman et al. 2003, Smith et al. 2010). The USDA Forest Service's Forest Inventory and Analysis (FIA) Program conducts a series of partial surveys per State each year with re-measurements at 5- to 10-year intervals, depending on the State (USDA FS 2015b). The term "survey" is used here to describe a complete inventory for a State for 1 year, which is repeated at regular intervals. The FIA Program defines the extent of forest land within each State (USDA FS 2014a,c), and limited adjustments on what to include in the greenhouse gas inventory to reflect United Nations Framework Convention on Climate Change reporting guidelines. Specifically, some of the forest area of southern coastal Alaska (which is the only portion of Alaska forests currently included, see Annex 3.13 of EPA 2015) is identified as unmanaged and excluded from these estimates (Ogle et al. In Prep). In addition, some stands of the woodland forest type groups are also excluded because they are on sites very unlikely to support trees meeting the minimum height defined for "forest" (Coulston et al. In Prep).

Current forest survey data for the United States are available from the FIA Database (FIADB) version 6.0.1 (USDA FS 2015c). All FIADB surveys used for carbon stock estimates were obtained from the FIADB data download Web site (http://apps.fs.fed.us/fiadb-downloads/datamart.html) on July 21, 2014. Surveys from the FIADB are supplemented with some older surveys; see Annex 3.13 of EPA (2015) for a list of the specific surveys used for the estimates. Carbon estimation factors (EPA 2015, Smith et al. 2010) were applied to the plot-level inventory data and summed to calculate carbon stocks for each survey of each State. Carbon stocks for each State or sub-State classification were assigned to survey years with net stock change based on the interval (in years) between the stocks (i.e., difference in successive stocks divided by the interval in years). In this way, State-wide annualized estimates of ecosystem stock and stock change can be calculated and summed to U.S. totals as presented in EPA (2015). A similar approach was taken to produce the estimates according to the additional classifications as provided here. Note that these stock change calculations are based on total forest land in each successive inventory, and an effect of land use change on these estimates is to increase apparent sequestration or emission in proportion to the land moved between sectors. Carbon estimates for harvested wood products are based on a separate stock change method (EPA 2015) and are not available for more detailed classifications other than national totals in the tables provided here. Methods are described below with additional details in EPA (2015), Smith et al. (2010), and Smith et al. (2013); in particular, see Annex 3.13 of EPA (2015).

4.5.1 Live Trees

Live tree carbon pools include aboveground and belowground (coarse root) biomass of live trees with diameter at diameter breast height (dbh) of at least 2.54 cm at 1.37 m above the forest floor. Separate estimates were made for above- and below-ground biomass components. When inventory plots included data on individual trees, tree carbon was estimated using approaches defined by Woodall et al. (2011), which is also known as the component ratio method (CRM) and is a function of volume, species, and diameter. An additional component of foliage, which was not explicitly included in Woodall et al. (2011), was added to each tree following the CRM method and component proportions. Some of the older forest inventory data did not provide measurements of individual trees. The carbon estimates for those plots were based on average densities (MT C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applies to less than 5 percent of the forest land inventory-plot-to-carbon conversions utilized for the 1990-2013 stock change estimates of Table 4-2.

4.5.2 Understory Vegetation

Understory vegetation is defined as all biomass of undergrowth plants in a forest, including woody shrubs and trees less than 2.54 cm dbh. We assumed that 10 percent of understory carbon mass is belowground. This general root-to-shoot ratio (0.11) is near the lower range of temperate forest values provided in Penman et al. (2003) and was selected based on two general assumptions: (1) ratios are likely to be lower for light-limited understory vegetation as compared with larger trees, and (2) a greater proportion of all root mass will be less than 2 mm diameter. See Annex 3.13 of EPA (2015) for calculation details.

4.5.3 Dead Organic Matter

Dead organic matter was calculated as three separate pools: standing dead trees, down dead wood, and litter. Sample data or models were used to estimate carbon stocks. The standing-dead-tree carbon pools include aboveground and belowground (coarse root) mass and include dead trees of at least 12.7 cm dbh. Calculations followed the basic method applied

to live trees (Woodall et al. 2011) with additional modifications to account for decay and structural loss (Domke et al. 2011, Harmon et al. 2011). Similar to the situation with live-tree data, some of the older forest inventory data did not provide sufficient data on standing dead trees to make accurate population-level estimates. The carbon estimates for these plots were based on average densities (MT C per hectare) obtained from plots of more recent surveys with similar stand characteristics and location. This applied to about 20 percent of the forest land inventory-plot-to-carbon conversions utilized for the 1990-2013 stock change estimates. Downed dead wood is defined as pieces of dead wood greater than 7.5 cm diameter, at transect intersection, that are not attached to live or standing dead trees. This includes stumps and roots of harvested trees. Downed-dead-wood estimates were a two-step calculation process detailed in Annex 3.13 of EPA (2015). Initial estimates based on live-tree carbon were modified according to measurements of a limited subset of FIA plots for downed dead wood (Domke et al. 2013, Woodall and Monleon 2008, Woodall et al. 2013). To facilitate the downscaling of downed-dead-wood carbon estimates from the State-wide population estimates to individual plots, downed-dead-wood models specific to regions and forest types within each region were used. Litter carbon is the pool of organic carbon (also known as duff, humus, and fine woody debris) above the mineral soil and includes woody fragments with diameters of up to 7.5 cm. Estimates are based on a model developed around measurements of a subset of FIA plots (Domke et al. 2016).

4.5.4 Soil Organic Carbon

Soil organic carbon (SOC) includes all organic material in soil to a depth of 1 meter but excludes the coarse roots of the biomass or dead wood pools. Estimates of SOC were based on the national STATSGO spatial database (USDA 1991), which includes region and soil type information. Soil organic carbon determination was based on the general approach described by Amichev and Galbraith (2004). Links to FIA inventory data were developed with the assistance of the USDA Forest Service FIA Geospatial Service Center by overlaying FIA forest inventory plots on the soil carbon map (see Annex 3.13 of EPA 2015 and Smith et al. 2013 for additional details about this approach). This method produced mean SOC densities stratified by region and forest type group. It did not provide separate estimates for mineral or organic soils but instead weighted their contribution to the overall average based on the relative amount of each within forest land. Thus, forest SOC is a function of species and location, and net change also depends on these two factors as total forest area changes. In this respect, SOC provides a country-specific reference stock for 1990-present, but it does not reflect effects of past land use.

4.5.5 Harvested Wood Products

Calculations for carbon in harvested wood products (HWP) are separate from the ecosystem estimates because the underlying datasets and methods are compiled separately. These methods are based on Eggleston et al. (2006) guidance for estimating HWP carbon (Skog 2008). Eggleston et al. (2006) provide methods that estimate HWP contribution using one of several different accounting approaches: production, stock change, and atmospheric flow, as well as a default method that assumes there is no change in HWP carbon stocks (see Annex 3.13 of EPA 2015 for more details about each approach). The U.S. GHG Inventory used the production accounting approach to report HWP contribution. Under the production approach, carbon in exported wood was estimated as if it remained in the United States, and carbon in imported wood was not included in inventory estimates. Annual estimates of change were calculated by tracking the additions to and removals from the pool of products held in end uses (i.e., products in use such as housing or publications) and the pool of products held in solid waste disposal.

