# Chapter 1: Introduction

## 1.1 Global Change and Global Greenhouse Gas Emissions in Agriculture and Forestry

Global concentrations of the three most important long-lived greenhouse gases (GHG) in the atmosphere have increased measurably over the past 255 years. Carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$) concentrations in the atmosphere have increased by approximately 35%, 155%, and 18%, respectively, since 1750 (Keeling & Whorf 2005, Dlugokencky et al. 2005, Prinn et al. 2000). Agriculture and forestry practices may either contribute to or remove GHG from the atmosphere. Agriculture and forestry have affected GHG levels 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 for agriculture are $N_2O$ emissions from cropped and grazed soils, $CH_4$ emissions from ruminant livestock production and rice cultivation, and $CH_4$ and $N_2O$ emissions from managed livestock waste. 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. 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 U.S., agriculture accounted for close to 7% of total GHG emissions (7,260 Tg $CO_2$ eq., teragrams of carbon dioxide equivalents) in 2005 (EPA 2007). Greenhouse gas emissions 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). Agriculture in the United States, including livestock, grasslands, crop production, and energy use, contributed a total of 481 Tg $CO_2$ eq. to the atmosphere in 2005 (Table 1-1). This total includes an offset, or sink, from agricultural (cropped and grazed lands) soil carbon sequestration of roughly 32 Tg $CO_2$ eq. Forests in the United States contributed a net reduction in atmospheric GHGs of approximately 787 Tg $CO_2$ eq. in 2005, which offset total U.S. GHG emissions by almost 11% (EPA 2007). After accounting for C sequestration related to forestry, agricultural and forested lands in the U.S. were estimated to be a net sink of 306 Tg $CO_2$ eq. (Table 1-1). The 95% confidence interval for this estimate ranges from a sink of 499 to 110 Tg $CO_2$ eq. (Table 1-1).

**Table 1-1 Agriculture and Forestry Greenhouse Gas Emission Estimates and Uncertainty Intervals, 2005**

| | Estimate | Lower Bound | Upper Bound | Lower Bound | Upper Bound |
|---|---|---|---|---|---|
| **Source** | | *Tg $CO_2$ eq.* | | % | |
| Livestock | 162 | 148 | 184 | (9) | 14 |
| Crops[1] | 153 | 137 | 188 | (11) | 23 |
| Grassland | 96 | 79 | 143 | 18 | 48 |
| Energy Use[2] | 69 | | | | |
| Forestry | (699) | (890) | (513) | (27) | 27 |
| Urban Trees | (89) | | | | |
| ***Net Emissions*** | **(306)** | **(499)** | **(110)** | **(63)** | **64** |

Note: Parentheses indicate net sequestration.

[1] Includes sequestration in agricultural soils.

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

A little more than one-third (35%) of agriculture's GHG emissions in 2005 were due to crop production. Most of the emissions from crop production were from non-rice soils, with residue burning and rice cropping accounting for about 2% of overall agricultural emissions (Figure 1-1). Livestock production is responsible for most of the remaining agricultural emissions, with about 22% from enteric fermentation,

**BOX 1-1**

The USDA GHG Inventory report follows the international convention for reporting greenhouse gas emissions, as described in the introduction of the U.S. GHG Inventory (EPA 2006). Emissions of greenhouse gases are expressed in equivalent terms, normalized to carbon dioxide using Global Warming Potentials (GWPs) published by the IPCC (IPCC SAR). Global Warming Potentials, which are based on physical and chemical properties of gases, represent the relative effect of a given greenhouse gas on the climate, integrated over a given time period, relative to carbon dioxide ($CO_2$) (IPCC 2001). The GWP values used in the U.S. GHG Inventory and this report are recommended by the IPCC for national greenhouse gas inventory reporting (Table B1-1). These values for methane ($CH_4$) and nitrous oxide ($N_2O$) are referenced to $CO_2$ and based on a 100-year time period (IPCC 1996).

Table B1-1 (Reproduced from U.S. GHG Inventory 2003, Table 1-2:
Global Warming Potentials of Selected Greenhouse Gases

| Gas | Atmospheric lifetime (yrs) | GWP* |
|---|---|---|
| $CO_2$ | 50-200 | 1 |
| $CH_4$ | 12 | 21 |
| $N_2O$ | 120 | 310 |

*For consistency with international reporting standards, the U.S. GHG Inventory uses GWP values published in the IPCC Second Assessment Report (1996). Global warming potential values and estimated atmospheric lifetime were revised for some gases in the IPCC Third Assessment Report (2001).

