Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States

ICF International

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Table of Contents

1 Introduction

1. INTRODUCTION

The U.S. agriculture sector consists of more than 2 million farms. Collectively, these farms manage more than 922 million acres of cropland, grassland pasture, and range (USDA NASS, 2008).[1] U.S. farms exhibit immense diversity across a wide array of economic, production, socio-demographic, geographic, and environmental characteristics—such as their size of operation, business model employed, commodities produced, production technologies and practices in use, climate conditions, soil composition, and location-specific environmental factors. This diversity can and will affect where and when farmers choose to adopt technologies and practices that mitigate greenhouse gas (GHG) emissions.

The primary purpose of this report is to facilitate a better understanding of the financial incentives that would be necessary for agriculture producers to start adopting specific mitigation practices and technologies as part of their normal production and land management operations. For these technologies and practices, the incentive levels developed in this report can be viewed as the carbon price (stated in 2010 dollars per metric ton of carbon dioxide [CO_2] equivalent) at which "representative" farms would view adoption as a break-even undertaking. As such, the focus in this report is on mitigation technologies and practices that have readily available data on farm-level cost and GHG reduction potential. Other potential options exist, but due to data limitations this report provides only qualitative descriptions of them. For each practice and technology considered, this report provides:

1. A detailed technical description of the technology or practice, including information describing readily available data on the current level of adoption, the potential for additional adoption, and potential barriers to additional adoption;
2. Detailed estimates of farm-level costs for implementing the technology or practice for a set of representative farms;
3. Estimates of the farm-level GHG mitigation potential associated with adoption of the technology or practice (e.g., increase in carbon (C) sequestration or decrease in GHG emissions); and
4. Estimates of the GHG incentive levels that various representative farms would require to consider adoption of the technology or practice at a break-even undertaking (see Textbox 1-1).

A number of mechanisms could create financial incentives for farmers to mitigate GHG emissions, including the establishment of a formal carbon market (such as would occur under a State, regional, or national cap-and-trade program), the use of a direct government payment programs for GHG mitigating technologies and practices (analogous to payments that farmers receive under USDA's Conservation Reserve Program), and the development of voluntary mitigation-related contracts between two or more private parties. For the purposes of this report, it is only important that a mechanism exists through which farmers can convert units of GHG mitigation (either decreases in emissions or increases in carbon sequestration) into income. As such, this report simply takes the existence of a GHG incentive (or carbon price) as given without specifying the overarching framework that created it.

The specific GHG mitigation options addressed in this report are detailed in Exhibit 1-1. For all investments in GHG mitigating technologies considered in this report, the tax rate is assumed to be 15%[2] (Durst, 2009) and the discount rate is assumed to be 5%[3] (USDA ERS, 2011; Xu, 2012). The mitigation options are organized as sections (one per technology or practice) in three chapters:

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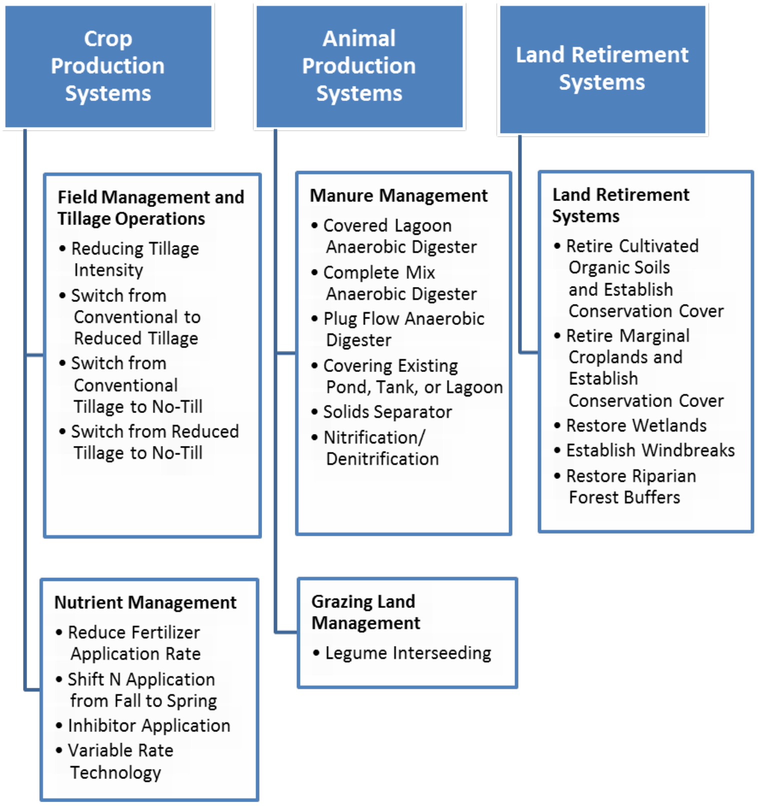
[1] Including grazing lands, both forested and non-forested, the acreage is 1.16 billion acres or about 51% of the total U.S. land area (Nickerson et al., 2011).

[2] Durst, Ron, *Federal Tax Policies and Farm Households*, USDA, Economic Research Service, May 2009. Summary report indicates that the average tax rate for farm sole proprietors was approximately 14.8% in 2004 and estimated to be below this level in 2009.

[3] Xu, Mark, *NRCS Use of Discount Rates in Conservation Programs and Projects*, 67th Annual SWCS International Conference. For a farmer-funded project, this presentation suggests that the discount rate be the rate of return for an alternative best investment project. The rate of return of 5% is based on USDA, Economic Research Service, Agricultural Resource Management Survey (ARMS) Farm Financial and Crop Production Practices data for 2010.

- **Crop Production Systems.** Nitrous oxide (N_2O) generation from crop nutrient management practices is the major GHG emissions source from cropping systems. Two key factors for these emissions at the field level are the quantity of nitrogen (N) applied and the efficiency with which it is taken up by plants. Consequently, the nutrient management options focus on nitrogen application rates, timing, inhibitor application, and method of application (i.e., Variable Rate Technology). Field management and tillage practices affect soil carbon storage. Mitigation options include the carbon sequestration potential of reducing tillage (i.e., switching from conventional till to reduced-till, and no-till management).

Exhibit 1-1: Summary of Mitigation Options



- **Animal Production Systems.** Although methane emissions from enteric fermentation exceed those from manure management, the opportunities for reducing emissions from enteric fermentation are not well understood. For that reason, the mitigation options presented for this sector focus primarily on those applicable to manure management. Anaerobic decomposition of manure is the primary source of methane from manure management systems; the options presented here focus on reducing these emissions through flaring, improved solids separation, and capture and use. Interseeding of legumes on grazing lands provides an opportunity to increase soil carbon sequestration.

- **Land Retirement Systems.** Agricultural lands that are of marginal or even moderate quality present an opportunity for GHG mitigation and carbon sequestration through retirement from commodity production. Land retirement could be applied to lands in crop or animal production systems. When croplands are retired from production and allowed to grow native vegetation, soil organic carbon accumulates at a faster rate than during crop cultivation (Follet, 2001). Retiring farm land to promote GHG mitigation typically involves establishing some type of long-term vegetation cover. As a result, these practices are often associated with a variety of environmental co-benefits (in addition to carbon sequestration), such as improved water quality, expanded wildlife habitat, and reduced soil erosion. Several USDA conservation programs encourage targeted land retirements to promote these co-benefits, including the Conservation Reserve Program, the Wildlife Habitats Incentives Program (WHIP), the Wetlands Reserve Program, and the Environmental Quality Incentives Program (EQIP).

Textbox 1-1: Methodology for Estimating Break-Even Price

Each mitigation option is characterized by its capital and recurring costs (e.g., operation and maintenance costs), cost savings or revenues, emissions reduction efficiencies, and equipment lifetime.

Table 1: Cost Characteristics of Mitigation Technology and Management Practice Options

Characteristic of Options	Unit	Definition
Equipment Lifetime (T)	Years	Average technical lifetime of an option.
Emissions Reduction (ER)	mt CO_2-eq	Absolute amount of emissions reduced by an option (as modelled) in a given year.
Capital Cost (CC)	$	Total fixed capital cost of an option.
Recurring Cost (RC)	$	Annual operating and maintenance costs, including reductions in costs resulting from the option (e.g., savings in fertilizer costs, savings from on-site generation of electricity).
Revenue (R)	$	Net changes in revenues (e.g., change in crop yield).

For a given GHG mitigating technology or practice, a break-even price is the payment level (or carbon price) at which a farm will view the economic benefits and the economic costs associated with adoption as exactly equal. Conceptually, a positive break-even price represents the minimum incentive level needed to make adoption economically rational. A negative break-even price suggests the following: (1) no additional incentive should be required to make adoption cost-effective; or (2) there are non-pecuniary factors (such as risk or required learning curve) that discourage adoption.

The break-even price is determined through a discounted cash-flow analysis such that the revenues or cost savings are equal to the costs. This relationship is demonstrated in the equation below, which uses the parameters described in Table 1.

$$\sum_{t=1}^{T}\left[\frac{(P\times ER_t)(1-TR)+R_t(1-TR)+TB}{(1+DR)^t}\right]=CC+\sum_{t=1}^{T}\left[\frac{RC_t(1-TR)}{(1+DR)^t}\right] \qquad \text{(Equation 1)}$$

where:

P = the break-even price of the option (\$/mt CO_2-eq);
ER_t = the emissions reduction achieved by the technology in year t (mt CO_2-eq);
R_t = the revenue generated in year t (\$);
T = the option lifetime (years);
DR = the selected discount rate (%);
CC = the one-time capital cost of the option (\$);
RC_t = the recurring (O&M) cost or savings in year t (\$/year);
TR = the business tax rate (%); and
TB = the tax break for standard depreciation of capital assets, equal to the capital cost divided by the option lifetime, multiplied by the tax rate (\$) (i.e., TB is expressed as TB = (CC / T) x TR).

Assuming that the emissions reduction (ER), the recurring costs (RC), and the revenue generated (R) remain constant on an annual basis, than the break-even price is as indicated below in Equation 2.

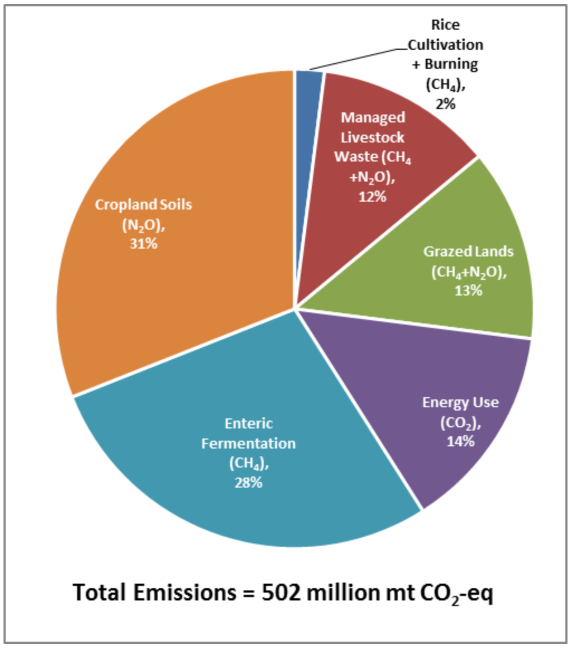
$$P=\frac{CC}{ER(1-TR)\sum_{t=1}^{T}\frac{1}{(1+DR)^t}}+\frac{RC}{ER}-\frac{R}{ER}-\left[\frac{CC}{ERxT}\times\frac{TR}{(1-TR)}\right] \qquad \text{(Equation 2)}$$

One important omission in this report is the option of afforesting existing cropland and pasture. Many economic studies have concluded that landowners could mitigate significant quantities of GHG emissions through afforestation (EPA, 2005; Lewandrowski et al., 2004; Lubowski et al., 2006; McCarl and Schneider, 2001). Because the GHG mitigation potential of this option is already relatively well understood, it is not considered in this report.

The information compiled for the mitigation options described in this report was collected from a diverse set of resources, including the scientific literature; Web sites and published products of government agencies, university departments, commodity groups, trade organizations, and vendors; and other sources. A comprehensive review of the information was conducted; however, due to the rapid rate of publication of new scientific findings, more recent reports and syntheses may be available. Each section includes citations for information presented, and highlights important knowledge gaps where information was not available. Dollar estimates are indicated in the report as cited in the literature, and are converted to 2010 dollars using the consumer price index as provided by the Bureau of Labor Statistics (Bureau of Labor Statistics, 2012). The consumer price index inflation scalar values can be found in Appendix 1-A.

The main focus of this report is on identifying specific technologies and practices that representative crop and livestock operations could adopt in response to financial incentives to mitigate GHG emissions, along with the associated magnitude of the financial incentive necessary to avoid a negative financial impact. Quantifying the net emissions reduction potential at the national level is beyond the scope of this report. However, to give a broader context of agriculture's potential to mitigate GHG emissions, the next three sections provide the following: (1) a GHG profile of U.S. agriculture on the magnitude and composition of agricultural GHG emissions and sinks; (2) overviews of the crop, beef, dairy, and swine sectors' structure and geographic distribution of commodity production; and (3) a discussion of Federal regulations that could potentially affect incentives for landowners to mitigation GHGs. The regions used in this report are the farm production regions as defined by the USDA Economic Research Service. See Appendix 1-B for a map of the production regions and a listing of the States in each region.

Exhibit 1-2: Agricultural Sources of Greenhouse Gas Emissions in 2008[a]



[a] Cropland soils emissions include emissions from major crops, non-major crops, histosol cultivation, and managed manure that accounts for the loss of manure nitrogen during transport, treatment, and storage, including volatilization and leaching/runoff.
Source: USDA (2011).

1.1 GHG Profile of U.S. Agriculture

As shown in Exhibit 1-2, gross GHG emissions from all agricultural sources in 2008 were 502 million mt CO_2-eq. Most GHG emissions from agricultural sources (86%) are nitrous oxide (N_2O) and methane (CH_4). Exhibit 1-3 shows agricultural emissions of N_2O and CH_4 by source for 1990, 2000, and 2008.[4] Collectively, emissions in 2008 were 3% higher than in 2000 and 8% higher than in 1990.

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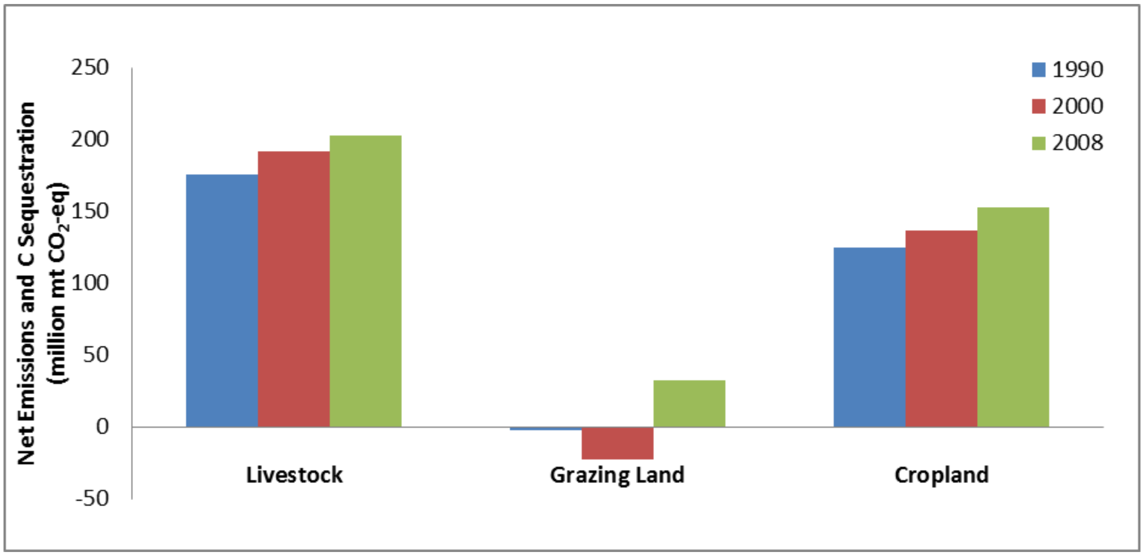
[4] "Grazed lands" is the terminology used in the USDA Agriculture and Forestry GHG inventory, 1990–2008. The definition of grazed lands is all lands grazed by livestock regardless of management intensity (e.g., rangeland, pasture, paddock) for both privately held and federally managed lands (USDA, 2011). For the purpose of this report, the terms "grazed lands" and "grazing lands" are used interchangeably.