4.6 Major Changes Compared to Previous Inventories

The estimates provided in Table 4-2 reflect a substantial number of incremental changes in methods and data between EPA (2010) and EPA (2015) in terms of net stock change since 1990. New annual inventory data for most States and adjustments to the identification of land area classified as forests included in the inventories have affected stock totals and changes. In addition, major changes in carbon conversion factors as applied to live and standing dead trees as well as the down dead wood and litter pools affected estimates as each update was implemented. When reviewing estimates provided for the 1990-to-present interval, it is important to note that data updates and methodological changes can affect stock and stock change estimates throughout the interval, as can be seen when comparing Table 4-2 with past versions of the same in USDA or EPA reports. See the methods (above) for general descriptions of new approaches, and compare EPA 2010 and 2015 for additional details and citations related to changes in the methods. The estimates for down dead wood have also been slightly modified—see the citations above and in the respective EPA annexes for additional information.

4.7 Uncertainty

Uncertainty estimates in this chapter are consistent with the IPCC-recommended methodology (Eggleston et al. 2006). Separate analyses were produced for forest ecosystem and HWP flux. The uncertainty estimates are from Monte Carlo simulations of the respective models and input data. Methods generally follow those described in Heath and Smith (2000), Smith and Heath (2001), Skog et al. (2004), and Skog (2008). Uncertainties surrounding input data or model processes were quantified as probability distribution functions, so that a series of sample values could be selected from the distributions. The separate results from the ecosystem and HWP simulations were pooled for total uncertainty.

Carbon stocks were based on forest plot-level calculations, and the Monte Carlo simulations for uncertainty estimates include probabilistic sampling at the plot level. That is, the deterministic stock change calculations of Smith et al. (2010) were repeated many times following the probabilistic sampling of input starting conditions. Uncertainty surrounding carbon density was defined for each of six pools for each inventory plot. Live and standing dead trees were generally assigned normal probability distributions, which vary according to species, number of trees, and area representation. Error estimates for volume and the CRM for estimating biomass are not available, so an assumed 10-percent error on biomass from volume was applied to the volume portion of the estimate; error information in Jenkins et al. (2003) was applied to uncertainty about the additional components (e.g., tops, leaves, and roots). Uniform probability distributions with a range of ±90 percent of the average were used for those plots that used carbon densities from similarly classified forest stands.

Probability distributions for the remaining C pools are triangular or uniform, which partly reflects the lower level of information available about these estimates. The functions defined for these four pools were sampled as marginal distributions. Downed dead wood, understory, and litter were assigned triangular distributions with the mean at the expected value for each plot and the minimum and mode at 10 percent of the expected value. In this method, we assumed that a small proportion of plots would have relatively high carbon densities. Soil organic carbon was defined as a uniform distribution at ±50 percent of the mean. Sub-State or State total carbon stocks associated with each survey are the cumulative sum of random samples from the plot-level of the

functions, which were then appropriately expanded to population estimates. These expected values for each carbon pool include uncertainty associated with sampling, which was also incorporated in the Monte Carlo simulation. Sampling errors were determined according to methods described for the FIADB (Bechtold and Patterson 2005), were assumed to be normally distributed, and were assigned a slight positive correlation between successive surveys for Monte Carlo sampling. More recent annual inventories were assigned higher sampling correlation between successive surveys based on the proportion of plot data jointly included in each. Errors for older inventory data are not available, and these surveys were assigned values consistent with those obtained from the FIADB.

Uncertainty about net carbon flux in HWP is based on Skog et al. (2004) and Skog (2008). Estimates of the HWP variables and HWP contribution under the production approach are subject to many sources of uncertainty. The uncertainty estimate for HWP resulted from our evaluation of the effect of uncertainty in 13 sources, including production and trade data and parameters used to make the estimate. Uncertain data and parameters include: (a) data on production and trade and factors to convert them to carbon, (b) the census-based estimate of carbon in housing in 2001, (c) the EPA estimate of wood and paper discarded to solid waste disposal sites (SWDS) for 1990 to 2000, (d) the limits on decay of wood and paper in SWDS, (e) the decay rate (half-life) of wood and paper in SWDS, (f) the proportion of products produced in the United States made with wood harvested in the United States, and (g) the rate of storage of wood and paper carbon in other countries that came from United States harvest, compared to storage in the United States.

SUGGESTED CITATION

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4.8 Planned Improvements

Developing improved monitoring and reporting techniques is a continuous process that occurs simultaneously with annual U.S. GHG Inventory submissions. Only forest carbon monitoring techniques that are reviewed and published are adopted as part of the forest carbon contribution to the U.S. GHG Inventory. Planned improvements can be broadly assigned to the following categories: pool estimation techniques, land use and land use change, and field inventories.

In an effort to reduce the uncertainty associated with the estimation of individual forest C pools, we are evaluating the empirical data and associated models for each pool for potential improvement (Woodall 2012). The exact timing of future pool estimation refinements is dependent on the vetting of current research outcomes. Research is underway to use a national inventory of SOC (Domke et al. in review) to refine estimates of these pools following the methods applied for litter (Domke et al. 2016). We expect that improvements to SOC estimates will be incorporated into the 2016 U.S. GHG Inventory submission. Despite a consistent nationwide, annual field survey of forests, additional research advances are needed to attain a complete, consistent, and accurate time series of annual land use and land-use change matrices from 1990 to the present report year. The stock change estimates in the 2016 submission will address changes in forest land use classifications. Researchers are exploring techniques for bringing together disparate sets of land use information (e.g., forest versus croplands) that rely on remotely sensed imagery from the 1980s to the present.

The ongoing annual surveys by the FIA Program are expected to improve the precision of forest carbon estimates as new State surveys become available (USDA Forest Service 2015c), particularly in Western States. As of July 21, 2014, Hawaii was the only State not yet reporting data from the annualized sampling design of FIA. The annual surveys will eventually include Hawaii. In addition, data from more intensive sampling of fine woody debris, litter, and SOC on some of the permanent FIA plots will substantially improve resolution of carbon pools (i.e., greater sample intensity) (Westfall et al. 2013) at the plot level for all U.S. forest land.

4.9 References

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4.10 Appendix C

Appendix Table C-1. Summary total from most recent survey data according to region, ownership, and forest type group for (a) current forest land area and (b) total stocks of carbon in live trees.

Appendix Table C-2. State-level annualized estimates for 2013 for: forest area, live tree stocks, non-soil stocks, soil organic carbon stocks, net annual stock change for live trees, and net annual stock change for total non-soil stocks.

Appendix Table C-3. Forest ecosystem carbon density based on most recent forest inventories according to stand age class, region, and ownership for three carbon pools – live tree, total non-soil, and soil organic carbon – as well as forest area. Note that the ownership classification is somewhat different; all reserved forest lands are combined in “reserved,” and the balance are classified according to private versus public ownership.

Appendix Table C-4. Forest ecosystem carbon density based on most recent forest inventories according to stand size class, region, and ownership for three carbon pools – live tree, total non-soil, and soil organic carbon – as well as forest area. Note that the ownership classification is somewhat different; all reserved forest lands are combined in “reserved,” and the balance are classified according to private versus public ownership.