In the USDA and U.S. GHG Inventories, carbon dioxide equivalent ($CO_2$ eq.) units are expressed in teragrams (Tg), where a teragram equals one million metric tons. The formula for converting gigagrams (1 Gg = $10^9$ grams) of a greenhouse gas to teragrams (1 Tg = $10^{12}$ grams) of carbon dioxide equivalent (Tg $CO_2$ eq.) is provided in the U.S. GHG Inventory and is repeated here for clarity:

$$\mathrm{TgCO_2\ eq.} = (\mathrm{Gg\ of\ gas}) \times (GWP) \times \left( {}^{1Tg}\!/_{1{,}000Gg} \right)$$

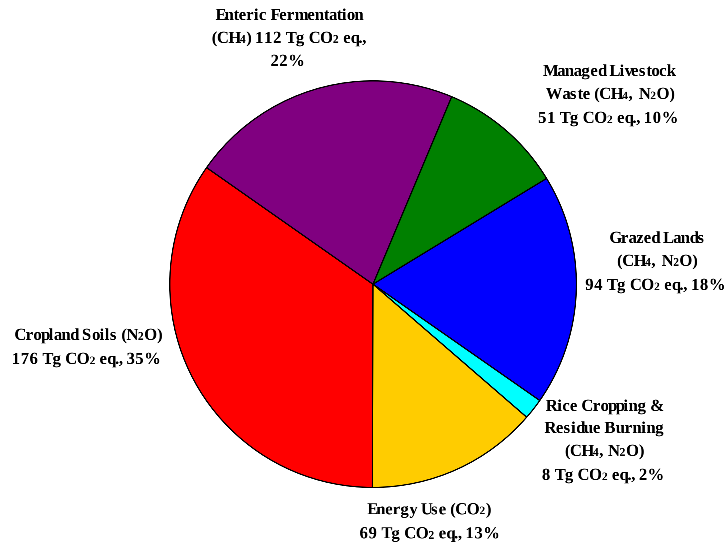
In the land use sector, where carbon dioxide gas is sequestered and stored as carbon (C) in biomass and soils, greenhouse gas removals are often expressed in units of million metric tons of carbon equivalent (MMTCE). The formula below shows how to convert MMTCE to Tg $CO_2$ eq., and is based on the molecular weights of carbon and carbon dioxide.

$$\mathrm{TgCO_2\ eq.} = \mathrm{MMTCE} \times \left( {}^{44}\!/_{12} \right)$$

10% from managed waste, and 18% from grazed lands. The remaining 13% of total emissions result from agriculturally related energy usage, which is listed under the Energy heading by EPA (2007), but is provided here for comprehensiveness. 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 harvested wood products, urban trees, and agricultural soils (Figure 1-2).