The trends shown in Exhibit 1-3 indicate a relative increase in emissions and decrease in agricultural carbon sequestration between 1990 and 2008. The decrease in grazing land carbon sequestration is likely to continue due to a decrease in the total acreage of grassland. In particular, total grazing land declined by 243 million acres (about 24%) from 1949–2007 (Nickerson et al., 2011). Corn and soybean production has increased over the last 18 years. A relatively high increase in corn production occurred between 2006 and 2008 as a result of soybean producers shifting acreage into corn production. This shift was due to higher corn prices and increased demand for corn as an ethanol feedstock (Nickerson et al., 2011). Livestock emissions have increased over the past two decades despite decreasing population sizes. This rise in emissions can be attributed to an increase in average weights for beef cattle, an increase in milk production per dairy cow, and changes in manure management practices.

Exhibit 1-3: Net Emissions and Carbon Sequestration from Agricultural Sources in 1990, 2000, and 2008



Source: USDA (2011).
Cropland soils include emissions from managed manure during storage and transport before soil application.
See footnote 4 for definition of grazing lands.

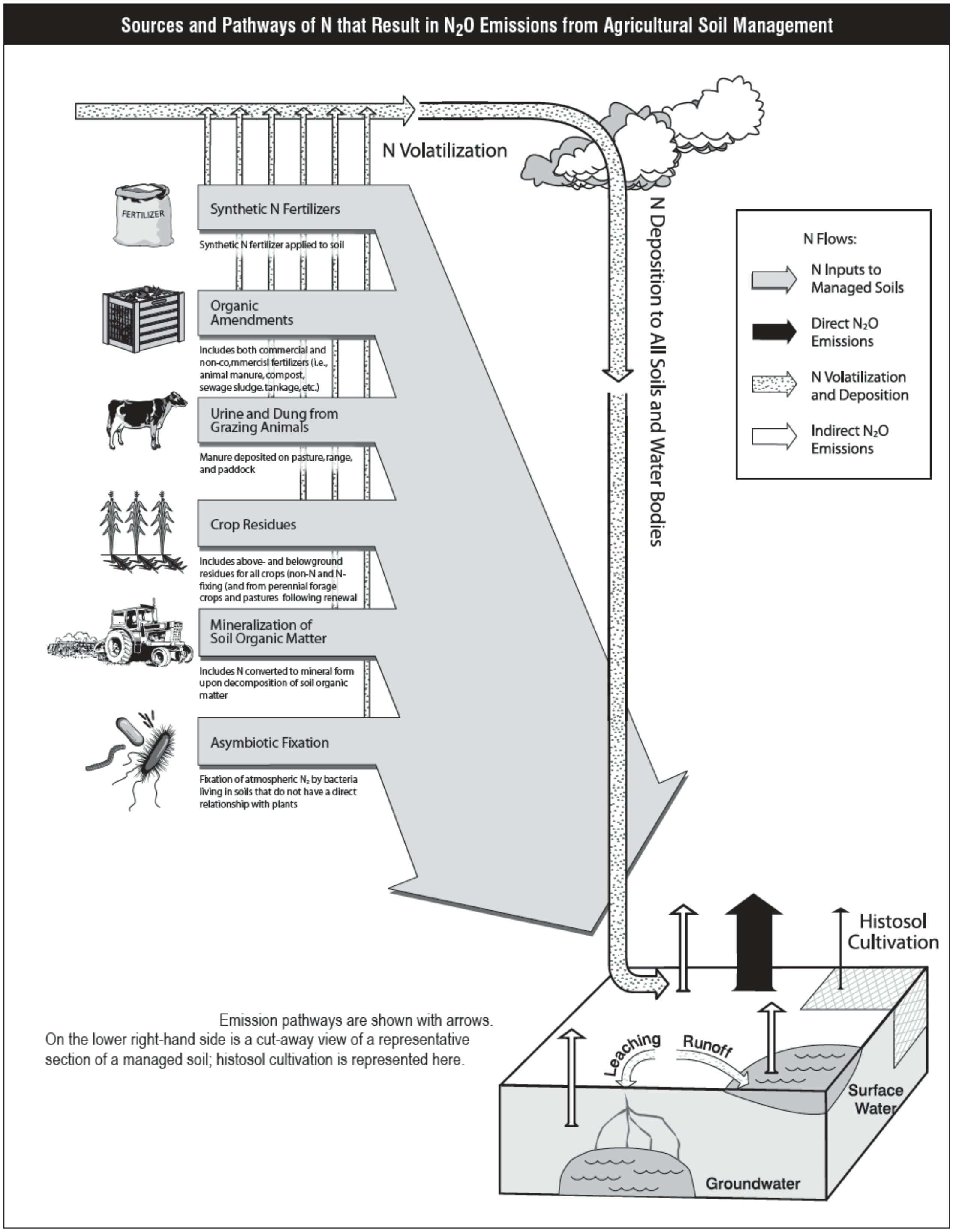
1.2 GHG Emissions from Crop Production Systems

Crop production systems can be both sources and sinks of GHGs, with the balance depending on a complex relationship of management practices, geographic region, and site-specific factors (e.g., weather conditions, soil type, proximity to surface and ground water bodies, topography). At the farm level, the following practices have overlapping and interacting effects on GHG emissions, particularly CO_2 and N_2O: tillage system, the timing of tillage and other field operations, residue management, crop selection and rotation, and the amount and timing of nutrient applications and other soil amendments. Cropland sources of CH_4 emissions include rice cultivation and the burning of agricultural residues. The sections below present the major sources of N_2O, carbon storage, and CH_4 emissions.

Nitrous Oxide (N_2O) Emissions

Cropland systems produce both direct and indirect N_2O emissions. Direct N_2O emissions come from cultivated soils and fertilized and/or grazed grasslands. Indirect emissions result when nitrogen is transported via runoff from agricultural systems into ground and surface waters, or when nitrogen is emitted as ammonia or nitrogen oxides and deposited elsewhere (Smith et al., 2006). Exhibit 1-4 provides a diagram of the sources of N_2O emissions from agricultural soil management. N_2O emissions from crop nutrient management practices depend on many factors, but two key factors are the quantity of nitrogen applied and the efficiency with which it is taken up by plants.

Exhibit 1-4: Sources and Pathways of Nitrogen that Result in N_2O Emissions from Agricultural Soil Management

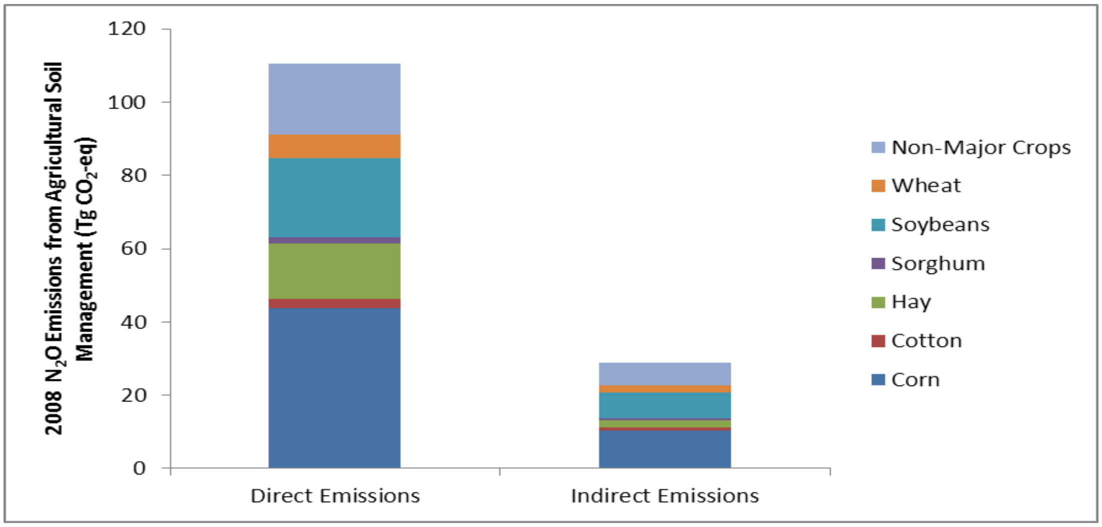


Emission pathways are shown with arrows. On the lower right-hand side is a cut-away view of a representative section of a managed soil; histosol cultivation is represented here.

Source: EPA (2011).

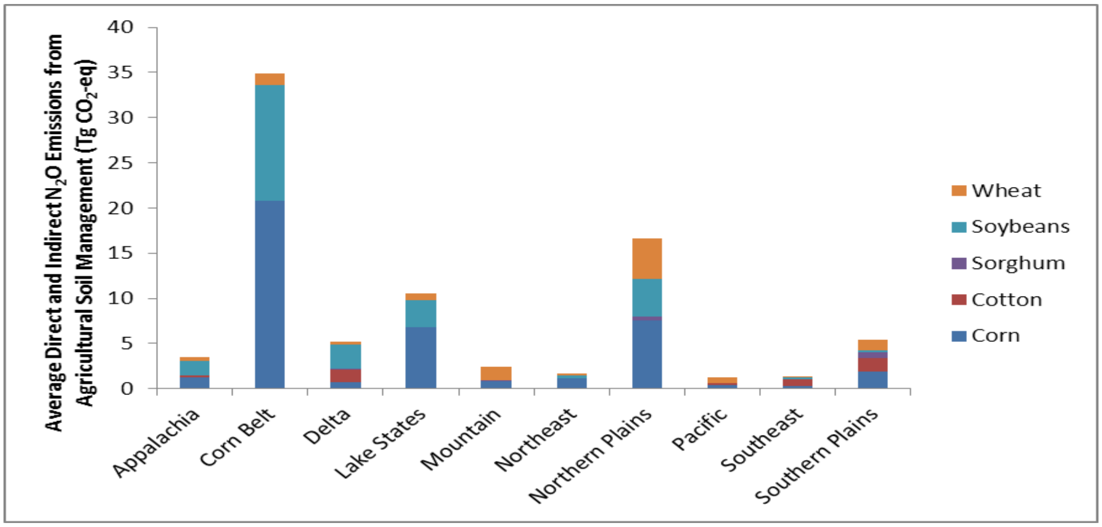
Total N_2O emissions (direct and indirect) produced from major and non-major crops in 2008 were approximately 140 million mt CO_2-eq (USDA, 2011), emissions from major crops (corn, cotton, hay, sorghum, soybeans, and wheat) were approximately 114 million mt CO_2-eq, and those from non-major crops were 26 million mt CO_2-eq (USDA, 2011). Exhibit 1-5 presents the 2008 emissions from major crops, broken out by crop type and direct vs. indirect emissions. Non-major crops are included in Exhibit 1-5 for illustrative purposes, but the remainder of this report focuses on emissions reductions related to major crop production. Exhibit 1-6 presents the average N_2O emissions from 2002–2007 by region and major crop type (EPA, 2011; Ogle, 2011b). As indicated in Exhibit 1-6, the majority of emissions are from the Corn Belt, Northern Plains, and Lake States.

Exhibit 1-5: Direct and Indirect N_2O Emissions from the Production of Major and Non-Major Crops in 2008[a]



[a] Major crop and non-major crop estimates are based on USDA GHG Inventory data (USDA, 2011).

Exhibit 1-6: Average (2002–2007) N_2O Emissions (Direct and Indirect) from Major Crop Production by Region[a]

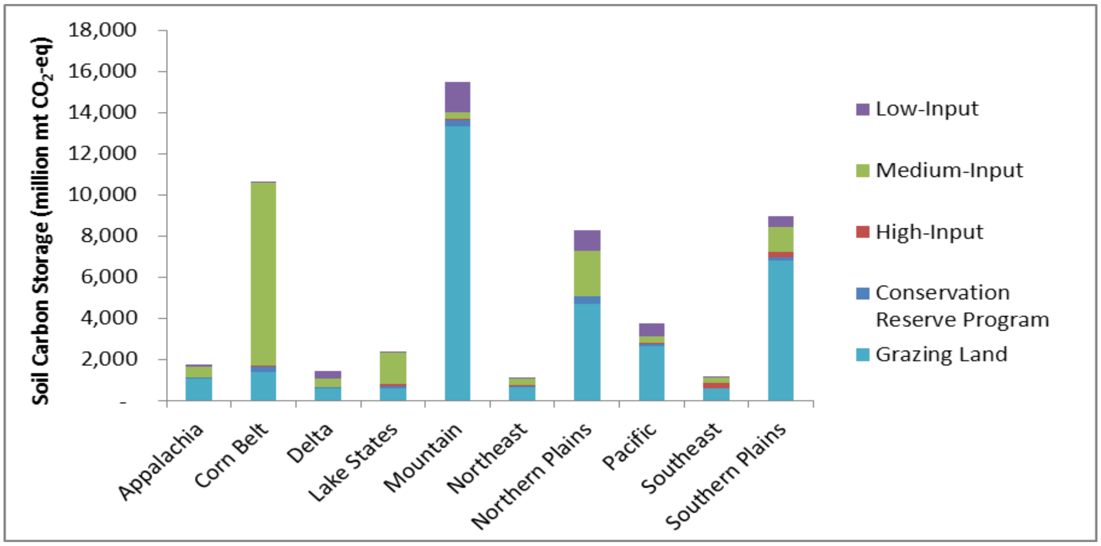


[a] Major crop estimates based on DAYCENT model output assuming synthetic, manure, and other nitrogen applications by region as this is the latest data. Estimates of non-major crops were not available by region.
Source: Ogle (2011b).

Carbon Storage

The rate at which soil organic carbon (SOC) is sequestered is influenced by a number of biological factors, including carbon inputs from plant residues (above- and below-ground), manures, and root exudates, as well as outputs from plant root respiration, nitrogen-fixing bacteria and mycorrhizal fungi, respiration from soil biota, and soil erosion and leaching. The rate at which SOC is lost from the soil is influenced by the chemical composition of the organic matter, soil attributes (e.g., percentage of clay), soil temperature and moisture, the abundances of soil biota, and the availability of nutrients (Christoffersen, 2011). Exhibit 1-7 illustrates the carbon stock for different input categories by region based on output from the CENTURY model, a biogeochemical model that uses data on monthly land use and management, along with weather and soil physical data, as inputs to simulate the dynamics of carbon and other elements.[5] The carbon stock values presented in Exhibit 1-7 include the following: (1) high-input land (e.g., irrigated cropland, annual crops in rotation with hay or pasture); (2) low-input land, which represents annual crop rotations with bare summer fallow, and/or annual crop rotations with cotton; (3) medium-input land, which represents all other rotations (i.e., wheat, corn, and soybeans); (4) the Conservation Reserve Program, where marginal land is set aside from crop production;[6] and (5) grazing land. Exhibit 1-8 is a companion graphic that illustrates the acreage by input category shown in Exhibit 1-7.

Exhibit 1-7: Soil Carbon Storage by Region and Input Category



Source: Ogle (2011a).

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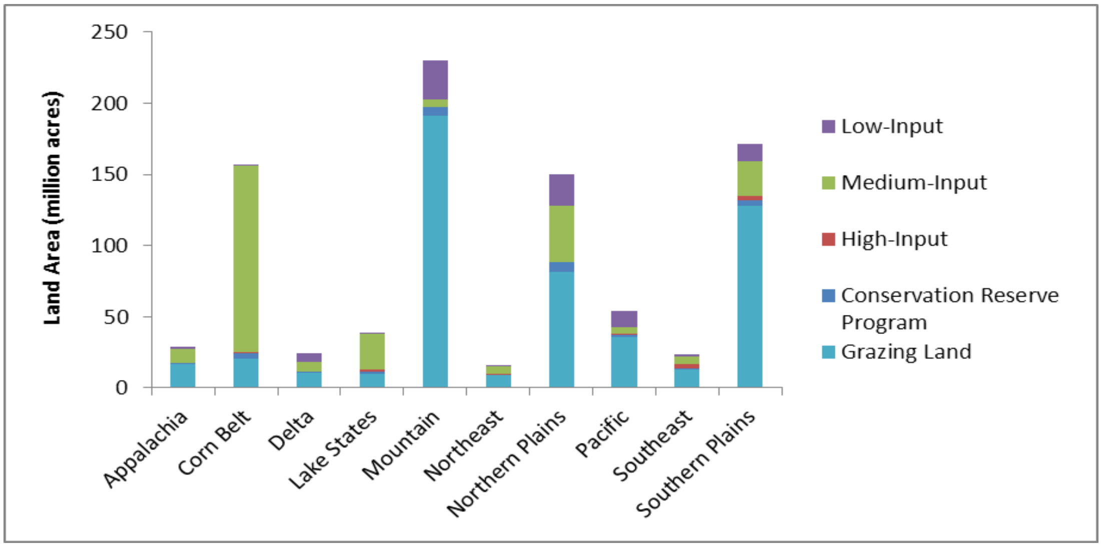
[5] For more information on the CENTURY model, see http://www.nrel.colostate.edu/projects/century5.