Appendix Table C-1a Current Forest Land Area According to Region, Ownership, and Forest Type Group, 2013

Region:	**Pacific Coast**			**Rocky Mountain**			**North**			**South**		
Ownership group:	*Federal*	*Other Public*	*Private*	*Federal*	*Other Public*	*Private*	*Federal*	*Other Public*	*Private*	*Federal*	*Other Public*	*Private*
Forest Type Group						*1,000 ha*						
White/Red/Jack Pine							545	889	2,258	63	8	126
Spruce/Fir	226	76	55				746	1,758	3,798	5	5	3
Longleaf/Slash Pine										829	573	3,883
Loblolly/Shortleaf Pine							93	215	360	1,767	562	21,028
Other Eastern Softwoods							9	16	417	32	24	681
Pinyon/Juniper	485	20	56	10,486	934	5,129	35	5	32	51	92	2,159
Douglas-Fir	3,820	796	3,796	5,186	327	1,617		0	2			
Ponderosa Pine	2,204	138	1,523	2,813	270	1,865	333	26	184			
Western White Pine	83			10	3	13						
Fir/Spruce/Mountain Hemlock	5,205	168	692	7,996	241	790			10			
Lodgepole Pine	1,360	47	264	4,159	74	349						
Hemlock/Sitka Spruce	2,792	525	1,037	272	44	127						
Western Larch	168	17	44	318	44	104						
Redwood	20	34	240									
Other Western Softwoods	1,395	49	560	892	62	120						
California Mixed Conifer	2,311	33	881									
Exotic Softwoods								44	227			
Other Softwoods									2			
Oak/Pine							232	387	1,789	902	399	7,821
Oak/Hickory			0	14		30	1,553	3,525	21,464	3,503	1,267	31,835
Oak/Gum/Cypress							27	75	196	1,077	887	7,935
Elm/Ash/Cottonwood	67	63	113	62	31	184	333	897	4,647	300	309	4,279
Maple/Beech/Birch							1,422	3,049	14,034	129	28	610
Aspen/Birch	182	37	138	2,307	93	660	906	1,914	3,870	2		4
Alder/Maple	176	222	851	4	3	2						
Western Oak	1,439	195	2,490									
Tanoak/Laurel	391	66	584									
Other Hardwoods	198	37	254	6	1	3	86	216	552	67	16	335
Woodland Hardwoods	180	10	56	1,964	184	1,026				30	121	4,655
Tropical Hardwoods										57	129	118
Exotic Hardwoods	1		1		2	6	0	15	92	9	26	395
Nonstocked	667	47	376	2,295	196	863	90	116	510	88	125	2,207

Notes:

See USDA Forest Service (2015a) for additional details on how classifications are defined.

Carbon densities are based on the most recent inventory per state for shaded area in Map 4-1.

Blank indicates that the type group does not appear within the inventory for that region and ownership, zeros are the result of rounding a small quantity.

Appendix Table C-1b Current Forest Carbon Stocks in Live Trees According to Region, Ownership, and Forest Type Group, 2013

Region:	**Pacific Coast**			**Rocky Mountain**			**North**			**South**		
Ownership group:	*Federal*	*Other Public*	*Private*	*Federal*	*Other Public*	*Private*	*Federal*	*Other Public*	*Private*	*Federal*	*Other Public*	*Private*
Forest Type Group	*1,000 ha*											
White/Red/Jack Pine							130	220	638	26	4	39
Spruce/Fir	14	2	3				117	230	593	2	1	1
Longleaf/Slash Pine										192	94	674
Loblolly/Shortleaf Pine							25	48	83	572	145	4,269
Other Eastern Softwoods							1	1	34	6	3	61
Pinyon/Juniper	24	1	2	683	57	296	2	0	2	4	4	113
Douglas-Fir	2,620	455	1,324	1,191	64	272		0	1			
Ponderosa Pine	483	22	234	472	36	234	47	3	22			
Western White Pine	18			1	1	2						
Fir/Spruce/Mountain Hemlock	2,092	57	145	1,913	58	139			1			
Lodgepole Pine	260	6	41	802	11	52						
Hemlock/Sitka Spruce	1,812	310	404	142	13	33						
Western Larch	58	4	9	90	14	17						
Redwood	44	73	182									
Other Western Softwoods	85	2	27	109	3	8						
California Mixed Conifer	1,179	20	275									
Exotic Softwoods								11	44			
Other Softwoods									0			
Oak/Pine							50	93	430	240	84	1,504
Oak/Hickory			1	0		1	463	1,087	5,947	1,097	330	6,757
Oak/Gum/Cypress							7	25	60	287	303	2,145
Elm/Ash/Cottonwood	23	18	20	9	3	25	72	184	1,001	56	59	714
Maple/Beech/Birch							486	1,028	3,896	49	10	164
Aspen/Birch	21	4	16	336	14	79	145	246	567	0		1
Alder/Maple	66	97	268	0	0	0						
Western Oak	334	38	452									
Tanoak/Laurel	175	44	287									
Other Hardwoods	42	14	58	0	0	0	11	40	82	18	3	32
Woodland Hardwoods	9	1	4	110	8	64				1	5	175
Tropical Hardwoods										3	16	14
Exotic Hardwoods	0		0		0	0	0	2	12	1	3	31
Nonstocked	6	1	4	12	1	5	1	1	5	1	1	9

Notes:
See USDA Forest Service (2015a) for additional details on how classifications are defined.
Carbon densities are based on the most recent inventory per state for shaded area in Map 4-1.
Blank indicates that the type group does not appear within the inventory for that region and ownership, zeros are the result of rounding a small quantity.
MMT CO_2 eq. is million metric tons carbon dioxide equivalent.