Figure 1-1

**Agricultural Sources of Greenhouse Gas Emissions in 2005**

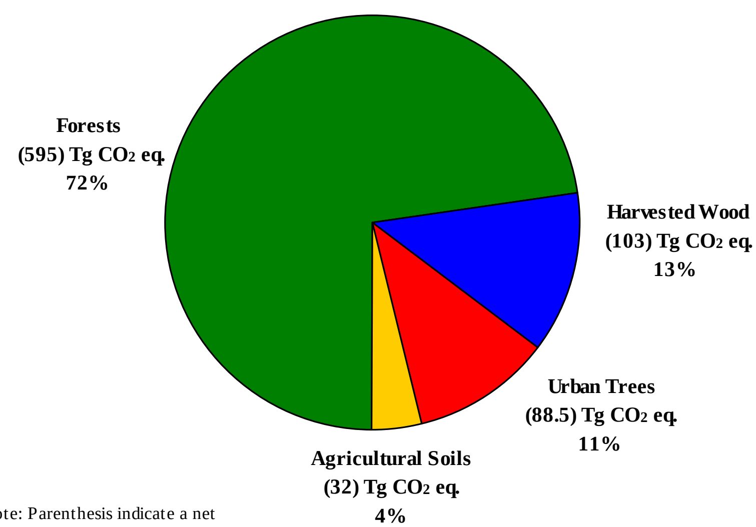



Sources and sinks of emissions are conveniently partitioned (sinks are less than 0) in Figure 1-3. Overall emissions profiles of agricultural sources, including energy use but excluding storage by soils and forestry, show that sources increased 8% between 1990 and 2005 (Table 1-2, Figure 1-3). The sink strength of the forest pool has increased 20% since 1990 (Table 1-2, Figure 1-3). Note that cropland soil $N_2O$ emissions reported here are lower than those reported in EPA (2007) because a mistake was found in the calculations reported in EPA (2007). The soil $N_2O$ emissions reported here are consistent with those reported in EPA (2008).

Annual $CO_2$ emissions from onfarm energy use in agriculture are small relative to total energy use across all sectors in the United States. In 2005, fuel and electricity consumption associated with crop and livestock operations resulted in 69 Tg $CO_2$ (Table 1-1), which is about 1% of overall energy-related $CO_2$ emissions for 2005 (5943 Tg $CO_2$). Electricity use led to about 30% of $CO_2$ emissions from energy use in agriculture; diesel fuel use led to about 46%, while gasoline, natural gas, and liquefied petroleum gas contributed 12%,

Figure 1-2

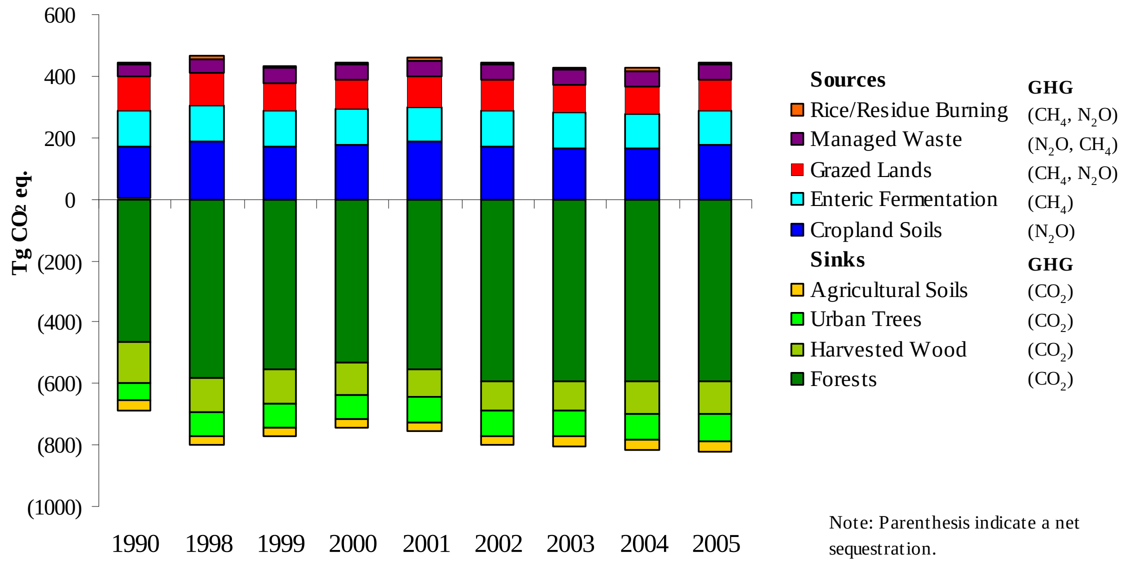
**Agricultural Sinks of Carbon Dioxide in 2005**




Note: Parenthesis indicate a net sequestration.

Figure 1-3

**Agriculture and Forestry Emissions and Offsets for 1990, 1998-2005**




7%, and 5%, respectively, to total $CO_2$ emissions from energy use in agriculture.

## 1.2 Sources and Mechanisms for Greenhouse Gas Emissions

Over half of global annual emissions of $CH_4$ and roughly a third of global annual emissions of $N_2O$ are believed to derive from human sources, mainly from agriculture (IPCC 2001). 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 natural 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 in soil from rice residue and organic fertilizers by $CH_4$-emitting soil microbes. Finally, burning of residues in agricultural fields produces $CH_4$ and $N_2O$ as by-products.