[6] The Conservation Reserve Program is a voluntary Farm Bill-derived USDA program that encourages farmers to convert highly erodible cropland or other environmentally sensitive areas to conservation vegetation, such as introduced or native grasses, trees, filter strips, or riparian buffers (Liebig et al., 2012).

Exhibit 1-8: Acreage by Input Category



High-input includes irrigated cropland, annual crops in rotation with hay or pasture.
Medium-input represents all other rotations (i.e., wheat, corn, and soybeans).
Low-input includes annual crop rotations with bare summer fallow, and/or annual crop rotations with cotton.
Source: Acreage values are based on estimates prepared for the 2007 U.S. Inventory of Greenhouse Gas Emissions and Sinks (Ogle, 2011a).

Methane (CH_4) Emissions

Methane emissions from cropland are primarily from rice cultivation and field burning of agricultural residues. Exhibit 1-9 presents 2008 methane emissions from rice cultivation (including emissions from primary and ratooned[7] crops), as well as from field burning of agricultural residues (See USDA, 2011). While crop residues are burned in all regions of the country except New England, more than 50% of GHG emissions associated with residue burning occur in the Southeast, the Great Plains, the Pacific Coast, and the Southwest. In general, crop residue burning is not a major residue management strategy in the United States.

Exhibit 1-9: Methane Emissions from Rice Cultivation and Agriculture Burning in 1990, 2000, and 2008

Source	Methane Emissions (million mt CO_2-eq)		
	1990	2000	2008
Rice Cultivation (Primary and Ratooned)	7.1	7.5	7.2
Field Burning of Agricultural Residues	0.77	0.89	0.97

Source: USDA (2011).

1.3 GHG Emissions from Animal Production Systems

Over the period 1990–2008, livestock sources accounted for a little more than half of all agriculture-related emissions in the United States. Enteric fermentation from ruminant livestock, managed livestock waste, and grazing land management are the largest sources of GHG emissions associated with livestock production. In 2008, emissions from these sources totaled 268 million mt CO_2-eq (USDA, 2011); however, they were

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[7] Ratooning a rice crop refers to the cultivation of two rice crops per season. The second crop is grown from the stubble of the first harvest by applying fertilizer and water after the crop has been harvested (Livezey and Foreman, 2004). This typically occurs in Arkansas, Florida, Louisiana, and Texas (USDA, 2011).

offset by carbon sequestration in grazing lands, resulting in net GHG emissions of 236 million mt CO_2-eq. Exhibit 1-10 provides a breakdown of these emissions by source of emissions, gas, and animal type.

Exhibit 1-10: GHG Emissions from Animal Production Systems in 2008

Animal Type	GHG Emissions (million mt CO_2-eq)								
	Enteric Fermentation	Managed Livestock Waste			Grazing Land[a]				Net Emissions[b]
	CH_4	CH_4	N_2O	Total	N_2O	CH_4	CO_2	Total[a]	
Beef Cattle	100.77	2.47	7.44	9.91	51.9	1.97	-26.4	27.47	138.15
Dairy Cattle	33.09	19.43	5.48	24.91	1.68	0.05	-0.85	0.88	58.88
Swine	3.59	19.58	1.65	21.23	0.20	0.01	-0.10	0.11	24.93
Horses	1.00	0.82	0.41	1.23	6.92	0.76	-3.52	4.16	6.39
Poultry	0.00	2.63	1.77	4.40	0.12	0.01	-0.06	0.07	4.47
Sheep	2.12	0.08	0.34	0.42	0.51	0.04	-0.26	0.29	2.83
Goats	0.27	0.02	0.02	0.04	0.39	0.02	-0.20	0.21	0.52
Total	**140.8**	**45.0**	**17.1**	**62.1**	**61.7**	**2.85**	**-31.4**	**33.15**	**236.05**

[a] This category is defined as Grazed Lands in the USDA GHG Inventory (USDA, 2011). The terms "Grazed Lands" and "Grazing Lands" are assumed to be equivalent in this report.
[b] Carbon sequestration is shown as negative in this table. Total from Grazing Lands includes impact of carbon sequestration.
Note: Columns may not add up correctly due to independent rounding.
Source: USDA (2011).

GHG Emissions from Manure Management Systems

In 2008, emissions related to livestock waste management were 62 million mt CO_2-eq, or about 26% of total emissions from livestock sources. In 1990, this value was 18%. The increase in waste management's share of livestock-related emissions is attributable to ongoing shifts in dairy, beef, and swine manure management practices from solid daily spread to liquid lagoons.

Among livestock types, dairy cattle and swine accounted for 40% and 34%, respectively, of GHG emissions related to manure management; about 74% of these emissions were methane and the balance was nitrous oxide. Manure management emissions from beef cattle totaled 10 million mt CO_2-eq of which 75% was nitrous oxide and the balance methane. Collectively, beef cattle, dairy cattle, and swine account for more than 90% of all emissions related to manure management. The remaining 10% (about 6.1 million mt CO_2-eq in 2008) was related to poultry, sheep, horses, and goats.

The amount of methane and nitrous oxide generated from manure management practices depends on the animal type, animal diet, and practice (i.e., the same quantity of manure will generate different methane emissions as the management practice defines the emission rate). The livestock type and diet will determine the volatile solids (VS) content of the manure excreted; VS[8] is the portion of the manure from which methane is generated. The left column of Exhibit 1-11 illustrates the distribution of total VS excreted by animal type and manure management practice. The center and right columns illustrate the distribution of total CH_4 emissions and total N_2O emissions, respectively, by both type of animal and manure management practice.

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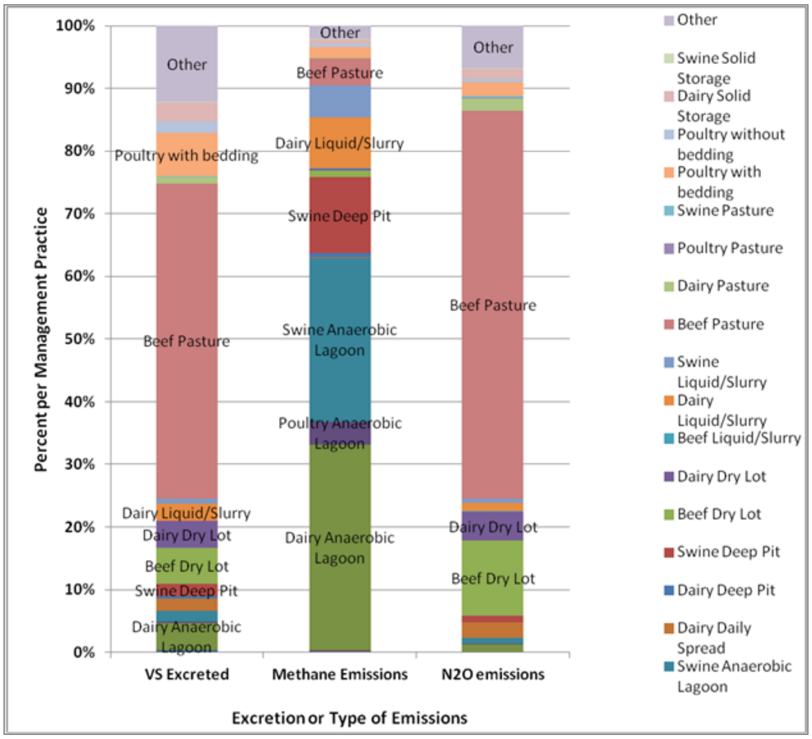
[8] Volatile solids content of manure is the fraction of the diet consumed by an animal that is not digested and thus excreted as fecal material; fecal material combined with urinary excretions constitutes manure (EPA, 2011).

Exhibit 1-11: Distribution of Volatile Solids Excreted and Methane and Nitrous Oxide Emissions, by Manure Management Practice[9]



Source: Based on data obtained from EPA (2010).

GHG Emissions from Enteric Fermentation

Enteric fermentation is a process through which microbes present in the digestive tract of livestock break down ingested feed, emitting methane as a byproduct. Ruminant animals, such as cattle, sheep, and goats, have digestive systems that produce more methane than those of non-ruminant animals. Animal type, quantity and quality of the feed source, additives, and other factors influence methane emissions from enteric fermentation. As indicated in Exhibit 1-10, methane emissions in 2008 from enteric fermentation in the United States were 141 million mt CO_2-eq (i.e., more than half of the emissions from animal production systems). More than 70% of these emissions were from beef cattle and more than 95% were from beef and dairy cattle.

GHG Emissions from Grazing Lands

Nitrous oxide emissions on grazing land are largely influenced by fertilizer application, nitrogen fixing legumes, and livestock manure (feces and urine) deposits. Increased soil compaction and anaerobic environments caused by livestock treading on soil can affect the rate of nitrification and denitrification, along with the N_2O emissions associated with these processes (Paustian et al., 2004). In 2008, grazing lands emitted approximately 62 million mt CO_2-eq of N_2O and 3 million mt CO_2-eq of CH_4, and sequestered about 31 million mt CO_2-eq. Grazing lands contributed GHG emissions of 33 million mt CO_2-eq, with N_2O contributing the greatest emissions. Direct N_2O emissions are a result of beef cattle production on grazing lands (primarily in Texas and Oklahoma) (USDA, 2011).

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[9] Management practices, as defined in U.S. GHG Emissions and Sinks: 1990–2008 (EPA, 2010), see Appendix 3-B.

1.4 Overview of Crop Production

As indicated in Exhibit 1-12, more than 1.3 million farms in the United States engage in crop production. Viewed by region, U.S. crop production is centered in the middle of the country. The Corn Belt has the largest number of farms with crops (i.e., 283,975 farms) and the most harvested acres (i.e., 81.5 million acres) of all USDA production regions. Collectively, the Corn Belt, Lake States, and the Great Plains account for 53% of all farms with crops and 71% of all harvested acres. Crop production in the Eastern United States is characterized by mostly smaller farms. Collectively, the Northeast, Appalachia, and Southeast regions have about 28% of farms with crops, but account for less than 12% of all harvested acres.

Exhibit 1-12: Farms and Acres Harvested by USDA Production Region and Farm Size

By USDA Production Region

USDA Production Region	Farms	Land Area Harvested (millions of acres)
Appalachia	186,680	16.7
Corn Belt	283,975	81.5
Delta	61,606	14.9
Lake States	145,916	35.0
Mountain	80,023	24.1
Northeast	109,678	10.9
Northern Plains	120,578	75.4
Pacific	101,690	15.2
Southeast	79,963	9.0
Southern Plains	157,895	26.8
Total	**1,328,004**	**309.6**

By Farm Size

Farm Size (acres)	Farms	Land Area Harvested (millions of acres)
1 to 9	91,191	0.3
10 to 49	298,858	4.3
50 to 69	88,505	2.5
70 to 99	117,021	4.5
100 to 139	109,554	5.8
140 to 179	88,133	6.6
180 to 219	60,334	5.6
220 to 259	48,977	5.7
260 to 499	159,319	30.4
500 to 999	121,080	51.6
1,000 to 1,999	78,927	69.8
2,000 or more	66,105	122.5

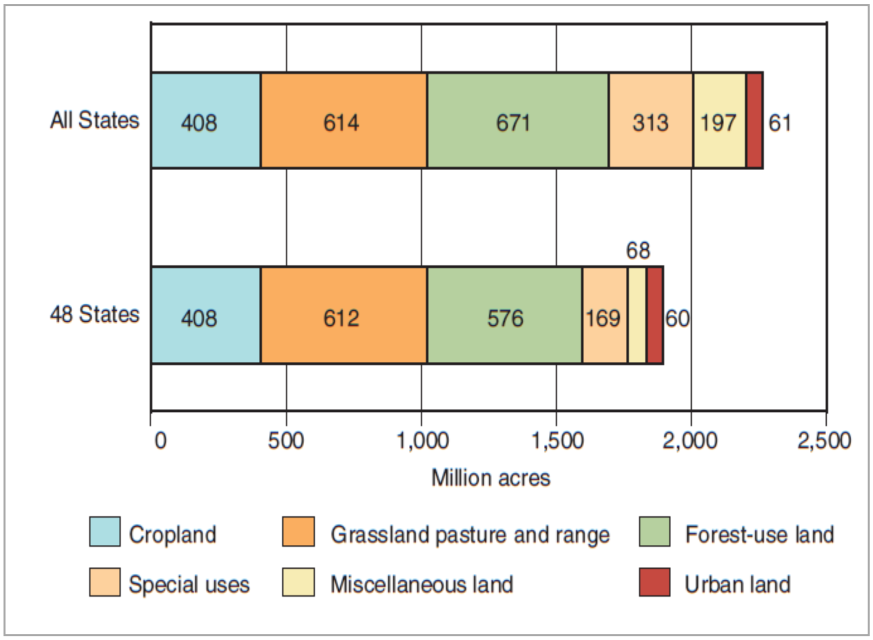
Source: USDA NASS (2008).
Note: Land area harvested only includes the acres of harvested cropland in the United States.

Smaller operations account for the majority of farms with crops nationwide, but larger operations account for the majority of acres harvested. Almost 30% of farms with crops have fewer than 100 acres harvested and more than 50% have fewer than 140 acres. This 50 percent, however, accounts for about 5% of all harvested acres. By contrast, farms with more than 1,000 harvested acres account for about 11% of all farms with crops, but more than 62% of all harvested acres

Exhibit 1-13 illustrates the major uses of land in relation to the total U.S. land base, and Exhibit 1-14 illustrates major uses of land, by State, for the contiguous 48 States in 2007 based on data from the USDA ERS Major Uses of Land report (Nickerson et al., 2011). The United States has a land area of approximately 2.3 billion acres. USDA divides this land into cropland, grassland pasture and range, forest-use land, and special uses (USDA, 2011). With more than 1 billion acres in cropland and grassland pasture or range, the management of this land has the potential to significantly affect U.S. GHG emissions.

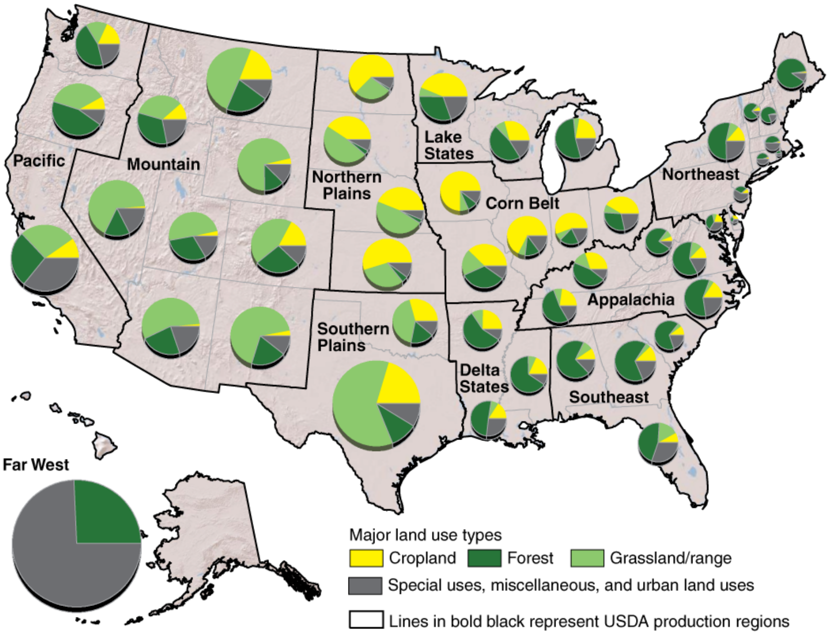
Exhibit 1-14 shows the highest concentrations of cropland are in the Lake States, Northern Plains, Southern Plains, and Corn Belt regions; the highest concentrations of pasture and range are in the western States and Texas.