Appendix Table C-2 Annualized Carbon Stock Estimates per State, 2013

State	Forest area	Live tree stock	Total non-soil stock	Soil organic carbon stock	Live tree net stock change	Total non-soil net stock change
	1,000 ha	*MMT CO_2 eq.*	*MMT CO_2 eq.*	*MMT CO_2 eq.*	*MMT CO_2 eq. yr^{-1}*	*MMT CO_2 eq. yr^{-1}*
Alabama	9,272	1,927	2,495	1,457	(28.8)	(30.1)
Alaska (Coastal)	5,841	2,049	3,165	1,865	(3.5)	(2.5)
Arizona	6,234	543	864	510	5.3	5.8
Arkansas	7,675	1,670	2,128	1,187	(21.7)	(22.6)
California	13,022	4,212	5,660	1,864	(36.2)	(38.8)
Colorado	8,435	1,319	2,119	966	6.6	(1.9)
Connecticut	702	259	324	159	(4.1)	(4.3)
Delaware	141	49	62	36	(0.4)	(0.2)
Florida	6,990	1,215	1,787	2,657	(15.4)	(15.5)
Georgia	10,017	2,210	2,690	3,047	(21.1)	(21.7)
Idaho	8,626	1,816	2,868	1,295	(1.1)	(5.3)
Illinois	1,984	504	600	412	(8.2)	(9.5)
Indiana	1,973	548	663	383	(7.0)	(8.3)
Iowa	1,201	248	318	246	(3.7)	(4.5)
Kansas	1,045	177	228	308	(4.0)	(5.2)
Kentucky	5,063	1,359	1,650	754	(14.5)	(15.3)
Louisiana	6,018	1,239	1,584	1,026	(13.3)	(15.4)
Maine	7,137	1,455	2,093	2,152	(10.7)	(11.7)
Maryland	990	368	447	231	(3.0)	(3.0)
Massachusetts	1,225	434	534	308	(4.6)	(4.7)
Michigan	8,238	1,784	2,360	4,463	(26.9)	(33.6)
Minnesota	7,033	1,004	1,508	4,290	(10.4)	(15.0)
Mississippi	7,879	1,689	2,100	1,265	(33.4)	(33.0)
Missouri	6,253	1,305	1,645	1,116	(12.5)	(16.3)
Montana	10,251	1,712	2,962	1,486	(0.9)	(18.7)
Nebraska	623	95	126	158	(1.5)	(2.2)
Nevada	3,547	206	371	284	(0.5)	0.3
New Hampshire	1,956	589	760	526	(4.6)	(4.8)
New Jersey	796	232	295	199	(2.6)	(2.3)
New Mexico	7,115	626	1,033	606	0.9	0.1
New York	7,691	2,294	2,941	2,026	(19.3)	(23.8)
North Carolina	7,536	2,008	2,493	1,974	(27.6)	(28.4)
North Dakota	309	39	57	86	(0.4)	(0.4)
Ohio	3,297	974	1,156	774	(10.5)	(12.2)
Oklahoma	4,913	574	839	763	(2.5)	(2.7)
Oregon	12,061	4,288	5,855	3,516	(51.7)	(52.7)
Pennsylvania	6,778	2,139	2,680	1,540	(19.8)	(23.4)
Rhode Island	147	50	62	34	(1.2)	(1.2)
South Carolina	5,279	1,294	1,582	1,570	(21.8)	(21.6)
South Dakota	781	94	139	161	(0.1)	(0.8)
Tennessee	5,633	1,581	2,095	836	(8.2)	(10.4)
Texas	18,856	1,695	2,730	3,373	(1.2)	(1.2)
Utah	5,962	572	967	586	5.2	1.1
Vermont	1,860	583	759	500	(4.7)	(4.9)
Virginia	6,428	1,857	2,329	1,352	(18.8)	(18.6)
Washington	9,039	3,740	5,379	2,849	(24.8)	(33.7)
West Virginia	4,921	1,651	1,967	1,051	(20.5)	(23.3)
Wisconsin	6,921	1,317	1,725	3,569	(15.1)	(19.1)
Wyoming	4,010	583	1,115	445	12.6	8.3

Notes:
Carbon stocks, stock changes, and forest areas are based on annualized estimates for 2013 for shaded area in Map 4-1.
Parentheses (i.e., negative net annual change) indicate net forest ecosystem sequestration, by convention.
Note that total non-soil stock and stock change also includes live trees.
MMT CO_2 eq. is million metric tons carbon dioxide equivalent. MMT CO_2 eq. yr^{-1} is million metric tons carbon dioxide equivalent per year.

Appendix Table C-3a Mean Carbon Density, Range of Plot-Level Densities, and Forest Area on Publicly Owned Forestland (non-reserved) by Region and Stand-Age Class, 2013

Region	Stand age class	Live tree carbon density	Live tree 5th and 95th percentiles	Total non-soil carbon density	Total non-soil 5th and 95th percentiles	Soil organic carbon density	Forest area
	Years	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*1,000 ha*
Pacific Coast	<20	36.7	0 – 161	178.3	69 – 427	253	1,363
Pacific Coast	20-40	194.3	5 – 558	317.3	81 – 745	291	1,692
Pacific Coast	40-60	339.1	8 – 942	464.8	66 – 1134	271	1,541
Pacific Coast	60-80	350.0	11 – 1119	478.3	69 – 1339	244	2,513
Pacific Coast	80-100	357.4	22 – 1047	490.6	80 – 1281	237	2,538
Pacific Coast	100-150	460.8	19 – 1301	614.5	83 – 1530	241	3,649
Pacific Coast	150-200	496.9	22 – 1338	675.4	90 – 1610	263	1,906
Pacific Coast	200+	646.5	49 – 1544	864.6	127 – 1880	304	2,587
Pacific Coast	unknown	375.6	3 – 1272	517.3	48 – 1579	217	1,269
Rocky Mountain	<20	23.6	0 – 95	124.4	37 – 303	127	4,652
Rocky Mountain	20-40	62.2	6 – 150	153.8	48 – 311	138	1,177
Rocky Mountain	40-60	103.9	11 – 283	178.5	43 – 406	125	1,357
Rocky Mountain	60-80	158.3	16 – 447	243.4	45 – 611	126	3,411
Rocky Mountain	80-100	179.0	20 – 468	270.7	52 – 631	120	5,398
Rocky Mountain	100-150	192.6	24 – 512	292.2	55 – 704	113	10,060
Rocky Mountain	150-200	168.5	24 – 493	259.2	53 – 695	102	4,733
Rocky Mountain	200+	152.1	25 – 488	234.6	55 – 660	93	1,973
Rocky Mountain	unknown	151.2	28 – 404	240.9	59 – 570	94	1,076
North	<20	43.1	0 – 140	106.0	45 – 219	471	1,615
North	20-40	122.6	16 – 279	182.8	60 – 353	443	2,002
North	40-60	201.3	25 – 435	268.6	74 – 519	434	2,905
North	60-80	270.9	59 – 532	347.9	115 – 626	401	4,741
North	80-100	322.3	73 – 612	403.6	129 – 709	368	3,674
North	100-150	312.9	41 – 626	393.4	95 – 743	416	1,633
North	150-200	237.9	43 – 534	314.7	100 – 642	582	78
North	200+	211.2	211 – 211	257.2	257 – 257	178	1
North	unknown	429.3	133 – 757	524.9	179 – 867	334	19
South	<20	62.2	0 – 223	120.6	38 – 297	249	1,406
South	20-40	200.0	17 – 443	264.9	66 – 520	247	1,991
South	40-60	264.0	30 – 581	330.2	72 – 667	229	2,493
South	60-80	327.8	85 – 625	401.0	146 – 719	207	3,571
South	80-100	367.9	114 – 707	448.5	172 – 808	228	1,871
South	100-150	391.7	120 – 721	479.7	195 – 825	225	474
South	150-200	679.3	679 – 679	786.2	786 – 786	154	2

Note: MT CO_2 eq/ha is metric tons carbon dioxide equivalent per hectare.