Livestock grazing, production, and waste cause $CH_4$ and $N_2O$ emissions to 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

**Table 1-2 Summary of Agriculture and Forestry Emissions and Offsets, 1990, 1998-2005**

| | | 1990 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 |
|---|---|---|---|---|---|---|---|---|---|---|
| Source | GHG | | | | | *Tg $CO_2$ eq.* | | | | |
| **Livestock** | | **157.4** | **164.6** | **164.3** | **164.0** | **164.6** | **165.5** | **164.9** | **161.8** | **162.9** |
| Enteric Fermentation | $CH_4$ | 117.9 | 116.7 | 116.8 | 115.6 | 114.6 | 114.7 | 115.1 | 112.6 | 112.1 |
| Managed Waste | $CH_4$ | 30.9 | 38.7 | 38.3 | 38.7 | 40.1 | 41.1 | 40.5 | 39.7 | 41.3 |
| Managed Waste | $N_2O$ | 8.6 | 9.2 | 9.2 | 9.6 | 9.8 | 9.7 | 9.3 | 9.4 | 9.5 |
| **Grassland** | | **96.5** | **104.0** | **88.5** | **93.5** | **102.3** | **101.4** | **89.8** | **89.6** | **96.5** |
| Grassland | $CH_4$ | 2.6 | 2.7 | 2.6 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 | 2.5 |
| Grassland | $N_2O$ | 108.4 | 101.3 | 85.9 | 91.0 | 99.8 | 99.0 | 87.5 | 87.3 | 94.2 |
| Grassland | $CO_2$ | (14.4) | 0.0 | 0.0 | (0.0) | (0.1) | (0.1) | (0.1) | (0.2) | (0.2) |
| **Crops** | | **157.2** | **169.5** | **154.5** | **158.2** | **163.0** | **148.0** | **143.6** | **142.9** | **153.0** |
| Cropland Soils[1] | $N_2O$ | 168.5 | 188.3 | 172.9 | 178.8 | 184.9 | 170.6 | 166.5 | 166.1 | 176.9 |
| Cropland Soils[2] | $CO_2$ | (19.5) | (28.0) | (28.0) | (29.3) | (30.8) | (30.6) | (31.1) | (32.2) | (32.2) |
| Rice Cultivation | $CH_4$ | 7.1 | 7.9 | 8.3 | 7.5 | 7.6 | 6.8 | 6.9 | 7.6 | 6.9 |
| Residue Burning | $CH_4$ | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.7 | 0.8 | 0.9 | 0.9 |
| Residue Burning | $N_2O$ | 0.4 | 0.5 | 0.4 | 0.5 | 0.5 | 0.4 | 0.4 | 0.5 | 0.5 |
| **Energy Use[3]** | $CO_2$ | **44.3** | **57.1** | **60.1** | **53.8** | **73.5** | **52.6** | **44.8** | **52.0** | **69.4** |
| **Forestry** | | **(656.0)** | **(769.2)** | **(743.7)** | **(716.9)** | **(725.9)** | **(770.4)** | **(771.0)** | **(783.7)** | **(787.2)** |
| Forests | $CO_2$ | (466.5) | (584.2) | (551.8) | (529.4) | (555.5) | (595.3) | (595.3) | (595.3) | (595.3) |
| Harvested Wood | $CO_2$ | (132.0) | (111.1) | (115.9) | (109.3) | (90.2) | (92.8) | (91.3) | (101.9) | (103.4) |
| Urban Trees[4] | $CO_2$ | (57.5) | (74.0) | (76.0) | (78.2) | (80.2) | (82.3) | (84.4) | (86.4) | (88.5) |
| ***Net Emissions*** | ***All GHGs*** | **(200.6)** | **(274.1)** | **(276.3)** | **(247.4)** | **(222.5)** | **(302.9)** | **(327.9)** | **(337.5)** | **(305.5)** |

Note: Parentheses indicate a net sequestration.
[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 CRP program, in addition to cultivated mineral and organic soils.
[3] Includes emissions from electricity use only for 2001 and 2005.
[4]All years except 2001 and 2005 are interpolated values.

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 offset GHG emissions 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 experienced a relatively small net loss of roughly 4.2 million hectares (Kimble et al. 2003). 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 U.S.

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 for capturing and using $CH_4$ emissions from livestock waste as an alternative energy source. Nitrous oxide emissions from soils can be reduced by precision application of nitrogen fertilizers and use of nitrification inhibitors. These and other practices, many of which have additional benefits beyond GHG emission reductions, are discussed further in this report.