Exhibit 1-13: Total U.S. Land Base by Major Uses of Land



Adapted from Nickerson et al. (2011).
Note: USDA NASS (2008) estimates 922 million acres of "land in farms," while USDA ERS, Nickerson et al. (2011) indicates 1.16 billion acres of land for *agricultural purposes* (i.e., cropland, grassland pasture and range, forestland grazed, land in farmsteads, and farm roads and lands). Miscellaneous other land, urban land, and special uses are not included in the 1.16 billion acre estimate. The difference between the USDA NASS "land in farms" value and the USDA ERS "land for agricultural purposes" is due primarily to USDA ERS inclusion of forested and non-forested grazing land.

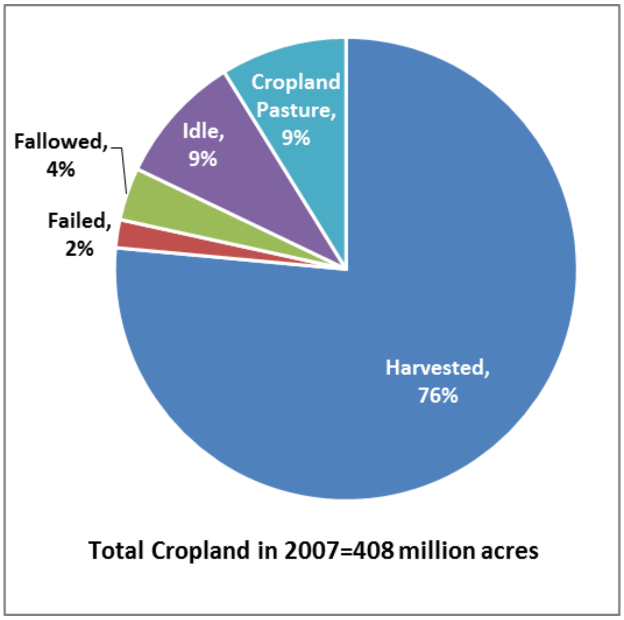
Exhibit 1-14: Shares of Land in Major Uses by State, 2007



Note: The size of the pie charts is proportional to the land area in each State. The special uses, miscellaneous, and urban land uses area categories were too small to effectively illustrate separately.
Source: Nickerson et al. (2011).

The USDA ERS (2011) divides cropland into cropland harvested, crop failure, cultivated summer fallow, cropland pasture, and idle cropland (see Exhibit 1-15). In 2007, 82% of the U.S. cropland based in the United States (i.e., 335 million acres) was used for crop production. The remaining nearly 18% (i.e., 73 million acres) were idle or in cropland pasture (Nickerson et al., 2011). Exhibit 1-16 shows crop production by acres harvested and percentage change in harvested acres for the period 1981–2007. Corn acreage was the largest in 2007, followed by soybeans, hay, and wheat. Collectively, these four crops accounted for 86% of total harvested acres in the United States in 2007. Wheat acreage declined by nearly 30% between 1981 and 2007. The reduction in wheat acres is due to the development of new corn and soybean seed varieties that led to the expansion of these crops into parts of the Great Plains States where wheat had been the primary crop.

Exhibit 1-15: Major Uses of Cropland for 2007



Source: Adapted from Nickerson et al. (2011).

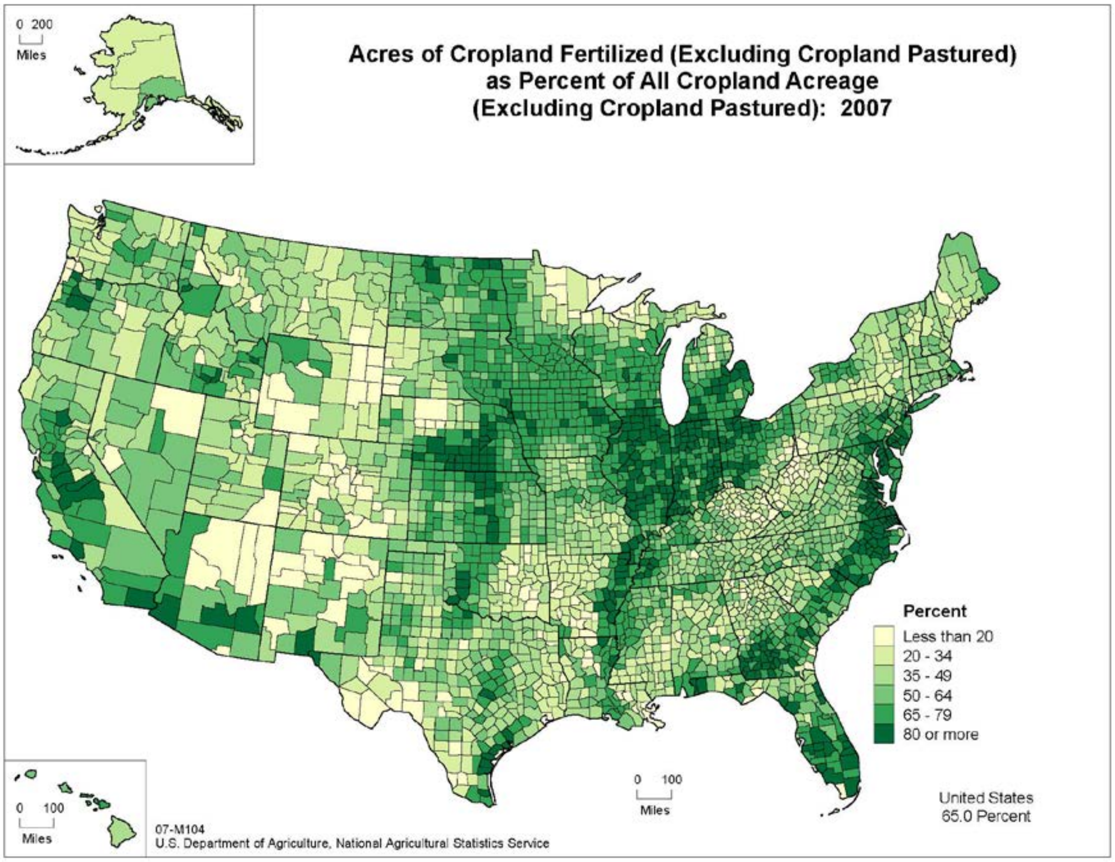
Exhibit 1-16: Principal U.S. Crops Harvested and Trends from 1981–2007

Crop	Harvested Crop in 2007 (million acres)	Percent Change from 1981–2007	Crop	Harvested Crop in 2007 (million acres)	Percent Change from 1981–2007
Food Crops			**Feed Crops**		
Wheat	51.0	-29.6%	Corn, All	92.6	9.4%
Soybeans	64.1	-2.1%	Sorghum, All	7.2	-8.3%
Rice	2.7	-1.1%	Oats	1.5	-7.9%
Rye	0.3	-0.5%	Barley	3.5	-5.5%
Peanuts	1.2	-0.3%	Hay	61.0	1.4%
Sunflowers	2.0	-1.8%	**Total Feed Crops**	**165.8**	**-10.9%**
Dry edible beans	1.5	-0.7%	**Other Crops**		
Dry edible peas	0.8	0.7%	Cotton	10.5	-3.3%
Potatoes	1.1	-0.1%	Flaxseed	0.3	-0.3%
Sweet Potatoes	0.1	0%	Tobacco	0.4	-0.6%
Sugar Beets	1.2	0%	**Total Other Crops**	**11.2**	**-4.2%**
Sugarcane	0.9	0.2%	**Total for All Harvested Crops**	**303.9**	**-50.4%**
Total Food Crops	**126.9**	**-35.3%**			

Source: Nickerson et al. (2011).

Finally, Exhibit 1-17 shows the percentage of cropland acres that were fertilized by county in the United States in 2007. N_2O emissions from crop nutrient practices are the leading source of GHG emissions from agriculture, and several of the mitigation options discussed in this report target changes in nutrient management practices. The highest application densities occur in the Great Plains, Corn Belt, Lake States, and Florida, and in bands in California's Central Valley and the East Coast south of New England.

Exhibit 1-17: Acres of Cropland Fertilized (Excluding Cropland Pastured) as Percentage of All Cropland Acreage (Excluding Cropland Pastured) in 2007



Source: USDA NASS (2008).

1.5 Overview of Beef, Dairy, and Swine Operations

The options considered in this report for reducing GHG emissions from livestock operations focus on managing manure on confined beef, dairy, and swine operations. This section provides overviews of these industries in the United States.

Exhibit 1-18 details the number of swine farms by farm size, and Exhibit 1-19 details the number of cattle by farm size. The majority of swine and beef farms are considered "small" operations, but "large" operations manage the majority of the country's swine and cattle (USDA NASS, 2008).

- **Swine.** Although farms with fewer than 100 head account for almost 70% of the country's swine operations, they manage less than 1% of the U.S. swine population. The majority of swine in the United States are contained in operations with more than 1,000 head. Large operations account for approximately 16% of swine farms, but more than 93% of the swine population.

- **Beef.** Farms with fewer than 20 head account for more than 50% of U.S. beef operations. Larger operations (100+ head) account for just 10% of beef cattle farms, but more than 50% of the beef cattle population. The distribution of head is fairly even (approximately 20%) across farm sizes, ranging from 20–49, 50–99, 100–199, and 200–499.
- **Dairy.** Farms with fewer than 50 head account for 49% of U.S. dairy farm operations, but only 7% of the U.S. dairy cow population (i.e., approximately 93% of the dairy population is on farms with more than 50 head). Dairy operations with more than 1,000 head account for approximately 3% of dairy farms, but 40% of the national dairy cow herd.
- **Cattle on Feed.** The profile of cattle on feed (i.e., those in feedlots) by farm size is similar to that of dairy and swine farms, with the majority of farms being small and the majority of head being on large farms. In particular, feedlots with fewer than 50 head account for 64% of operations and less than 3% of feed cattle, while feedlots with more than 2,500 head account for about 2% of operations, but 68% of the cattle on feed population.
- **Other Cattle.** As indicated in Exhibit 1-19, this population is much more evenly distributed across farm sizes than are the other cattle types.

Exhibit 1-18: Number of Swine by Farm Size

Farm Size (No. of Head)	Swine			
	Number of Farms	Percentage of Farms	Total Number of Head	Percentage of Head
1 to 24	45,047	60%	260,154	0%
25 to 49	4,292	6%	146,672	0%
50 to 99	3,182	4%	215,206	0%
100 to 199	2,590	3%	354,203	1%
200 to 499	4,524	6%	1,467,383	2%
500 to 999	3,588	5%	2,488,234	4%
1,000 or more	12,219	16%	62,854,466	93%
Total	**75,442**	**100%**	**67,786,318**	**100%**

Source: USDA NASS (2008).

Exhibit 1-19: Number of Cattle by Farm Size

No. of Head	Farm Size (No. of Head)									
	1 to 9	10 to 19	20 to 49	50 to 99	100 to 199	200 to 499	500 to 999	1,000 to 2,499	2,500 or more	Total
Beef										
No. of Farms	246,863	160,005	200,840	84,253	43,575	23,635	4,413	1,215	185	764,984
Percentage of Farms	32%	21%	26%	11%	6%	3%	1%	0%	0%	
Total No. of Head	1,160,439	2,162,448	6,090,407	5,656,207	5,753,342	6,722,106	2,861,202	1,648,412	780,238	32,834,801
Percentage of Head	4%	7%	19%	17%	18%	20%	9%	5%	2%	
Dairy										
No. of Farms	14,426	3,568	16,344	18,986	8,975	4,307	1,702	1,104	478	69,890

No. of Head	Farm Size (No. of Head)									
	1 to 9	10 to 19	20 to 49	50 to 99	100 to 199	200 to 499	500 to 999	1,000 to 2,499	2,500 or more	Total
Percentage of Farms	21%	5%	23%	27%	13%	6%	2%	2%	1%	
Total No. of Head	38,147	48,821	576,070	1,280,983	1,180,985	1,278,721	1,161,865	1,673,772	2,027,210	9,266,574
Percentage of Head	0%	1%	6%	14%	13%	14%	13%	18%	22%	
Other Cattle[a]										
No. of Farms	0	147,914	155,011	72,829	40,703	27,467	9,344	4,122	1,650	459,040
Percentage of Farms	0%	32%	34%	16%	9%	6%	2%	1%	0%	
Total No. of Head	1,386,215	1,973,684	4,684,915	4,904,323	5,433,374	8,131,785	6,412,405	5,974,122	15,345,660	54,246,483
Percentage of Head	3%	4%	9%	9%	10%	15%	12%	11%	28%	
Cattle on Feed[b]										
No. of Farms	15,818	7,072	9,136	6,313	4,375	3,744	1,997	780	774	50,009
Percentage of Farms	32%	14%	18%	13%	9%	7%	4%	2%	2%	
Total No. of Head	65,809	93,242	280,083	426,159	586,624	1,118,788	1,429,215	1,152,679	10,946,311	16,098,910
Percentage of Head	0%	1%	2%	3%	4%	7%	9%	7%	68%	

Source: USDA NASS (2008).

[a] Other Cattle: In the 2007 census, data include heifers that have not calved, steers, calves, and bulls.

[b] Cattle on Feed: Cattle on feed are defined as cattle and calves that were fed a ration of grain or other concentrates that will be shipped directly from the feedlot to the slaughter market and are expected to produce a carcass that will be grade select or better. This category excludes cattle that were pastured only, background feeder cattle, and veal calves.

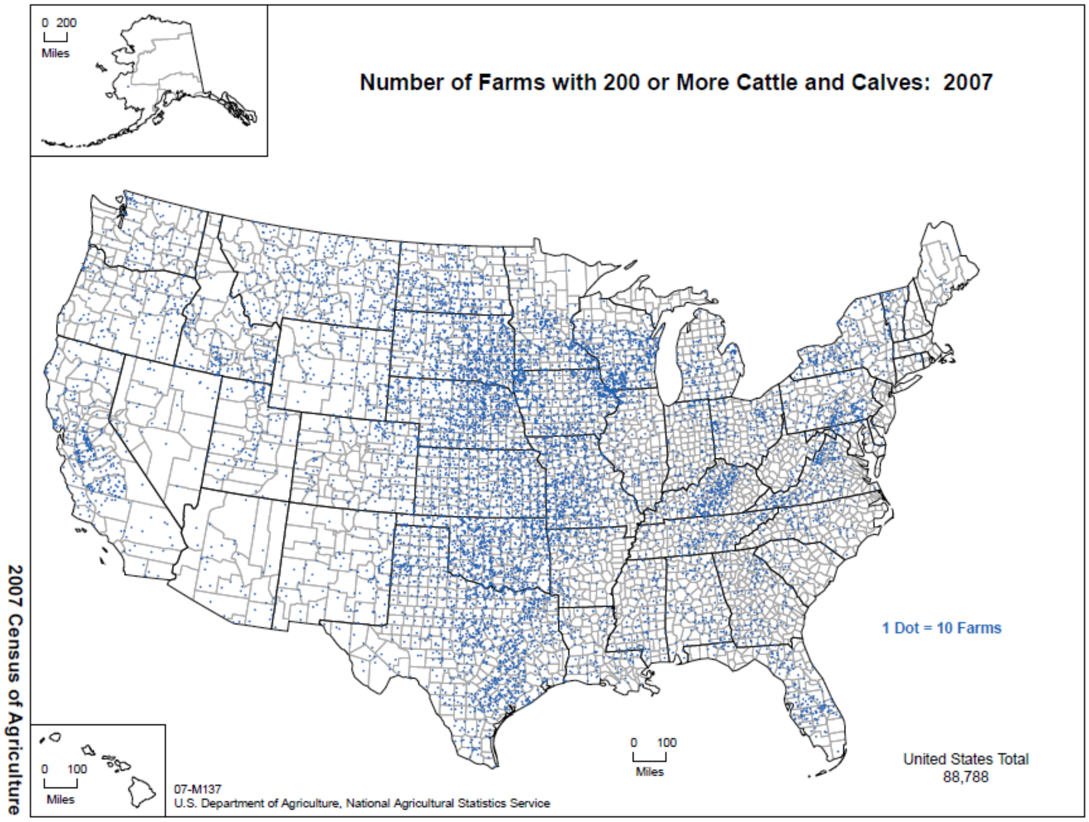
1.5.1 Beef Cattle Operations

Methane (CH_4) from enteric fermentation is the primary GHG produced by beef cattle. Feed intake and composition are linked strongly to the amount of emissions produced. For example, digestible energy (DE) in low-quality feed is less than that in high-quality feed; therefore, cattle will need to eat more low-quality feed in order to get the same amount of energy. Generally, cattle fed on relatively low-quality feed have greater enteric CH_4 emissions than those fed a higher quality feed. A number of studies indicate that increasing the ratio of grains (and other concentrates) to forage and increasing dietary fat content can decrease CH_4 emissions from enteric fermentation in beef cattle.