Appendix Table C-3b Mean Carbon Density, Range of Plot-Level Densities, and Forest Area on Privately Owned Forestland (non-reserved) by Region and Stand-Age Class, 2013

Region	Stand age class	Live tree carbon density	Live tree 5th and 95th percentiles	Total non-soil carbon density	Total non-soil 5th and 95th percentiles	Soil organic carbon density	Forest area
	Years	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*1,000 ha*
Pacific Coast	<20	56.2	0 - 230	185.2	84 - 377	317	2,361
Pacific Coast	20-40	298.4	21 - 698	430.8	98 - 877	318	2,096
Pacific Coast	40-60	383.5	25 - 992	498.2	81 - 1171	263	2,310
Pacific Coast	60-80	307.4	18 - 958	410.0	66 - 1113	230	2,375
Pacific Coast	80-100	331.4	24 - 882	440.7	75 - 1074	221	1,737
Pacific Coast	100-150	317.0	19 - 1043	426.6	66 - 1231	216	1,312
Pacific Coast	150-200	403.3	21 - 1288	542.2	64 - 1374	223	290
Pacific Coast	200+	433.2	29 - 1363	611.6	96 - 1693	302	203
Pacific Coast	unknown	182.6	7 - 498	243.4	44 - 583	120	1,328
Rocky Mountain	<20	22.4	0 - 82	98.7	39 - 188	125	2,270
Rocky Mountain	20-40	56.0	6 - 171	124.2	37 - 275	127	573
Rocky Mountain	40-60	88.3	11 - 271	151.2	40 - 385	125	882
Rocky Mountain	60-80	110.3	16 - 319	175.5	43 - 435	116	1,622
Rocky Mountain	80-100	131.4	18 - 350	200.0	42 - 472	110	2,113
Rocky Mountain	100-150	123.6	17 - 379	186.7	41 - 508	98	3,179
Rocky Mountain	150-200	93.8	19 - 261	146.0	45 - 393	83	1,282
Rocky Mountain	200+	92.4	21 - 207	139.9	50 - 274	76	570
Rocky Mountain	unknown	85.1	15 - 203	132.6	41 - 264	77	290
North	<20	45.1	0 - 172	104.3	40 - 239	367	3,574
North	20-40	138.4	14 - 327	199.8	57 - 401	332	6,992
North	40-60	229.4	48 - 474	293.7	96 - 559	308	13,898
North	60-80	289.8	88 - 541	361.4	142 - 632	298	17,226
North	80-100	319.4	104 - 587	396.0	159 - 678	294	9,545
North	100-150	328.5	107 - 599	407.0	160 - 699	302	3,102
North	150-200	333.8	127 - 599	424.6	209 - 678	439	89
North	200+	562.1	373 - 670	634.8	457 - 735	290	3
North	unknown	402.1	105 - 900	491.2	167 - 998	262	14
South	<20	77.6	0 - 246	132.6	40 - 317	213	24,831
South	20-40	184.2	14 - 418	240.5	47 - 493	212	21,996
South	40-60	219.1	17 - 510	277.4	50 - 585	194	20,516
South	60-80	294.3	40 - 608	361.3	81 - 695	193	15,222
South	80-100	319.4	30 - 679	391.0	64 - 764	207	4,338
South	100-150	319.0	26 - 730	390.1	65 - 810	220	1,101
South	150-200	113.9	19 - 429	171.3	47 - 481	173	68
South	unknown	24.2	19 - 31	54.3	50 - 60	183	5

Note: MT CO_2 eq/ha is metric tons carbon dioxide equivalent per hectare.

Appendix Table C-3c Mean Carbon Density, Range of Plot-Level Densities, and Forest Area on Reserved Forestland (both public and private ownerships) by Region and Stand-Age Class, 2013

Region	Stand age class	Live tree carbon density	Live tree 5th and 95th percentiles	Total non-soil carbon density	Total non-soil 5th and 95th percentiles	Soil organic carbon density	Forest area
	Years	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*1,000 ha*
Pacific Coast	<20	25.4	0 - 104	235.8	75 - 545	234	340
Pacific Coast	20-40	98.6	0 - 455	233.8	75 - 582	228	187
Pacific Coast	40-60	214.9	0 - 860	356.0	96 - 964	236	314
Pacific Coast	60-80	269.6	1 - 958	408.6	96 - 1197	227	564
Pacific Coast	80-100	357.5	10 - 993	509.5	91 - 1161	219	611
Pacific Coast	100-150	437.2	24 - 1197	616.0	116 - 1482	236	1,331
Pacific Coast	150-200	502.5	35 - 1238	695.0	111 - 1550	234	952
Pacific Coast	200+	646.5	88 - 1523	878.9	197 - 1981	277	1,811
Pacific Coast	unknown	470.2	2 - 1333	643.4	54 - 1666	203	783
Rocky Mountain	<20	16.9	0 - 78	175.8	56 - 382	134	1,379
Rocky Mountain	20-40	52.9	4 - 145	144.1	59 - 298	139	339
Rocky Mountain	40-60	92.4	7 - 255	174.4	37 - 377	126	189
Rocky Mountain	60-80	136.1	22 - 384	227.7	54 - 513	123	530
Rocky Mountain	80-100	178.0	24 - 422	286.0	53 - 578	123	824
Rocky Mountain	100-150	190.7	22 - 451	318.4	53 - 649	117	1,962
Rocky Mountain	150-200	202.6	33 - 486	329.3	67 - 712	111	1,369
Rocky Mountain	200+	203.6	30 - 549	314.3	61 - 694	105	625
Rocky Mountain	unknown	253.1	35 - 793	380.5	62 - 1008	109	343
North	<20	31.9	0 - 122	130.3	50 - 230	504	93
North	20-40	142.4	20 - 384	214.1	69 - 448	400	118
North	40-60	198.5	35 - 386	274.9	84 - 484	375	359
North	60-80	287.4	90 - 542	384.8	159 - 636	354	774
North	80-100	347.9	91 - 620	449.6	183 - 734	321	952
North	100-150	375.8	98 - 612	477.6	170 - 748	317	557
North	150-200	348.8	131 - 574	474.4	188 - 723	329	30
North	unknown	510.1	452 - 535	652.5	576 - 685	410	9
South	<20	27.3	0 - 124	101.1	52 - 193	419	174
South	20-40	111.5	3 - 355	173.3	53 - 424	419	235
South	40-60	187.1	20 - 479	262.1	49 - 586	371	337
South	60-80	327.7	87 - 608	419.7	148 - 746	298	445
South	80-100	389.7	83 - 711	485.9	159 - 840	226	333
South	100-150	382.1	196 - 640	505.8	263 - 867	238	147
South	150-200	576.5	576 - 576	666.5	666 - 666	166	2

Notes:
See USDA Forest Service (2015a) for additional details on how classifications are defined.
Carbon densities and forest areas are based on the most recent inventory per state for shaded area in Map 4-1.
Note that total non-soil stock also includes live trees.
MT CO_2 eq/ha is metric tons carbon dioxide equivalent per hectare.

Appendix Table C-4a Mean Carbon Density, Range of Plot-Level Densities, and Forest Area on Publicly Owned Forestland (non-reserved) by Region and Stand-Age Class, 2013

Region	Stand size class	Live tree carbon density	Live tree 5th and 95th percentiles	Total non-soil carbon density	Total non-soil 5th and 95th percentiles	Soil organic carbon density	Forest area
		MT CO_2 eq/ha	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*1,000 ha*
Pacific Coast	large diameter	486.9	32 - 1324	651.0	90 - 1604	265	14,545
Pacific Coast	medium diameter	167.8	9 - 460	274.8	67 - 588	229	1,637
Pacific Coast	small diameter	43.7	0 - 143	154.1	54 - 321	242	2,342
Pacific Coast	nonstocked	11.4	0 - 51	160.8	67 - 437	229	533
Rocky Mountain	large diameter	177.4	22 - 507	266.6	52 - 692	107	23,199
Rocky Mountain	medium diameter	149.5	18 - 352	253.3	54 - 520	137	4,867
Rocky Mountain	small diameter	46.1	0 - 136	151.4	59 - 326	139	3,826
Rocky Mountain	nonstocked	4.9	0 - 28	95.1	36 - 270	111	1,946
North	large diameter	333.8	113 - 608	414.7	177 - 709	326	8,541
North	medium diameter	187.5	67 - 341	257.5	118 - 432	469	4,557
North	small diameter	58.9	0 - 166	117.4	48 - 238	557	3,383
North	nonstocked	8.4	0 - 33	74.5	44 - 119	466	187
South	large diameter	345.9	102 - 652	421.1	160 - 748	220	7,821
South	medium diameter	183.5	47 - 362	248.7	95 - 446	230	2,245
South	small diameter	45.1	0 - 137	98.9	33 - 204	257	1,570
South	nonstocked	6.5	0 - 29	75.0	43 - 122	278	171

Note: MT CO_2 eq/ha is metric tons carbon dioxide equivalent per hectare.