## 1.4 Purpose of this Report

The U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2005 was developed to include emission estimates for years not included in the first U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2001 (USDA 2004) and to revise estimates for previous years based on improved methodologies. This inventory provides a comprehensive assessment of the contribution of U.S. agriculture 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 (UNFCCC) (EPA 2007). 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 county, State, and regional emissions data are part of the inventory development process and can be used for more disaggregated analyses.

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 county, State, region, and land use, and by crop, pasture, range, livestock and forest management systems. The potential to mitigate emissions from cropped soils is also quantified in this edition of the inventory. 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 Global 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, including quantitative estimates of GHG emissions reductions and carbon sequestration through agriculture and forest management. Extensive and in-depth 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 county, 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 county, 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,
- Quantify the mitigation potential of land management practices intended to reduce GHG emissions

## 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 county, 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 stored and managed in 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 methane and nitrous oxide in forestry are not addressed since little information is currently available to develop estimates for these sources for forests. Qualitatively, forest soils are net methane sinks in the U.S. and soil $N_2O$ emissions are small because forests do not receive large N additions. The energy chapter provides information on carbon dioxide 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 category of emissions covered by each chapter. A summary of GHG emissions at the national level is provided initially, 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 first 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 Second Edition of the Inventory

This edition includes three major improvements. First, more sophisticated methodologies were used to estimate GHG emissions from cropped and grazed soils. Second, the livestock chapter now includes emissions from grazed soils that were previously included in the cropland chapter. Lastly, this report includes more quantitative estimates of uncertainty and mitigation potential. The first edition qualitatively discussed uncertainty and mitigation but quantitative analyses were limited. Similarly, the first edition included little quantification of mitigation potential, which is now included in chapters 2 and 3. In addition to updating GHG flux estimates for 1990-2001, estimates for 2002-2005 are included.

The first edition of the USDA GHG inventory estimated GHG emissions and sinks from non-rice crops and grazed lands based solely on IPCC (1997) Tier 1 methodology. Instead of relying exclusively on IPCC (1997) Tier 1 methodology for these sources, the current inventory uses the CENTURY and DAYCENT ecosystem models to simulate GHG fluxes for cropped and grazed lands. Use of more sophisticated process based models is known as an IPCC Tier 3 methodology. The 2005 EPA GHG inventory was the first to use a process-based model (DAYCENT) to estimate $N_2O$ emissions and the 2006 EPA inventory was the first to use a process-based model (CENTURY) to estimate $CO_2$ fluxes. Tier 1 IPCC (1997) methodology has traditionally been used to estimate U.S. GHG fluxes, although other higher tier methods which have been demonstrated to accurately represent GHG emissions and sequestration are encouraged by IPCC's guidelines. The major advantages of the Tier 1 methodology are ease of implementation and high degree of transparency. GHG flux estimates are based on simple empirical relations that can easily be implemented using spreadsheets. For example, IPCC (2006) Tier 1 methodology assumes that 1.0% of the nitrogen in fertilizer added to soils is emitted directly as $N_2O$ from soils on an annual basis. The method also accounts for nitrogen that is added to cropped soils but is removed either by volatilization or leaching and deposited elsewhere by prescribing an emission factor of 1% and 0.75%, respectively. The disadvantage of this method is that other factors which influence emissions (e.g., soil type, weather, previous land use) are not accounted for or are only included in a rudimentary manner. To more realistically account for these other factors, simulation models have been developed that can be applied at large scales to estimate GHG fluxes. More advanced methods which use simulation models should yield more reliable estimates because they account for many of the factors that influence emissions but are not included in IPCC (2006) Tier 1 methodology. The disadvantage of using simulation models for regional and national assessments is that considerable computational power and programming expertise are required to perform large-scale simulations. Additionally, large amounts of time and data are required to acquire and format model inputs and to test the reliability of model outputs. This is why these types of models have not been used for national assessments until recently.

Another major change relates to emissions from livestock production. The livestock chapter is now entitled "Livestock and Grazed Land Emissions." In the first edition, carbon stock changes for grazed lands were included with Cropland Agriculture. However, carbon fluxes for grazed lands are now included in the livestock chapter (Chapter 2) so that all fluxes associated with livestock production are attributed to the livestock sector.