While CH_4 emissions per head of beef cattle have increased over the past few decades, CH_4 emissions per pound of beef produced have declined as a result of breeding cattle with more meat per animal. In 1975, there were 140.2 million beef cattle in the United States, which produced 54.7 billion pounds of beef (Mitloehner and Place, 2009). In 2008, 86.5 million beef cattle (EPA, 2012) were used to produce 54.2 billion pounds of beef (Mitloehner and Place, 2009). Hence, a 26% decrease in the beef cattle population coincided with a decrease in beef production of less than 1%. EPA's 1990–2010 U.S. GHG inventory indicates that the average beef cow's weight increased from 1,221 pounds in 1990 to 1,348 pounds by 2007. Simultaneously, the average CH_4 emissions per beef cow increased from 1.9 metric tons CO_2-eq per year to 2.0 metric tons CO_2-eq per year (EPA, 2012). A 10.4% increase in weight resulted in only a 6.4% increase in CH_4 emissions (from enteric fermentation) per beef cow (EPA, 2012).

Exhibit 1-20 presents a map of U.S. farms that contain 200 or more cattle and calves. Among the beef cow, dairy, and swine industries, beef cow operations are the most diffusely distributed across the country. The three largest producing regions (the Southern Plains, Northern Plains, and Mountain States) account for 55% of the national herd, while the three smallest producing regions (the Northeast, Lake States, and Pacific) account for 8.5%.[10] Feedlot operations are concentrated in the Great Plains, and parts of the Corn Belt, Southwest, and Pacific regions.

Exhibit 1-20: Inventory of U.S. Farms with 200 or More Cattle and Calves in the United States in 2007



Source: USDA NASS (2008).

The large majority of beef cattle in the United States are produced in three stages: cow-calf, backgrounding, and feedlot. Cow-calf operations raise calves from birth to weaning. Beef cows are typically kept on pasture year-round and fed little to no grain. Prior to weaning, calves increasingly graze and ultimately receive most of their nutrients from forage. At weaning, calves are 7–8 months old and weigh, on average, about 500 pounds. After weaning, some cattle are placed directly into feedlots (the final production stage), but the large majority pass through a stage called backgrounding, where they gradually gain weight over a period of several months to a year. In the backgrounding stage, animals are pastured (stockered), fed forage, and/or placed in dry lots and fed light-grain growing rations. Short yearlings spend 5–6 months in some combination of pasture and/or drylot, and generally enter a feedlot weighing 700–800 pounds.

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[10] Information on industry obtained from Matthews and Johnson (2011).

Long yearlings spend about a year on pasture and typically enter a feedlot weighing 800–900 pounds. Because of the cow-calf and backgrounding stages, the large majority of beef cattle spend most of their lives on pasture or range. During this time, animals gain an average of between 0.75 and 2.0 pounds per day, depending on the quality of the forage.

About 85% of beef cattle end up in feedlots[11] where they are fed "finishing" rations formulated to quickly bring them up to a slaughter weight of 1,000–1,400 pounds (these animals are called "fed cattle"). Finishing rations typically consist of 70–90% grain (or other sources of starch/energy), 10–15% forage (e.g., hay or silage), and 5% supplemental protein (e.g., soybean meal). Total dietary protein is provided not only by the supplement but also in small amounts from the starch and forage components, for a total dietary protein composition of approximately 10%. Generally, cattle are kept in a feedlot for about 150 days; however, the feeding period can vary from 90–300 days. During its stay in a feedlot, an animal will consume, on average, 4,000–4,300 pounds of feed and will gain 2.5–4.0 pounds per day.

1.5.2 Dairy Operations

CH_4 from enteric fermentation is the primary GHG produced by dairy cows (Phetteplace et al., 2001). Emissions are largely related to dietary composition and feed intake needs (e.g., lactating cows have higher energy requirements than non-lactating cows). Cows in intensive dairy production systems are usually fed high ratios of forages to concentrates. Feed types include corn silage, alfalfa or grass silage, alfalfa hay, ground or high-moisture shelled corn, soybean meal, fuzzy whole cottonseed, and sometimes commodity feeds (e.g., corn gluten, distillers grains, soybean hulls, citrus pulp, beet pulp). Dairy cows are fed diets that are balanced for their milk production level or stage of lactation.

Housing and manure management systems vary considerably throughout the country and can differ in a region and by the size of the herd. Tie stall (stanchion) barns limit the cows' mobility, as the cows are tethered in the stalls and are fed and milked in the stalls; a gutter is used to remove the manure by a barn cleaner, which typically places the manure directly into a manure spreader or in a temporary storage pile. Some freestall barns have slotted floors with long-term manure storage below the floors.

When manure has a lower solids content, it is typically stored in a tank or pit as a slurry, or transported to a solid–liquid separation system with the liquid fraction conveyed (pumped or by gravity) to a long-term storage pond. The solids can be dewatered naturally and reused as bedding, composted, land-applied, and/or sold. In open-lot systems, the manure in the pens is typically stacked; following storage, it is either land-applied or composted. Lot runoff is typically pumped to a storage pond. In pasture-based systems, manure is deposited directly onto the pasture and, therefore, not intensively managed, but may accumulate in areas where animals tend to congregate (e.g., watering areas, shade).

Exhibit 1-21 shows a map of the U.S. dairy herd. Milk production occurs in all 50 states, but is concentrated in the Lake States, the Northeast, and parts of California, the Northwest, Texas, and the Southwest. Over the last several decades, the U.S. dairy industry has experienced a steady increase in productivity—both in total milk output and output per cow—and a gradual decrease in the number of cows. Between 1970 and 2007, U.S. milk production increased almost 50%, while the national herd of milk cows declined from about 12 million to 9 million. The concurrent increase in total milk production and the decline in the national herd have been made possible by a large increase in per-cow milk production. In 1970, average milk production per cow was about 9,750 pounds per year. In 2007, this value was more than 20,000 pounds per year (USDA NASS, 2008).

The U.S. dairy industry has also experienced a decades-long contraction with respect to the number of dairy operations and an accompanying expansion with respect to the average size of a dairy operation. Between 1970 and 2007, the number of dairy operations fell from about 650,000 to about 70,000. Over this period, the average herd size increased from about 20 cows to more than 100 cows (USDA NASS, 2008).

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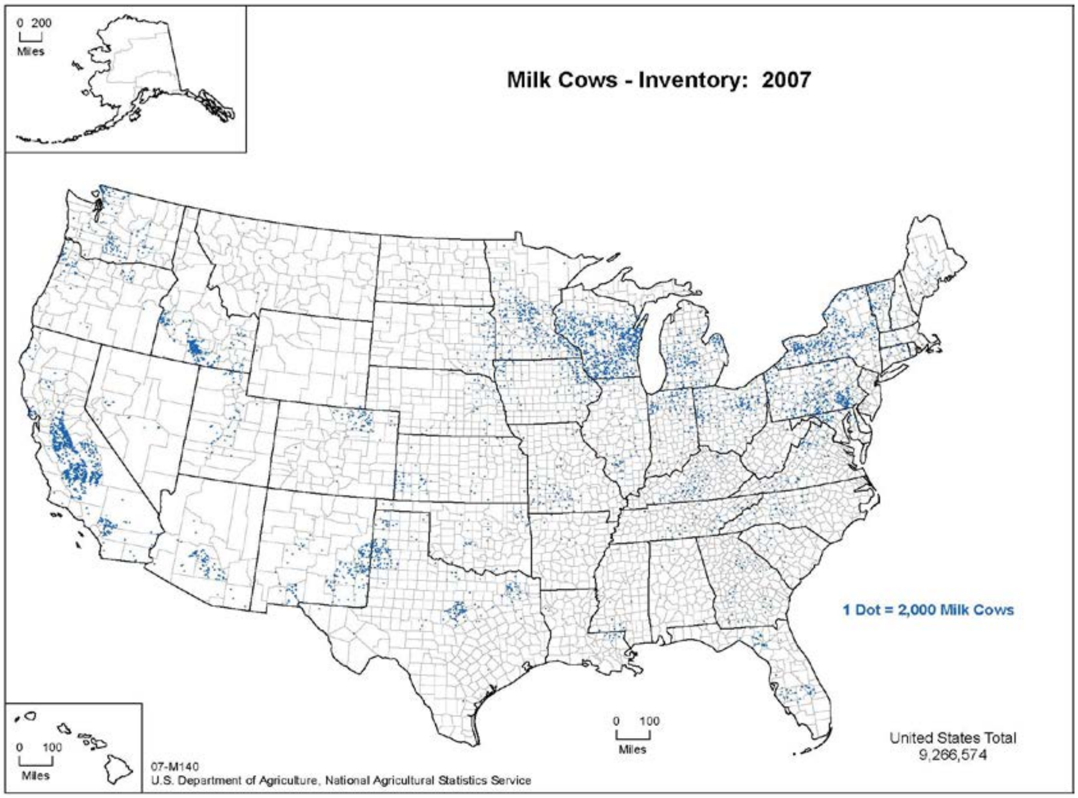
[11] Another 15% are "non-fed" cattle, consisting of culled beef, dairy cows, and bulls and other non-fed natural, grass-fed, and most organic cattle.

Exhibit 1-21: Inventory of Milk Cows in the United States in 2007



Source: USDA NASS (2008).

1.5.3 Swine Operations

GHG emissions from swine result primarily from manure management. Liu et al. (2011) analyzed factors that contribute to GHG emissions from swine production and found that animal housing and manure storage facilities were significant for CO_2 and CH_4 emissions but not for N_2O emissions. The geographic location of a swine operation was significant for CH_4 emissions, but was not significant for CO_2 and N_2O emissions. The swine category (the stage of production) was a significant factor for all three GHGs.

Exhibit 1-22 is a map of swine production in the United States. Swine production, which includes both hogs and pigs,[12] is concentrated in the Corn Belt (particularly Iowa), the Lake States (particularly southern Minnesota), and eastern North Carolina. Collectively, these areas account for about 76% of domestic swine production. Most swine are produced and raised in some type of confined animal facility. Typically, pregnant sows are kept in farrowing houses through gestation, birth, and weaning (a period lasting 18–19 weeks). On average, litters contain nine piglets and sows produce two litters per year. After weaning, piglets are placed in a nursery where they mature into feeder pigs weighing 10–60 pounds (about 6 weeks). Finally, they are transferred to a finishing facility where they are fed up to a slaughter weight of 240–270 pounds (about 16–20 weeks).[13]

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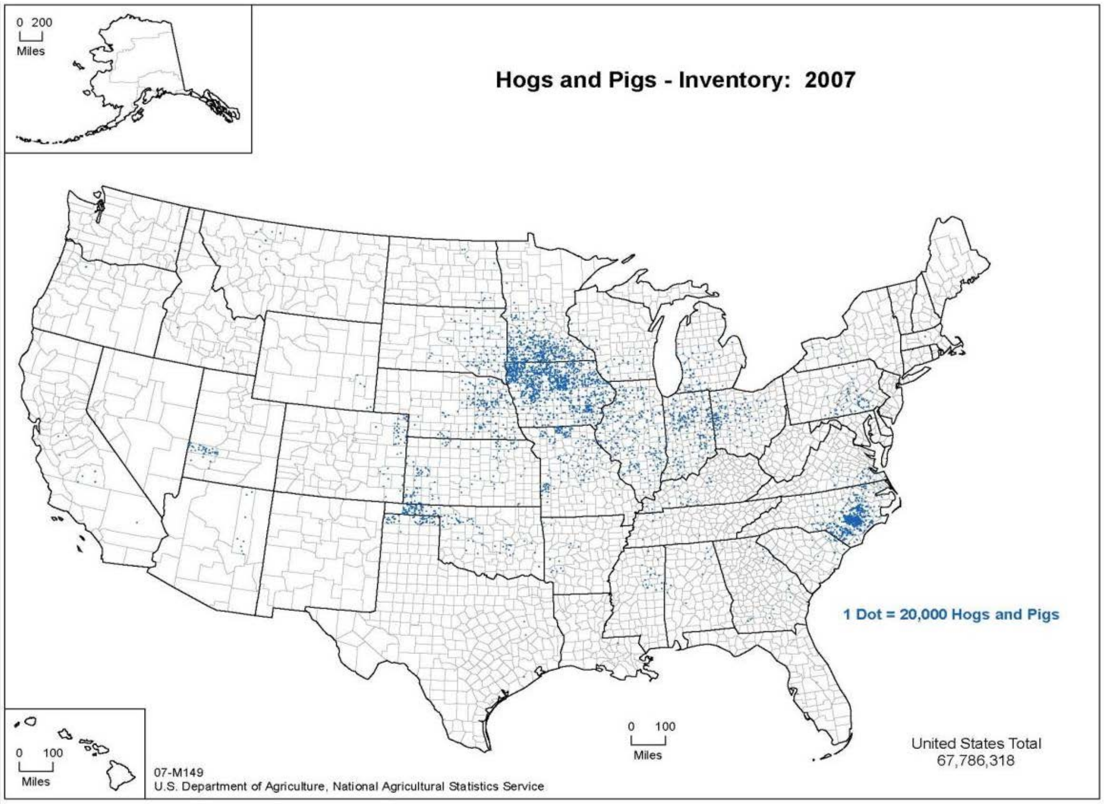
[12] Hogs are swine that weigh more than 120 pounds; pigs are young swine that weigh less than 120 pounds (USDA NASS, 2009).

[13] Information on industry obtained from USDA ERS (2007) and USDA NASS (2008).

Exhibit 1-22: Inventory of Swine in the United States in 2007



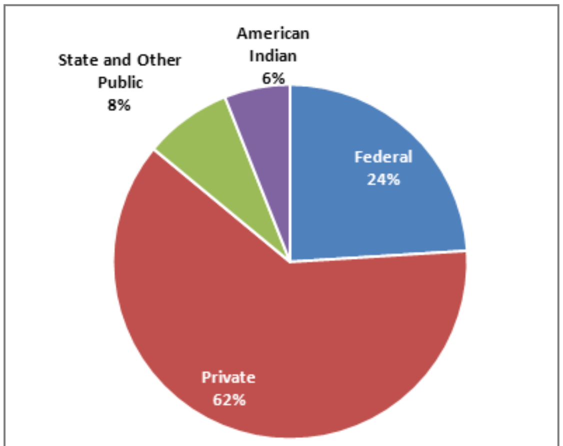
Source: USDA NASS (2008).

Since the early 1990s, the number of swine operations in the United States has decreased by more than 70%. With this contraction has come a trend toward larger, and often more specialized, operations. Three types of operations dominate swine production in the United States: (1) farrow-to-finish operations raise swine from birth to slaughter weight; (2) feeder pig operations raise pigs from birth to between 10 and 60 pounds; and (3) finishing operations raise feeder pigs to slaughter weight. Large operations tend to specialize in either the production of feeder pigs or the finishing of these animals to slaughter weight. The use of production contracts has increased in recent years as larger, vertically integrated operations are more likely to engage in contract production.

1.5.4 Characterization of U.S. Grazing Lands

Total grassland pasture and range (Federal and non-Federal) is estimated to be 612 million acres in the lower 48 States (Nickerson et al., 2011). The majority of this land (62%) is privately held (see Exhibit 1-23).