Table C-4b Mean Carbon Density, Range of Plot-Level Densities, and Forest Area on Privately Owned Forestland (non-reserved) by Region and Stand-Age Class, 2013

Region	Stand size class	Live tree carbon density	Live tree 5th and 95th percentiles	Total non-soil carbon density	Total non-soil 5th and 95th percentiles	Soil organic carbon density	Forest area
		MT CO_2 eq/ha	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*1,000 ha*
Pacific Coast	large diameter	384.1	36 - 990	505.0	89 - 1171	248	8,500
Pacific Coast	medium diameter	170.0	21 - 433	259.2	67 - 563	233	2,560
Pacific Coast	small diameter	41.9	0 - 145	150.0	61 - 275	281	2,574
Pacific Coast	nonstocked	12.0	0 - 54	137.1	79 - 224	254	376
Rocky Mountain	large diameter	115.7	16 - 336	175.9	42 - 468	97	8,351
Rocky Mountain	medium diameter	97.7	13 - 301	168.4	41 - 425	128	1,760
Rocky Mountain	small diameter	35.7	0 - 101	114.4	45 - 207	128	1,813
Rocky Mountain	nonstocked	5.5	0 - 26	72.7	38 - 121	117	858
North	large diameter	324.2	120 - 583	397.0	173 - 672	278	30,673
North	medium diameter	194.2	66 - 357	260.3	113 - 444	337	14,982
North	small diameter	67.3	0 - 189	127.4	42 - 274	369	8,278
North	nonstocked	9.9	0 - 37	70.8	42 - 120	427	510
South	large diameter	286.1	44 - 589	351.8	83 - 672	203	42,729
South	medium diameter	157.1	28 - 322	214.6	66 - 397	206	23,052
South	small diameter	41.9	0 - 141	89.3	33 - 200	204	20,088
South	nonstocked	4.1	0 - 16	60.8	42 - 102	241	2,207

Note: MT CO_2 eq/ha is metric tons carbon dioxide equivalent per hectare.

Table C-4c Mean Carbon Density, Range of Plot-Level Densities, and Forest Area on Reserved Forestland (both public and private ownerships) by Region and Stand-Age Class, 2013

Region	Stand size class	Live tree carbon density	Live tree 5th and 95th percentiles	Total non-soil carbon density	Total non-soil 5th and 95th percentiles	Soil organic carbon density	Forest area
		MT CO_2 eq/ha	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*MT CO_2 eq/ha*	*1,000 ha*
Pacific Coast	large diameter	555.6	67 - 1381	755.8	146 - 1687	249	5,279
Pacific Coast	medium diameter	180.1	3 - 504	302.4	59 - 670	191	495
Pacific Coast	small diameter	43.8	0 - 145	187.6	69 - 362	217	938
Pacific Coast	nonstocked	6.9	0 - 58	215.3	72 - 503	222	181
Rocky Mountain	large diameter	197.9	26 - 499	316.8	56 - 691	112	4,795
Rocky Mountain	medium diameter	151.9	22 - 351	268.8	54 - 515	130	966
Rocky Mountain	small diameter	36.1	0 - 141	162.9	60 - 358	137	1,251
Rocky Mountain	nonstocked	5.1	0 - 36	184.2	47 - 428	128	551
North	large diameter	370.2	148 - 617	470.2	236 - 734	297	1,900
North	medium diameter	215.4	79 - 391	308.8	147 - 493	376	672
North	small diameter	70.0	0 - 189	151.0	57 - 364	566	302
North	nonstocked	4.8	0 - 25	105.7	40 - 153	537	19
South	large diameter	352.3	86 - 660	449.1	167 - 816	268	1,054
South	medium diameter	165.8	30 - 350	245.5	87 - 455	331	246
South	small diameter	43.2	0 - 142	102.3	40 - 243	490	332
South	nonstocked	13.3	0 - 43	81.5	49 - 132	310	41

Notes:
See USDA Forest Service (2015a) for additional details on how classifications are defined.
Carbon densities and forest areas are based on the most recent inventory per State for shaded area in Map 4-1.
Note that total non-soil stock also includes live trees.
MT CO_2 eq/ha is metric tons carbon dioxide equivalent per hectare.

Chapter 5

Download data: http://dx.doi.org/10.15482/USDA.ADC/1264249

Energy Use in Agriculture

5.1 Summary of Greenhouse Gas Emissions From Energy Use in Agriculture

Approximately 0.83 quadrillion BTU of direct energy were used in agricultural production in 2013, resulting in more than 74 MMT of CO_2 emissions (Table 5-1). The total energy consumption for all sectors in the United States, including agriculture, resulted in 5,331.5 MMT of CO_2 emissions (EPA 2015). Production agriculture contributed approximately 1.4 percent of those total emissions. Within production agriculture, diesel fuel accounted for 41.9 percent of CO_2 emissions and electricity contributed 37.4 percent of CO_2 emissions. Gasoline consumption accounted for 9.6 percent of CO_2 emissions, while liquefied petroleum (LP) gas and natural gas accounted for 6.8 percent and 4.1 percent respectively.

5.2 Spatial and Temporal Trends in Greenhouse Gas Emissions From Energy Use in Agriculture

The highest emissions from agricultural energy use in 2013 were in the Corn Belt and Northern Plains (Figure 5-1), followed by the Mountain, Southern Plains, Lake States, and the Pacific, which had the lowest emissions in this group. Relatively small emissions were estimated for the Southeast, Northeast, Delta, and Appalachian States (regions are defined in Table 5-2). There is a strong correlation between production and energy use/emissions. Generally, the States with the most agricultural production use the most energy and therefore have the highest CO_2 emissions from agricultural production (Figure 5-1). However, emissions also vary by the types of energy used for farm production in each region. For example, even though the Pacific region was the third-highest energy user among the regions, it ranked only sixth in CO_2 emissions due to its reliance on hydroelectric power (Figure 5-1).