Exhibit 1-23: U.S. Grassland Pasture and Range[a] Ownership,[b] 2007



Total Grassland Pasture and Range in 2007=612 million acres

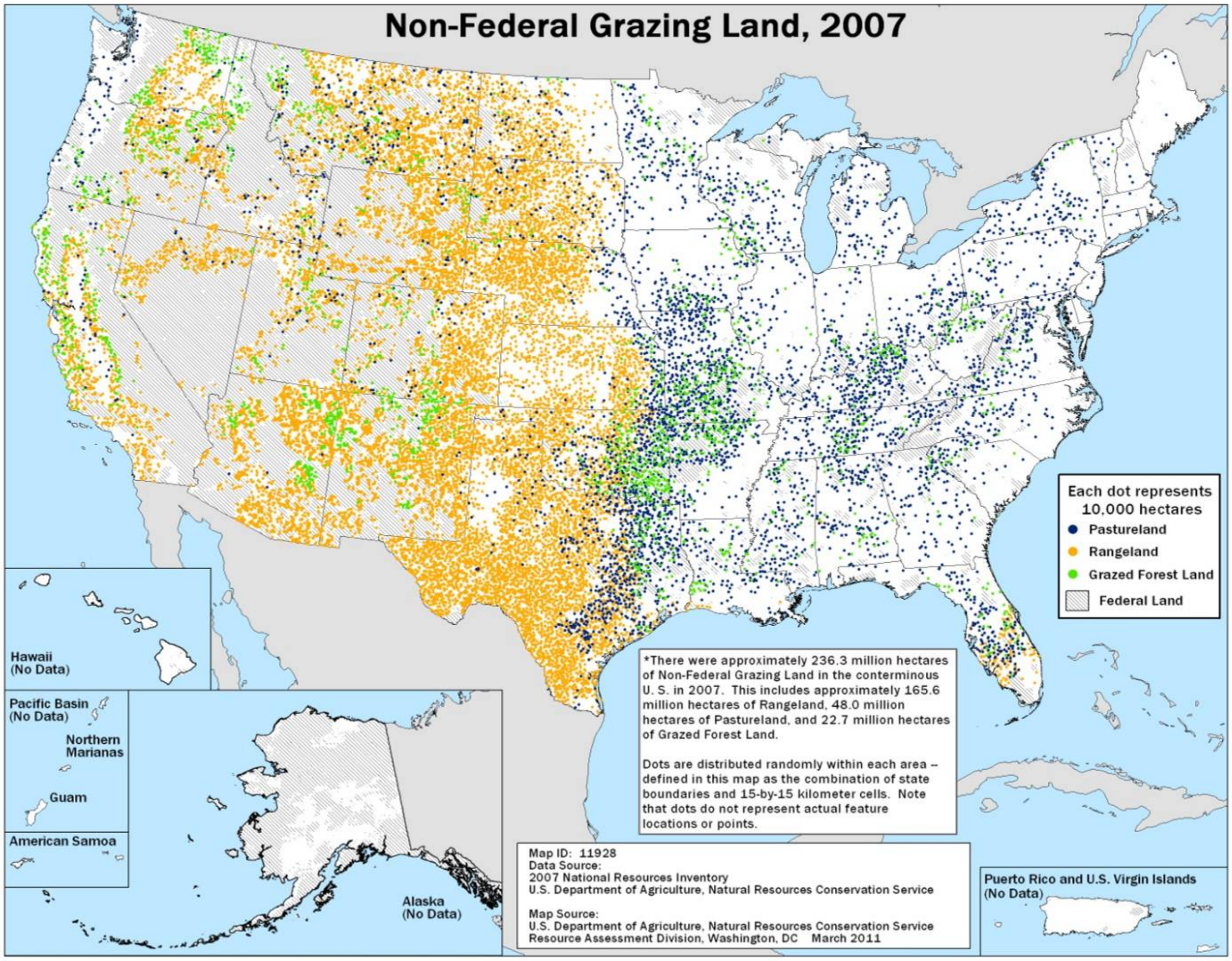
[a] Open permanent pasture and range, both in farms and not in farms, excluding cropland pasture.

[b] Federal includes reserved forestland in parks and other special uses.

Source: Nickerson et al. (2011).

Federal grazing lands include reserved forestland in parks and other special uses. Exhibit 1-24 shows the divisions and distribution of grazing land management in the United States for non-Federal grazing lands.

Exhibit 1-24: Distribution of Private Pastureland, Rangeland, and Grazed Forest Land[14] in the 48 Contiguous United States, 2007



*There were approximately 236.3 million hectares of Non-Federal Grazing Land in the conterminous U. S. in 2007. This includes approximately 165.6 million hectares of Rangeland, 48.0 million hectares of Pastureland, and 22.7 million hectares of Grazed Forest Land.

Dots are distributed randomly within each area -- defined in this map as the combination of state boundaries and 15-by-15 kilometer cells. Note that dots do not represent actual feature locations or points.

Map ID: 11928
Data Source:
2007 National Resources Inventory
U.S. Department of Agriculture, Natural Resources Conservation Service

Map Source:
U.S. Department of Agriculture, Natural Resources Conservation Service
Resource Assessment Division, Washington, DC March 2011

Source: Liebig et al. (2012).

1.6 Regulatory Issues Affecting the Adoption of GHG Mitigation Technologies and Practices

Existing Federal and State regulatory frameworks, as well as provisions of certain voluntary agricultural programs, may affect how agricultural producers, in given locations and circumstances, view specific incentives to adopt GHG mitigating technologies and practices. A comprehensive review of such legal frameworks is beyond the scope of this report. However, for illustration, this section highlights four such Federal laws and programs and how they may affect efforts to incentivize GHG mitigating activities in the farm sector. This discussion is limited to illustrating several key impacts; for a comprehensive understanding of impacts, individual

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[14] Grazed forestland consists mainly of forest, brush-grown pasture, arid woodlands, and other areas within forested areas that have grass or other forage growth. The total acreage of forested grazing land includes woodland pasture in farms plus estimates of forested grazing land not in farms (Nickerson et al., 2011).

producers should check with their State and/or regional EPA and NRCS offices to determine what laws and/or programs might be applicable to their particular situation. To provide a snapshot of how existing State laws and programs may affect farmers' views of GHG mitigation incentives, Appendix 1-C contains a table summarizing State-level regulations for controlling the disposal of animal manure.

Clean Water Act

Selected Regulations Potentially Affecting Farm-level Adoption of GHG Mitigating Activities

- Clean Water Act (CWA)
- Endangered Species Act (ESA)
- Clean Air Act (CAA)
- Conservation Reserve Program

The key purposes of the Clean Water Act (CWA) are to accomplish the following: (1) restore and maintain the chemical, physical, and biological integrity of the Nation's waters by addressing point and nonpoint pollution sources; and (2) maintain the integrity of wetlands (EPA, 2007a). A 1999 study by the U.S. Geological Survey demonstrated that the highest concentrations of nitrogen in U.S. surface and ground waters were correlated with nitrogen inputs from fertilizers and manure (Ribaudo et al., 2003). In some locations, incentivizing the adoption of GHG mitigating technologies and practices that reduce the quantity of nitrogen applied to fields and/or increase the share of applied nitrogen utilized by crops increases the likelihood that a given body of water is in compliance with the CWA (i.e., fishable and swimmable).

Concentrated Animal Feeding Operations (CAFOs) are defined as facilities that confine more than 1,000 animal units, or confine between 301 and 1,000 animal units and discharge pollutants into waters, and are determined to be a significant contributor of pollutants to U.S. waters (Ribaudo et al., 2003). These operations produce a variety of pollutants, including organic matter, urea, ammonia, nitrous oxide, phosphorus, methane, carbon dioxide, pathogens, antibiotics, and hormones (Aillery, 2005).

Agricultural Systems Potentially Affected by CWA

- Field and Tillage Operations
- Nutrient Management
- Cropland Retirement
- Manure Management
- Enteric Fermentation
- Land Retirement

CAFOs are the largest source of ammonia emissions in the United States (Aillery, 2005). Section 502 (14) of the CWA requires CAFOs to obtain a National Pollutant Discharge Elimination System (NPDES) permit and to develop and implement a nutrient management plan (NMP). The permit specifies a specific level of treatment for the effluent prior to its release. The NMP identifies site-specific actions to be taken by the CAFO to ensure proper and effective manure and wastewater management, including compliance with the Effluent Limitations Guidelines (EPA, 2003). Section 404 of the CWA requires a permit to discharge dredged or fill materials into the waters of the United States (including wetlands). Agricultural activities are generally exempt from Section 404, except for the conversion of wetlands to agricultural production (EPA, 2007b). In designing incentives to encourage livestock operations to adopt GHG mitigation practices and technologies (particularly those dealing with manure management), there may be opportunities to enable farms to go beyond meeting the minimum nutrient management plan goals required under the CWA.[15]

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[15] Other water-related Federal regulations could affect how farmers in specific circumstances view GHG mitigation incentives. These regulations include the Swampbuster provisions of the Food Security Act of 1985 (administered by USDA's NRCS) and EPA's Total Maximum Daily Loads (TMDLs). The Swampbuster provisions allow USDA to deny certain agricultural program benefits to farmers who convert non-exempt wetlands to cropland without developing an approved wetlands conservation plan (Salzman and Thompson, 2007). In some States, where EPA has determined that impaired waters exist, TMDLs are established to address water quality standards. Farmers may have to implement agricultural best management practices to achieve TMDL allocations (EPA, 2007b).

Endangered Species Act

Systems Potentially Affected by ESA

- Field and Tillage Operations
- Nutrient Management
- Land Retirement
- Grazing Land Management

The purposes of the Endangered Species Act (ESA) include conservation of ecosystems on which species designated as threatened or endangered with extinction depend, and conservation and recovery of such species to levels such that they no longer require the protections of the Act. In some instances (e.g., endangered animal species on private lands and any endangered species on Federal lands), the ESA has the potential to restrict how farmers and ranchers manage land, water, and chemical resources otherwise used for commodity production. GHG mitigation incentives will likely target changes in the management of these same resources. Farmer response to GHG mitigation incentives will be much more favorable if they include protections against applications of the ESA resulting from their adoption of GHG mitigating technologies and practices.

Clean Air Act

The Clean Air Act (CAA) was passed to "protect human health, welfare and the environment by maintaining and improving the quality of the air" (EPA, 2007b).The degree of regulation resulting from the CAA will vary depending upon whether landowners are in air non-attainment areas. Those in non-attainment areas could be subject to regulations in the State Implementation Plans (SIPs), which vary based on air quality issues in that area (EPA, 2007b). EPA recently developed regulations for reducing fine particulates in the atmosphere (PM2.5 for particles less than 2.5 microns in size). In some locations, this regulation could affect CAFOs, as they are a significant source of ammonia—a major precursor of fine particles (Aillery, 2005).

Conservation Reserve Program

The Conservation Reserve Program (CRP) provides technical and financial assistance to agricultural landowners to help them reduce soil erosion, protect the Nation's ability to produce food and fiber, reduce sedimentation in streams and lakes, improve water quality, establish wildlife habitat, and enhance forest and wetland resources. Landowners voluntarily contract to convert highly erodible cropland or other environmentally sensitive acreage to vegetative cover—such as tame or native grasses, wildlife plantings, trees, filter-strips, or riparian buffers—in exchange for an annual rental payment and cost-share assistance to establish the vegetative covers. CRP contracts are 10 to 15 years in duration.

When lands are placed in the CRP, the associated changes in land uses and production practices generally yield GHG mitigation benefits. These benefits include increased carbon sequestration in soils and biomass, decreased N_2O emissions due to lower nitrogen fertilizer use and reduced field operations, and decreased CO_2 emissions from less fossil fuel combustion and tillage. Estimates of total carbon sequestration attributable to CRP lands for fiscal years (FYs) 2000–2006 range from 42.7 million mt CO_2-eq in FY 2000 to 50.6 million mt CO_2-eq in FY 2006. Estimated reductions in CO_2 and N_2O emissions associated with decreased field operations and use of nitrogen fertilizers ranged from 7.86 million mt CO_2-eq in FY 2000 to 8.98 million mt CO_2-eq in FY 2006 (Lewandrowski, 2008).

Since 2002, USDA has explicitly granted landowners the legal right to any carbon benefits associated with CRP lands (USDA, 2007). Absent a mechanism for landowners to convert these benefits to income, the provision has little impact on how farmers currently manage CRP lands. At the same time, this provision positions the CRP to facilitate the adoption of GHG mitigation land management practices under a wide range of potential GHG mitigation incentive frameworks.

Absent a specific set of GHG mitigation incentives, it is difficult to generalize as to whether existing legal frameworks would facilitate or hinder the adoption of GHG mitigating technologies or practices. It is clear, however, that in designing such incentives, existing laws, regulations, and program provisions may affect how farmers in a given area or situation will view and respond to the incentives.

1.7 Organization of This Report

This report presents key information that is relevant to the potential farm-level decision to adopt specific GHG mitigating commodity production and land management practices and technologies. Recognizing the diversity of U.S. farms, the information presented should be viewed as reflective of a set of representative farms rather than a set of actual farms.

The technologies and practices highlighted in the next three chapters were selected because adequate information was available to:

- Provide a detailed technical description of the technology or practice;
- Assess the farm-level costs for implementing the technology or practice;
- Quantify the decrease in farm-level GHG emissions or increase in farm-level carbon sequestration associated with adoption of the technology or practice; and
- Estimate the GHG incentive levels that various representative farms would require to consider adoption of the technology or practice as a break-even undertaking.

Chapter 2 addresses GHG mitigation options for crop production systems. The options highlighted focus on field management and nutrient management operations. Chapter 3 addresses GHG mitigation options for animal production systems. The options highlighted emphasize manure management for dairies, swine, and (to a lesser extent) beef feedlot operations and a grazing lands management option for beef cattle. Other livestock—including poultry, sheep, goats, horses, and other animals—account for a relatively small share of GHG emissions from livestock systems, and consequently are not considered. Chapter 4 presents GHG mitigation options for land retirement practices, including options related to land-use change and agroforestry. Chapter 5 presents a summary of all of the technologies and practices described in Chapters 2, 3, and 4 by break-even price. The goal is to give readers an understanding of which practices would be economical for farmers to consider adopting at a given incentive level, and which practices farmers would consider adding (dropping) as the incentive level is increased (reduced).

Textbox 1-2: Purpose of the Report

This report aims to:

- Facilitate a better understanding of the financial incentives that are necessary for agriculture producers to adopt specific GHG mitigating production and land management practices and technologies, with positive impacts on their revenue stream;
- Provide a compendium of the mitigation options for which cost and GHG reduction data are readily available, along with the associated range of incentive levels;
- Evaluate the variability in incentive levels across farm sizes, farm types, and USDA regions; and
- Summarize in qualitative terms other potential mitigation options for which cost and GHG reduction data are fairly limited.

This report is not:

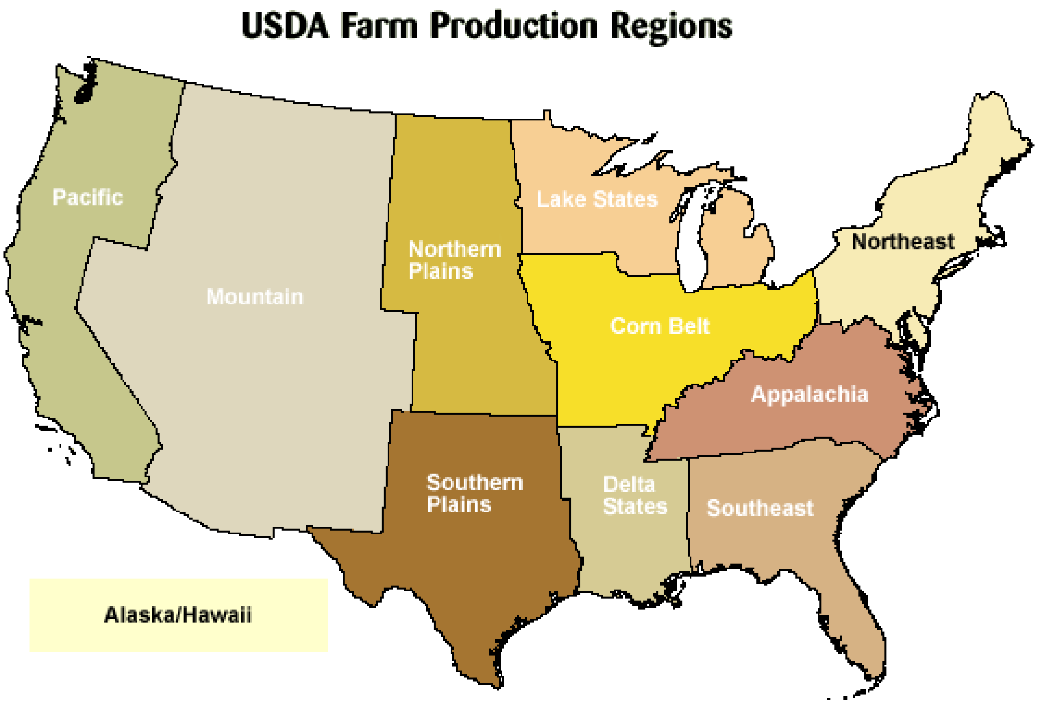
- A farm-level guide to assist agriculture producers in identifying farm-specific mitigation options and associated costs and net GHG emissions impacts;
- Intended to provide a break-even price for all farms, rather it provides a range of representative conditions;
- Intended to project future mitigation potential across all national farms; rather it focuses on the incentive levels that would be required for a farm to adopt a mitigation option with a positive impact on its revenue stream; and
- Intended to provide detailed evaluation of negative break-even prices (i.e., options that are cost-effective without an incentive) as these prices represent situations where a landowner is reluctant to implement the option due to the perceived risk or other issues, such as a reluctance to change or hesitancy to learn new practices.

APPENDIX 1-A: CONSUMER PRICE INDEX INFLATION SCALAR

Year	Year X $ Value	2010 $ Value	% Change/ Scaling Factor	Multiplier
1997	$1.00	$1.36	36%	136%
1998	$1.00	$1.34	34%	134%
1999	$1.00	$1.31	31%	131%
2000	$1.00	$1.27	27%	127%
2001	$1.00	$1.23	23%	123%
2002	$1.00	$1.21	21%	121%
2003	$1.00	$1.19	19%	119%
2004	$1.00	$1.15	15%	115%
2005	$1.00	$1.12	12%	112%
2006	$1.00	$1.08	8%	108%
2007	$1.00	$1.05	5%	105%
2008	$1.00	$1.01	1%	101%
2009	$1.00	$1.02	2%	102%
2010	$1.00	$1.00	0%	100%
2011	$1.00	$0.97	-3%	97%
2012	$1.00	$0.95	-5%	95%

Source: Bureau of Labor Statistics (2012).

APPENDIX 1-B: USDA PRODUCTION REGIONS



USDA Farm Production Regions

Source: USDA ERS (2005).

Note: Alaska and Hawaii are not part of the Farm Production Region classification scheme, although they are included here as a region and in the U.S. totals.

States included in Regions:

Northeast

- Connecticut
- Delaware
- Maine
- Maryland
- Massachusetts
- New Hampshire
- New Jersey
- New York
- Pennsylvania
- Rhode Island
- Vermont

Lake States

- Michigan
- Minnesota
- Wisconsin

Corn Belt

- Illinois
- Indiana
- Iowa
- Missouri
- Ohio

Northern Plains

- Kansas
- Nebraska
- North Dakota
- South Dakota

Appalachia

- Kentucky
- North Carolina
- Tennessee
- Virginia
- West Virginia

Southeast

- Alabama
- Florida
- Georgia
- South Carolina

Delta

- Arkansas
- Louisiana
- Mississippi

Southern Plains

- Oklahoma
- Texas

Mountain

- Arizona
- Colorado
- Idaho
- Montana
- Nevada
- New Mexico
- Utah
- Wyoming

Pacific

- California
- Oregon
- Washington

Not included

- Alaska
- Hawaii
- Pacific Basin
- Puerto Rico

APPENDIX 1-C: STATE REGULATIONS FOR CONTROLLING ANIMAL MANURE

	Permit Type			Permit Conditions		
State	**Federal NPDES**	**State NPDES**	**State Non-NPDES**	**Effluent Limits**	**Management Plan**	**Land Application Plan**
AL		X		X	X	X
AK	X					
AR		X	X	X	X	X
AZ	X		X			X
CA		X	X	X		X
CO			X	X	X	X
CT		X	X		X	X
DE		X	X			
FL		X	X	X		X
GA		X	X	X		X
HI		X				
IA	X	X	X	X		
ID	X		X	X	X	X
IL		X	X	X	X	X
IN		X	X		X	X
KY		X	X	X	X	X
KS		X	X		X	X
LA		X	X	X	X	X
MA	X					
MD		X	X			X
ME	X					
MI			X	X		
MN		X	X	X	X	X
MO		X	X	X	X	X
MS		X	X	X		
MT		X	X	X		X
NE		X	X	X	X	X
NC			X	X	X	X
ND		X	X			X
NH	X					
NJ		X				X
NM	X		X		X	X
NV		X				
NY	X				X	
OH		X	X		X	X
OK		X	X	X	X	X
OR		X	X			X
PA		X	X		X	X
RI		X				
SC		X	X	X	X	
SD		X	X	X		
TN		X		X		
TX		X	X	X	X	X
UT		X				X
VA		X	X	X	X	X
VT		X		X		X
WA		X	X	X	X	X
WI		X	X	X		X
WV		X		X	X	
WY		X		X	X	X
Totals	**9**	**39**	**35**	**29**	**25**	**34**

Source: Ribaudo et al. (2003) from EPA (2002).
Note: Permit conditions are requirements imposed through either NPDES or State non-NPDES programs.

CHAPTER 1: REFERENCES

Aillery, M., N. Gollehon, R. Johansson, J. Kaplan, et al. 2005. *Managing Manure to Improve Air and Water Quality*: US Department of Agriculture, Economic Research Service (ERS).

Bureau of Labor Statistics. 2012. *CPI Inflation Calculator*. Washington, DC: U.S. Department of Labor, Bureau of Labor Statistics. http://www.bls.gov/data/inflation_calculator.htm.

Christoffersen, A.H. 2011. *Carbon Storage and Turnover*. http://ecofinders.dmu.dk/ecosystem-services/carbon-storage-and-turnover/.

Durst, R. 2009. *Federal Tax Policies and Farm Households*. Washington, DC: U.S. Department of Agriculture, Economic Research Service.

EPA. 2002. *State Compendium: Programs and Regulatory Activities Related to Animal Feeding Operations*. Washington, DC: U.S. Environmental Protection Agency. http://www.epa.gov/npdes/pubs/statecom.pdf.

EPA. 2003. *National Pollutant Discharge Elimination System Permit Regulation and Effluent Limitation Guidelines and Standards for Concentrated Animal Feeding Operations (CAFOs); Final Rule*. Wasington D.C.: U.S. Environmental Protection Agency.

EPA. 2005. *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture*. Washington, DC: U.S. Environmental Protection Agency. http://www.epa.gov/sequestration/greenhouse_gas.html.

EPA. 2007a. *Major Existing EPA Laws and Programs That Could Affect Agricultural Producers*: U.S. Environmental Protection Agency, Agricultural Counselor, Office of the Administrator. http://www.epa.gov/agriculture/agmatrix.pdf.

EPA. 2007b. *Agriculture Regulatory Matrix*: U.S. Environmental Protection Agency. http://www.epa.gov/oecaagct/agmatrix.pdf.

EPA. 2010. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*. Washington, DC: U.S. Environmental Protection Agency.

EPA. 2011. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2009*. Washington, DC: U.S. Environmental Protection Agency.

EPA. 2012. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010*. Washington, DC: U.S. Environmental Protection Agency.

Follet, R.F. 2001. Soil Management Concepts and Carbon Sequestration in Cropland Soils. *Soil & Tillage Research*, 61:77-92.

Lewandrowski, J., M. Peters, C. Jones, R. House, et al. 2004. *Economics of Sequestering Carbon in the U.S. Agricultural Sector*. Washington DC: U.S. Department of Agriculture.

Lewandrowski, J. 2008. Impact of Climate Change on Agriculture and the Food System: A U.S. Perspective. Proceedings of the The Pacific Food System Outlook Meeting, Honolulu, HI.

Liebig, M.A., A.J. Franzluebbers, and R.F. Follett, eds. 2012. *Managing Agricultural Greenhouse Gases Coordinated Agricultural Research through GRACEnet to Address Our Changing Climate*. Waltham, MA: Academic Press, Elsevier.

Liu, Z., H. Liu, and W. Powers. 2011. Meta-analysis of Greenhouse Gas Emissions from Swine Operations. Proceedings of the ASAE Annual Meeting, August 7–10 Louisville, KY.

Livezey, J., and L. Foreman. 2004. *Characteristics and Production Costs of U.S. Rice Farms*. Washington, DC: U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/media/761284/sb974-7_1_.pdf.

Lubowski, R.N., M. Vesterby, S. Bucholtz, A. Baez, et al. 2006. *Major Uses of Land in the United States, 2002*. Washington DC: Economic Information Bulletin (EIB) No. 14.

Mathews, K.H.J., and R.J. Johnson. 2011. *Cattle Sector Production Practices and Regional Price Differences*. Washington DC: U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/Publications/LDP/2011/04Apr/LDPM2021/.

McCarl, B.A., and U.A. Schneider. 2001. Greenhouse Gas Mitigation in U.S. Agriculture and Forestry. *Science Magazine*, 294:2481–2482.

Mitloehner, F., and S. Place. 2009. Livestock's Role in Climate Change. *Beef Issues Quarterly*:1–3.

Nickerson, C., R. Ebel, A. Borchers, and F. Carriazo. 2011. *Major Uses of Land in the United States, 2007.* Washington DC: U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/media/188404/eib89_2_.pdf.

Ogle, S. 2011a. Data on Soil C Sequestration Potential of Changing Tillage Intensities, by Crop Type and Region. Stephen Ogle, Colorado State Unviersity, Fort Collins, CO.

Ogle, S. 2011b. Data on N_2O emissions from N Management Options, by Crop and Region. Stephen Ogle, Colorado State Unviersity, Fort Collins, CO.

Paustian, K., B., A. Babcock, J. Hatfield, C.L. Kling, et al. 2004. *Climate Change and Greenhouse Gas Mitigation: Challenges and Opportunities for Agriculture*. Ames, IA: Council on Agricultural Science and Technology (CAST).

Phetteplace, H., D. Johnson, and A. Seidl. 2001. Greenhouse Gas Emissions from Simulated Beef and Dairy Livestock Systems in the United States. *Nutrient Cycling in Agroecosystems*, 60(1):99–102.

Ribaudo, M., N. Gollehon, M. Aillery, J. Kaplan, et al. 2003. *Manure Management for Water Quality: Costs to Animal Feeding Operations of Applying Manure Nutrients to Land*. Washington, DC: U.S. Department of Agriculture, Economic Research Service, Resource Economics Division.

Salzman, J., and B.H.J. Thompson. 2007. *Environmental Law and Policy*. New York, New York: Foundation Press.

Smith, K., L. Bouwman, and B. Braatz. 2006. *N_2O: Direct Emissions from Agricultural Soils*: Intergovernmental Panel on Climate Change. http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/4_5_N2O_Agricultural_Soils.pdf.

USDA. 2007. *Agricultural Resource Conservation Program 2-CRP (Revision 5)*. Washington, DC: U.S. Department of Agriculture, Farm Service Agency. http://www.fsa.usda.gov/Internet/FSA_File/2-crp_r05_a14.pdf.

USDA. 2011. *U.S. Agriculture and Forest Greenhouse Gas Inventory: 1990-2008*. Washington, DC: U.S. Department of Agriculture.

USDA ERS. 2005. *Farm and Farm-Related Employment Data*: U.S. Department of Agriculture, Economic Research Service. http://webarchives.cdlib.org/wayback.public/UERS_ag_1/20111128200127/http://www.ers.usda.gov/Data/FarmandRelatedEmployment/.

USDA ERS. 2007. *The Changing Economics of U.S. Hog Production*: U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/publications/err-economic-research-report/err52.aspx.

USDA ERS. 2011. ARMS Farm Financial and Crop Production Practices. Washington, DC: U.S. Department of Agriculture Economic Research Service.

USDA NASS. 2008. *2007 Census of Agriculture*. Washington, DC: U.S. Department of Agriculture, National Agricultural Statistics Service. http://www.agcensus.usda.gov/Publications/2007/index.php.

USDA NASS. 2009. *Overview of the U.S. Hog Industry*. Washington, DC: U.S. Department of Agriculture, National Agricultural Statistics Service. http://usda.mannlib.cornell.edu/usda/current/hogview/hogview-10-30-2009.pdf.

Xu, M. 2012. NRCS Use of Discount Rates in Conservation Programs and Projects. Proceedings of the 67th Annual Soil and Water Conservation Society International Conference, Fort Worth, TX.

2. CROP PRODUCTION SYSTEMS

This chapter discusses GHG mitigation options for crop production systems, focusing primarily on changes to field management, in particular tillage systems, and nutrient management practices. By adopting reduced tillage systems as part of their field management practices, farmers can reduce net GHG emissions through increased carbon sequestration in cropland soils. Improved nutrient management practices focus on the rate, timing, form, and method of nitrogen application to reduce N_2O emissions from agricultural soils. As appropriate, operations are distinguished by size (i.e., small, medium, and large farms)[1] and geographic region (i.e., the 10 USDA production regions). For each technology, information is provided on the current level of adoption, the potential for additional adoption, environmental and production performance, barriers to adoption, and economic information related to adoption cost and break-even prices (in dollars per metric ton of CO_2-eq mitigated). Additional mitigation options for crop production systems are discussed qualitatively as significant uncertainties exist with the mitigation potential and/or cost-effectiveness of this subset of practices. In the final section of this chapter, the ranges of break-even prices are summarized.

2.1 Field Management Operations

Field management includes tillage practices and management of the amount, orientation, and distribution of crop or biomass residues on the soil surface (USDA NRCS, 2012). Reductions in tillage can prevent erosion and reduce CO_2 losses from the soil, thereby increasing soil carbon availability. Residue management can also improve soil organic matter content, increase plant available moisture, and prevent erosion. Reductions in tillage are analyzed quantitatively in this section and residue management practices (i.e., crop rotation changes,[2] field burning elimination, lime application, and rice cultivation) are reviewed qualitatively. The options considered in this report are summarized in the adjacent textbox.

Field Management Options

- Reduced Tillage Intensity
  - Switch from Conventional to Reduced Tillage
  - Switch from Conventional Tillage to No-Till
  - Switch from Reduced Tillage to No-Till
- Qualitative Assessments
  - Crop Rotation Changes
  - Field Burning Elimination
  - Reduced Lime Application
  - Rice Cultivation

2.1.1 Reducing Tillage Intensity

Changes in tillage can significantly affect soil carbon storage, mostly by changing the rate of residue decomposition and carbon loss from the soil. Options for reducing tillage intensity are discussed together because the specific steps involved in switching among conventional, reduced, and no tillage have several elements in common.

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[1] For this study, the break-even price is estimated for several farm sizes to illustrate the range of costs and benefits. Small, medium, and large farms are defined by the number of acres.

[2] Although data are available to quantify the break-even prices for crop rotation, a detailed evaluation of break-even prices was not conducted as break-even prices are either highly negative (in particular, eliminating fallow results in additional revenue and farmers would undertake this option if it was agronomically feasible) or highly positive (i.e., cost prohibitive to transition to alternative crops).

Textbox 2-1: Tillage Practices Overview

- Conventional tillage: A system where a moldboard plow or other intensive tillage instrument is used and less than 15% of crop residue cover remains (Heimlich, 2003).
- Reduced tillage: A system where no moldboard plow is used and 15–30% of crop residue cover remains (Heimlich, 2003).
- Strip tillage: This practice is becoming more widely adopted in the United States. Strip tillage creates residue-free strips between existing residues by using a knife implement. These residue-free strips are approximately 6 inches wide and 4–8 inches deep. Fertilizer and seeds are placed into the strips (USDA NRCS Iowa, 2012). This practice facilitates optimum seed and fertilizer placement while minimizing soil disturbance.
- No-till: This system leaves the soil undisturbed between planting and harvest with the exception of nutrient injection, herbicide application, or emergency cultivation for weed control. Seeds are planted or drilled in a narrow seedbed or row created by coulters, row cleaners, disk cleaners, disk openers, in-row chisels, or rototillers (Heimlich, 2003).

2.1.1.1 Technology Characterization

Three specific tillage changes are considered: (1) a switch from conventional to reduced tillage, (2) a switch from conventional tillage to no-till, and (3) a switch from reduced tillage to no-till.

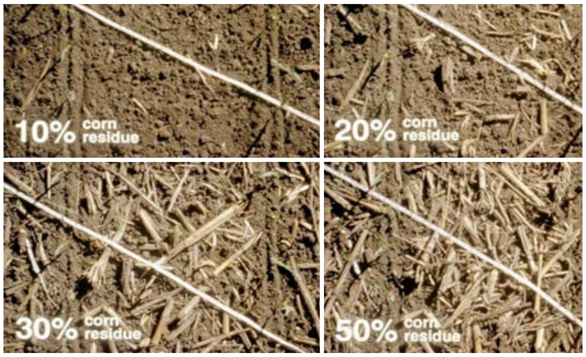
Traditionally, farmers have used conventional tillage prior to planting in order to prepare the soil for seed, reduce weeds and other pests, mix nutrients throughout the tillage depth, and aerate the soil. The standard modern equipment for conventional tillage is a moldboard plow or its variants. Relative to other tillage systems, conventional tillage is often associated with lower soil carbon content and higher soil erosion.