Agricultural energy use and the resulting CO_2 emissions grew throughout the 1960s and 1970s, peaking in the late 1970s (Figure 5-2). High energy prices, stemming from the oil crises of the 1970s and early 1980s, drove farmers to be more energy efficient, resulting in a decline in total energy use and CO_2 emissions throughout most of the 1980s (Miranowski 2005). This decline is attributed to switching from gasoline-powered to more fuel-efficient diesel-powered engines, adopting energy-conserving tillage practices, shifting to larger multifunction machines, and adopting energy-saving methods for crop drying and irrigation (Uri and Day 1991; Sandretto and Payne 2006; Lin et al. 1995). Furthermore, policies such as the Energy Policy and Conservation Act of 1975 resulted in greater average fuel economy standards, and both gasoline- and diesel-powered equipment became

Table 5-1 Energy Use and Carbon Dioxide Emissions by Fuel Source on U.S. Farms, 2013

Fuels	Energy consumed	Carbon content	Fraction oxidized	CO_2 emissions
	QBTU	*MMT C/QBTU*		*MMT CO_2 eq.*
Diesel	0.422	20.17	1	31.20
Gasoline	0.101	19.46	1	7.21
LP[1] gas	0.082	16.83	1	5.08
Natural gas	0.058	14.46	1	3.07
Electricity	0.165	**	**	27.86
Total	0.828			74.42

Notes: QBTU is quadrillion British thermal units. MMT C/QBTU is million metric tons carbon per quadrillion British thermal units. MMT CO_2 eq. is million metric tons carbon dioxide equivalent.
[1] LP gas = liquefied petroleum gas
** Varies dependent on fuel source used to generate electricity and heat rate of power generating plants.

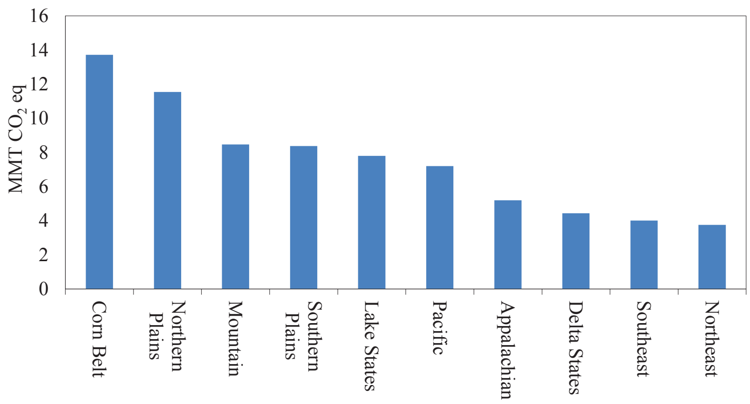

Figure 5-1 CO_2 Emissions from Energy Use in Agriculture, by Region, 2013
(MMT CO_2 eq. is million metric tons of carbon dioxide equivalent)

increasingly energy efficient throughout the 1980s and 1990s. Declines in farm energy use leveled off in the late 1980s as energy prices dropped (Figure 5-2). Total energy use increased throughout most of the 1990s but, since 2000, yearly changes in total energy use have been annually variable with a slight average decreasing trend (-4.6 trillion BTU per year). However, energy productivity (i.e., output per unit of energy input) has increased significantly over that time, due to higher crop yields and more energy efficient input use. The spikes in diesel and gasoline use in 2009 reflect record-breaking U.S. corn and soybean production that year.

5.3 Sources of Greenhouse Gas Emissions From Energy Use on Agricultural Operations

Agricultural operations—including crop and livestock farms, dairies, nurseries, orchards, and greenhouses—require a variety of energy sources. Energy use varies by commodity produced, size of operation, and geographic location. Energy use also varies over time, depending on weather conditions, changes in energy prices, and changes in total annual crop and livestock production. For example, estimated diesel use spiked in 2009 when corn and soybean production reached all-time highs (Figure 5-2). The demand for diesel fuel in 2009 may have also been boosted by low bulk diesel prices, which fell to their lowest level in 5 years, dropping to $1.68 compared to $3.62 the year before (USDA/NASS 2008-09). In 2012, when corn production was down because of a drought, the energy-use estimates for diesel fuel, LP gas, and natural gas all moved downward (USDA/NASS 2014a).

Energy used on farms is typically categorized as direct or indirect energy (Maranowski 2005). Direct energy is energy used on the farm, whereas indirect energy is the energy used to produce energy-intensive farm inputs, such as commercial fertilizers.

Liquid fuel is the most versatile form of direct energy used on farms because it can be used in vehicles and stationary equipment. Crop production uses large amounts of diesel fuel, gasoline, and LP gas for field operations. Most large farms use diesel-fueled vehicles for tilling, planting, cultivating, disking, harvesting, and applying fertilizers and pesticides. Gasoline is used for small trucks and older harvesting equipment. Smaller farms are more likely to use gasoline-powered equipment. As farms have grown larger over time, overall gasoline consumption has declined (Figure 5-2).

Farmers use a significant amount of energy to dry crops such as grain, tobacco, and peanuts. LP gas, electricity, diesel fuel, or natural gas can be used for crop drying. Annual rainfall can have a significant effect on the amount of energy used to dry crops from year to year. Above average rainfall, especially just prior to harvest time, increases the moisture level of grain, and more energy may be required to dry the grain to meet quality standards. The 2009 corn crop, for example, had high moisture content due to unusually wet weather that that fall (USDA/WAOB, 2009). Because 2009 was also a record year for corn and soybean production, energy requirements for drying were extremely high and the estimated LP use was a record high that year.

Weather can also affect the energy used in livestock facilities, greenhouses, and other farm buildings. Natural gas and electricity are commonly used for controlling indoor temperatures. A significant amount of electricity is also used for lighting, air circulation, and powering electric motors with various functions. For example, dairies rely heavily on electricity to power milking machines. The applications of electric-powered farm equipment have increased over time, contributing to higher on-farm electricity use.

There were about 55 million irrigated acres in 2013, about 200,000 less than reported in 2008. While some irrigation systems are gravity-flow systems that require relatively little energy for water distribution, irrigation systems that use pumps are energy intensive. Based on the 2013 USDA Farm and Ranch Irrigation Survey, about 52 million acres of U.S. farmland were irrigated with pumps powered by liquid fuels, natural gas, LP gas, and electricity, costing a total of $2.67 billion (USDA/NASS 2014b). Electricity was the principle power source for these

Table 5-2 Definition of Regions Used in Figure 5-1

Region	States of Region	Region	States of Region	Region	States of Region
Corn Belt	Illinois	**Pacific**	California	**Southeast**	Alabama
	Indiana		Oregon		Florida
	Iowa		Washington		Georgia
	Missouri	**Southern Plains**	Oklahoma		South Carolina
	Ohio		Texas	**Northeast**	Connecticut
Mountain	Arizona	**Lake States**	Michigan		Delaware
	Colorado		Minnesota		Maine
	Idaho		Wisconsin		Maryland
	Montana	**Appalachian**	Kentucky		Massachusetts
	Nevada		North Carolina		New Hampshire
	New Mexico		Tennessee		New Jersey
	Utah		Virginia		New York
	Wyoming		West Virginia		Pennsylvania
Northern Plains	Kansas	**Delta States**	Arkansas		Rhode Island
	Nebraska		Louisiana		Vermont
	North Dakota		Mississippi		
	South Dakota				

pumps, costing about $1.85 billion to irrigate over 33 million acres. Diesel fuel was used to power pumps on about 13 million acres, costing over $500 million, and natural gas was used on about 4 million acres, costing around $222 million (USDA/NASS 2014b). The remaining irrigation acreage was powered by LP gas, butane, and gasoline.

Indirect energy is used off the farm to manufacture farm inputs that are ultimately consumed on the farm. Some farm inputs such as fertilizers and pesticides are produced by energy-intensive industries. For example, commercial nitrogen fertilizer is made primarily from natural gas, and synthetic pesticides are made from a variety of chemicals. Although GHG emissions result from the energy consumption used in manufacturing agricultural inputs, these indirect emissions are not detailed in this inventory. For information on the GHG emissions associated with manufacturing commercial fertilizers, see *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2013* (EPA 2015).

5.4 Methods for Estimating Carbon Dioxide Emissions From Energy Use in Agriculture

CO_2 emission estimates for energy use are constructed from fuel consumption data using standardized methods published in the U.S. GHG Inventory. Emission estimates for fuel use in agriculture are not separately published in the U.S. GHG Inventory; however, they are contained in the estimates of fuel consumption and emissions by sectors. The emissions estimates presented in this chapter were prepared separately from the U.S. GHG Inventory.

Estimates of CO_2 from agricultural operations are based on annual energy expense data from the Agricultural Resource Management Survey (ARMS) conducted by the National Agricultural Statistics Service (NASS) of the USDA. NASS collects information on farm production expenditures including expenditures on diesel fuel, gasoline, LP gas, natural gas, and electricity use on the farm (USDA/NASS 2014c). NASS also collects data on price per gallon paid by farmers for gasoline, diesel, and LP gas (USDA/NASS 2013). Energy expenditures are divided by fuel prices to approximate gallons of fuel consumed on the farm. Gallons of gasoline, diesel, and LP gas are then

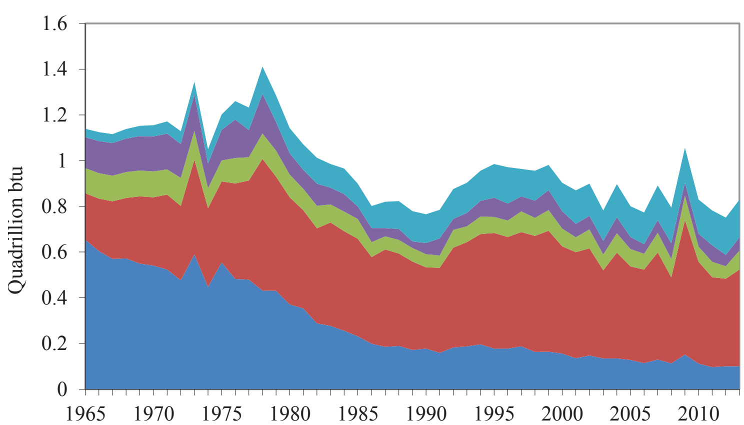

Figure 5-2 Energy Use in Agriculture, by Source, 1965-2013
(BTU - British thermal unit)

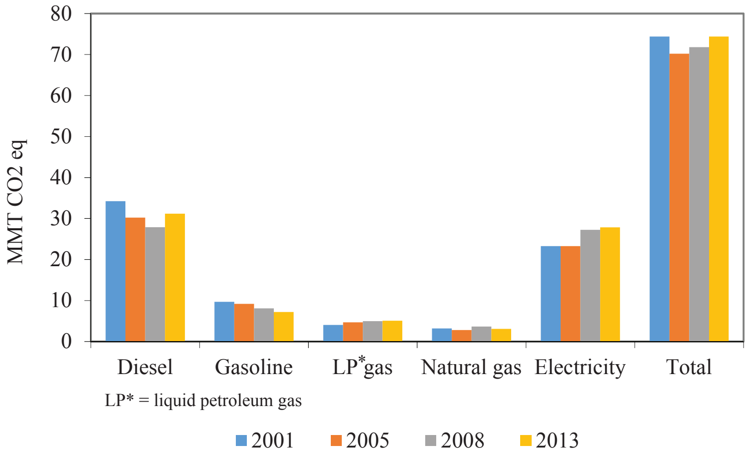

Figure 5-3 CO2 Emissions from Energy Use in Agriculture, by Fuel Source, 2001, 2005, 2008, and 2013
(MMT CO_2 eq. is million metric tons of carbon dioxide equivalent)

converted to BTU based on the heating value of each of the fuels. The individual farm data are aggregated by State, and the State data are grouped into 10 production regions, allowing fuel consumption to be estimated at the national and regional levels (Table 5-2). Farm consumption estimates for electricity and natural gas are also approximated by dividing prices into expenditures. Because the prices farmers pay for electricity and natural gas are not collected by NASS, we use data from the Energy Information Administration (EIA), which reports average prices by State (EIA 2015a; EIA 2015b). The EIA State data are grouped into the NASS production regions.

Following the method outlined in Annex 2 of the U.S. GHG Inventory, consumption of diesel fuel, gasoline, LP gas, and natural gas used on the farm was converted to CO_2 emissions using the coefficients for carbon content of fuels and fraction of carbon oxidized during combustion (Table 5-1). These carbon content coefficients were derived by EIA and are similar to those published by the Intergovernmental Panel on Climate Change (IPCC). For each fuel type, fuel consumption in units of quadrillion BTU was multiplied by the carbon content coefficient to estimate the million metric tons (MMT) of carbon contained in the fuel consumed. This value is sometimes referred to as "potential emissions" because it represents the maximum amount of carbon that could be released to the atmosphere if all carbon were oxidized (EPA 2015). To convert from carbon content to CO_2, it was assumed that 100 percent of the carbon became oxidized.

A different approach was used to estimate emissions from electricity that includes on-farm electricity use, as well as the energy required to generate the electricity off the farm. A number of fuel sources can be used to generate electricity, therefore the mix of fuel sources used by power plants in a region can vary significantly. Some regions of the country rely more on coal for electricity generation, while other regions use more natural gas to generate electricity. To account for this variation, the CO_2 emission estimates from electricity generation in this chapter are derived from State data available from EIA. In response to a special request from USDA, EIA tabulated State emission factors for the States in the NASS production regions. The regional electricity emission factors represent average CO_2 emissions generated by utility and non-utility electric generators for the 1998 through 2000 time period. These regional emission factors were multiplied by estimated electricity use in each farm production region to calculate CO_2 emissions. As reported above, electricity use is estimated from farm expenditure data collected by NASS. Price estimates for electricity published by EIA are divided into electricity expenditures to derive the kilowatt hours consumed on agricultural operations. The kilowatt hours of electricity used on the farm are converted to BTU, based on a standard conversion rate of 3,413 BTU per kilowatt hour.

5.5 Major Changes Compared to Previous Inventories

This report is the fourth edition of the U.S. Agriculture and Forestry Greenhouse Inventory, which estimates GHG emissions for the year 2013. Figure 5-3 compares the 2013 results with the three previous study periods, 2008, 2005 and 2001. As discussed in Section 5.3, annual GHG emissions from energy use in the agricultural sector will vary with changes in crop and livestock production levels and with changes in annual weather conditions. Total emissions in 2001 are slightly greater than the other 3 years, with most of the difference coming from a higher use of diesel fuel (Figure 5-3). It appears that changes in GHG emissions generally follow long-term energy trends as shown in Figure 5.2. When a short term fluctuation in GHG emissions occurred, it probably was related to a major weather event or other factors significantly affecting agricultural production.

SUGGESTED CITATION

Duffield, J., 2016. Chapter 5: Energy Use in Agriculture. In U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2013, Technical Bulletin No. 1943, United States Department of Agriculture, Office of the Chief Economist, Washington, DC. 137 pp. September 2016. Del Grosso S.J. and M. Baranski, Eds.

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