Exhibit 2-1 illustrates the varying degrees of residue cover remaining for alternative tillage practices. Over a period of several years, conservation tillage can improve soil structure, and build soil carbon levels. The additional soil carbon, however, will be quickly emitted back to the atmosphere if tillage that is more intensive is resumed. For GHG mitigation purposes, these farm-level shifts to less intense tillage systems must be permanent. This report follows USDA definitions of tillage intensity as described in the textbox above and in Exhibit 2-2. Exhibit 2-2 summarizes the various tillage management practices and the resulting residue cover. Key features of reduced till and no-till are summarized in the textboxes on the next two pages.

Key Features of Switching from Conventional to Reduced Till or No-Till

- Reduced till and no-till can increase soil carbon storage and decrease erosion.
- Reduced till and no-till reduce fuel and labor inputs.
- Management and equipment changes can make the transition challenging.
- No-till is less effective at sequestering carbon in cold, wet, or heavy soils when compared with conventional till.

Exhibit 2-1: Visual Identification of Residue Levels



Source: Missouri NRCS (2012).

Exhibit 2-2: USDA Crop Residue Management and Tillage Definitions

Conventional or Intensive Tillage	Conservation Tillage				
	Reduced Tillage	Mulch-Till	Ridge-Till	No-Till	Strip-Till
Moldboard plow or other intensive tillage used	No use of moldboard plow and intensity of tillage reduced	Further decrease in tillage intensity	Only ridges are tilled	No tillage performed	Strips are tilled, leaving residue-free rows for planting
<15% residue cover remaining	15–30% residue cover remaining	30% or greater residue cover remaining			

Source: Heimlich (2003).

Textbox 2-2: Switch from Conventional to Reduced Tillage

What constitutes "reduced tillage" can differ among studies. Relative to conventional tillage, reduced- and conservation-tillage systems (including mulch-till, ridge-till, no-till, and strip-till) reduce soil erosion and can increase soil carbon storage (Heimlich, 2003, Chapter 4.2). Moving from conventional tillage (i.e., less than 15% crop residue cover left on the field) to reduced tillage (15–30% crop residue cover left on the field) requires the use of alternative equipment and management practices. Reduced tillage is usually done with a chisel plow (USDA NRCS, 2010b) or with disk or field cultivators, or one of the many mulch finishers now on the market (Wittry, 2011). Planting equipment must be capable of handling the increased residue that will be present on the soil surface. A fluted coulter can be used when planting, or a chisel can be used to cut through residues or partially turn the soil and crop residue (see images below). Moving to reduced tillage can be a first step in transitioning to no-till.

Fluted coulter. Source: USDA NRCS (2010b).

A chisel partially turns the soil and crop residue (South Dakota). Source: USDA NRCS (2010b).

Tillage with a disk cultivator in central Iowa.

Source: USDA NRCS (2010b).

Conservation tillage in central Iowa. Leaving crop residues on the soil surface at harvest reduces soil erosion significantly. Source: USDA NRCS (2010b).

Textbox 2-3: Switch from Conventional to No-Till

In a no-till system, the soil is left undisturbed from harvest to planting except for nutrient injection. Switching from conventional tillage to no-till requires different equipment and management practices. Operating costs are generally lower with tillage reduction because less equipment is used for less time. Labor, fuel, maintenance, and repair costs are therefore decreased as well. Most no-till operations rely heavily on herbicides for weed control. Increased pressure from the presence of insects and disease makes well-selected crop rotation more important and can lead to increased insecticide and fungicide use. Short-term nitrogen requirements often go up, although nitrogen, phosphorous, and potassium fertilizer requirements will return to normal over the long term (Edwards et al., 2006). When combined with shifting the application of nitrogen fertilizer from fall to spring, no-till can reduce fertilizer requirements (Boyle, 2006).

With no-till management, nutrients (e.g., phosphorus) tend to accumulate on the soil surface over time. No-till is more attractive for soils that are steeper, stonier, and shallower because it reduces erosion, reduces stone-picking, and reduces water demand. However, no-till may take longer to become successful on degraded soils, because it takes time for no-till to produce the improved biological activity that leads to better soil structure and better yields (Duiker and Myers, 2006). Planning ahead (at least 9 months) is essential for a successful transition from conventional till to no-till. No-till can affect soil sampling, soil fertility management, crop variety selection, fertilizer handling, weed management, and harvesting. A good practice is to start slowly on fields where the transition will be easier, and also to get advice from those who have experience with no-till farming (Duiker and Myers, 2006).

The typical equipment needed for no-till is a planter (and/or drill), a sprayer, and a combine (Duiker and Myers, 2006). The type of planter (or equipment on the planter) will need to be able to handle the higher levels of residue that occur with no-till. The planting or drilling of seeds occurs in a slot created by coulters, row cleaners, disk openers, in-row chisels, or rototillers. Often, a fluted coulter is used to open a channel that is wide enough for equipment, such as a double-disk opener, to deposit the seed at the appropriate depth. Seed drills can also be used. Crop rotation and cover crops are important in no-till systems in order to provide sufficient soil cover, improve soil warming, create an environment for healthy soil organisms, promote more efficient nutrient use, break pest and disease cycles, and (in the case of cover crops) to provide weed control (Duiker and Myers, 2006).

No-till planting of corn into cover crop of barley, Washington County, Virginia. Source: USDA NRCS (2010b).

Large no-till planters are used on a steep slope in Washington State's Palouse region. Source: USDA NRCS (2010b).

Current and Potential Adoption

Data from various years of the USDA Agricultural Resource Management Survey (ARMS) allow the estimation of current adoption rates for various types of tillage systems by USDA production region and for selected crops. These estimates are shown in Exhibit 2-3. The values in Exhibit 2-3 do not include land in permanent conservation systems. While statistics are not readily available on the quantity of permanent no-till operations in the United States, survey data indicate that 13% of all cropland acres in the Upper Mississippi River Basin were in no-till every year over a 3-year period (2003–2006) (Horowitz et al., 2010). Conceptually, switching to reduced tillage from conventional tillage or to no-till from reduced or conventional tillage is theoretically possible for all crop acreage where tillage practices are ongoing. In practice, however, transition to reduced or (particularly) no-till will not be practical for all farmers.

Exhibit 2-3: Estimated Recent Adoption Levels of Tillage Practices in the United States by Region and Crop Type

Crop/Tillage Practice	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
	(percent of crop acreage)									
Corn (2005)										
No-Till	60	22	60	13	35	21	36	21	32	10
Reduced Tillage	15	22	15	25	13	16	14	16	9	12
Conventional Tillage	20	29	20	46	28	58	20	58	31	68
Other Conserv. Tillage	5	27	5	16	23	4	30	4	28	10
Cotton (2007)										
No-Till	56	19	11	N/A	11	N/A	0	0	35	6
Reduced Tillage	16	9	5	N/A	5	N/A	0	0	16	13
Conventional Tillage	23	69	83	N/A	83	N/A	0	100	38	79
Other Conserv. Tillage	5	4	2	N/A	2	N/A	100	0	10	3
Sorghum (2003)										
No-Till	25	22	0	22	30	0	45	0	45	12
Reduced Tillage	13	16	0	16	3	0	17	0	17	13
Conventional Tillage	41	54	0	54	23	0	14	0	14	53
Other Conserv. Tillage	21	9	100	9	44	100	24	100	24	22
Soybeans (2006)										
No-Till	77	58	25	34	25	34	39	0	39	0
Reduced Tillage	11	13	11	15	11	15	15	0	15	0
Conventional Tillage	11	8	56	14	56	14	6	0	6	0
Other Conserv. Tillage	1	21	8	37	8	37	39	100	39	100
Wheat (2004)										
No-Till	22	46	54	46	26	0	40	13	40	12
Reduced Tillage	22	11	17	24	20	24	20	24	20	34
Conventional Tillage	30	20	8	9	23	9	18	36	18	50
Other Conserv. Tillage	25	23	22	21	30	68	22	27	22	4

N/A = Not applicable

Source: USDA ERS (2011c).

Production and Environmental Impacts

Production Impacts. Using no-till in cold, wet regions can delay planting dates because tillage helps to warm and dry the soil, mostly by removing the residue that blocks or reflects sunlight (Duiker and Myers, 2006). Yield differences among tillage regimes vary by crop type, climate, soil, and weather events. In general, no-till has been shown to increase crop yields compared with conventional tillage in areas where the potential for drought is higher and in well-drained soils. In a study by Ogle (2011d), yield gains resulting from reduced tillage were due to increased water infiltration from improved soil structure and residue cover in no-till systems. The DAYCENT biogeochemical model output shown in this report indicated that switching from conventional tillage to reduced tillage and no-till resulted in either reduced crop yield or no change in yield for all rain-fed crops and regions considered. When switching from reduced tillage to no-till, yield gains were observed in the Mountain region and for corn in the Southern Plains. In a study by Archer and Halvorson (2010), economic and global warming potential measurements demonstrated that producers in northeastern Colorado had an economic incentive ($116 per acre) to switch from conventionally tilled, irrigated continuous corn to a no-till, irrigated corn–soybean rotation.[3] Generally, conventional tillage tends to give higher yields where rainfall is sufficient and consistent, and on poorly drained soils (Heimlich, 2003; Penn State, 1996).

Other Environmental Impacts. No-till reduces soil erosion and runoff when compared with conventional (e.g., moldboard) plow systems (Eagle et al., 2012). In addition, no-till can improve soil organic matter content, minimize CO_2 losses, increase plant-available moisture, and provide a habitat for wildlife (USDA NRCS, 2012).

Barriers to Adoption

While there are fewer barriers to adopting reduced tillage, potential challenges include the following:

- Farmers will have to familiarize themselves with the new equipment and learn new management practices.
- Adoption of no-till may cause a decrease in yield, especially in cool, wet climatic conditions where crop growth is reduced due to depressed temperatures in the residue layer (Ogle et al., 2012).

2.1.1.2 GHG Impacts

In general, no-till has been shown to have positive effects on soil carbon sequestration, in sub-humid regions, such as the Midwest and Southeast (Eagle et al., 2012). Although the effect varies by climate and soil type, Ogle et al. (2010) found little consistency among studies that assessed the soil carbon storage effect of reduced till. Cooler and moist soils—for example, those in the Lake States (e.g., Wisconsin, Minnesota)—may achieve maximum soil carbon storage with occasional (e.g., biennial) tillage (Eagle et al., 2012). Ogle et al. (2010) and Eagle et al. (2012) suggest that for some areas, particularly in the cold northern States and arid western United States, reducing tillage intensity could lead to losses of carbon on some farms. Often the soil organic carbon (SOC) content in conventional tillage systems is greater than that of no-till systems at greater depths (5–10 cm) because changes in agricultural management practices are often more pronounced at the surface rather than the subsurface layer (Liebig et al., 2012). Given the significant variability in topography, soil resources, climate, crops, and production methods, SOC sequestration potential is difficult to estimate (Liebig et al., 2012).

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[3] Incentives in this study were a result of cost savings due to reduced nitrogen fertilizer use in the soybean phase of the rotation, along with increased gross returns due to increased corn yield and the high price of soybeans (Archer and Halvorson, 2010).

The relationship of soil N_2O emissions to tillage regime is not clear, although, in general, the cold, wet conditions that tend to make reduced or no-till unfavorable for soil carbon or for crop production (e.g., delayed seeding) also lead to increased N_2O emissions. This is a result of greater soil bulk density, more soil carbon, and nitrogen, and greater soil water content, particularly in the Lake States and Northeastern regions (Eagle et al., 2012). While other studies have indicated no difference in N_2O emissions resulting from reductions in tillage, decreased emissions have been noted in warmer, drier regions due to increased aggregate stability and improved drainage (Eagle et al., 2012). Crop management practices that maintain low levels of nitrate (NO_3-N) in the upper 15 cm of the soil profile reduce N_2O emissions throughout the western United States (Liebig et al., 2012). Heavy clays with poor drainage may dry less well with reduced tillage, and may experience increased N_2O emissions.

Reduced fossil fuel combustion, resulting from fewer field operations, is likely to reduce GHG emissions; however, these reductions are not addressed in this report. Exhibit 2-4 presents the estimated soil carbon effects of reducing tillage by system and crop type (Ogle, 2011a). The first set of estimates represents the soil carbon effects of switching from conventional tillage to reduced tillage. The second set of estimates in Exhibit 2-4 presents the soil carbon effects of switching from conventional tillage to no-till. Finally, the third set of estimates illustrates the soil carbon effects of switching from reduced tillage to no-till. As indicated in Exhibit 2-4, the soil carbon effects resulting from the three tillage management scenarios varies by crop and region.

Exhibit 2-4: Emissions Reduction Potential of Reducing Tillage Intensity

Crop	Tillage Change	Emissions Reduction Potential by Region (mt CO_2-eq per acre)									
		Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn	Conventional Till to Reduced Till	0.13	0.22	0.20	0.15	0.19	0.13	0.17	+	0.03	0.11
Cotton	Conventional Till to Reduced Till	N/E	0.02	0.06	N/A	0.09	N/A	N/E	+	+	0.04
Sorghum	Conventional Till to Reduced Till	N/E	0.02	0.06	N/E	0.09	+	0.07	N/E	+	0.05
Soybeans	Conventional Till to Reduced Till	+	+	0.05	+	N/E	+	0.06	N/E	+	0.04
Wheat	Conventional Till to Reduced Till	+	0.03	0.05	0.06	0.08	+	0.07	+	+	+
Corn	Conventional Till to No-Till	0.53	0.65	0.77	0.70	0.41	0.53	0.52	0.26	0.42	0.47
Cotton	Conventional Till to No-Till	N/E	0.18	0.44	N/A	0.20	N/A	N/E	0.08	0.22	0.26
Sorghum	Conventional Till to No-Till	N/E	0.19	0.42	N/E	0.19	+	0.28	N/E	0.22	0.27
Soybeans	Conventional Till to No-Till	0.21	0.13	0.39	0.29	N/E	0.21	0.25	N/E	0.20	0.24
Wheat	Conventional Till to No-Till	0.27	0.21	0.42	0.42	0.18	0.27	0.28	0.08	0.21	0.20

Crop	Tillage Change	Emissions Reduction Potential by Region (mt CO_2-eq per acre)									
		Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn	Reduced Till to No-Till	0.41	0.42	0.56	0.55	0.22	0.41	0.36	0.26	0.39	0.35
Cotton	Reduced Till to No-Till	N/E	0.16	0.38	N/A	0.11	N/A	N/E	0.09	0.25	0.21
Sorghum	Reduced Till to No-Till	N/E	0.16	0.37	N/E	0.11	+	0.21	N/E	0.25	0.22
Soybeans	Reduced Till to No-Till	0.23	0.13	0.34	0.31	N/E	0.23	0.19	N/E	0.24	0.20
Wheat	Reduced Till to No-Till	0.27	0.17	0.36	0.36	0.10	0.27	0.21	0.09	0.24	0.22

+ = Negligible reduction in emissions
N/A = Not applicable
N/E = Not estimated
Source: Ogle (2011a).

2.1.1.3 Cost Profile

This section develops a set of representative cost profiles for switching among alternative tillage regimes for five crops (corn, cotton, sorghum, soybeans, and wheat). The costs address operation and overhead (e.g., fertilizer and pesticide applications), fuel and labor, and equipment depreciation. Capital costs, including depreciation, were annualized in the source data, and thus are included in operating costs rather than shown explicitly as capital costs. Costs were estimated on a per-acre basis based on cost comparisons of reduced tillage, conventional tillage, and no-till systems for corn and soybeans in Illinois from the University of Illinois Department of Agriculture and Consumer Electronics (DACE) (2006). These estimates were scaled to other crops and regions using USDA ERS cost-of-production estimates for each crop and region (USDA ERS, 2011a). This scaling step was necessary because no single source was readily available to compare the three tillage regimes for all crops examined. In general, there is a reduction in costs across crops and regions from a switch to a system with less tillage.

Basis for cost estimates:

- Costs are based on Illinois data from DACE (2006). Costs for soybeans are based on soybean data, while costs for all other crops (i.e., cotton, sorghum, and wheat) are based on corn. These costs are shown in Exhibit 2-5 and Exhibit 2-6, respectively.
- Total costs per acre for corn production in Illinois (the Heartland USDA resource region) are scaled to the costs for other crops in the Heartland region using scaling factors based on the relative costs per acre of production among crops in the Heartland region (USDA ERS, 2011a).
- The production costs by crop type in different USDA resource regions are from USDA ERS (2011a). The USDA ERS production cost data represent regional averages, and do not distinguish among different tillage regimes. In order to estimate price differences by crop, region, and tillage regime, the USDA ERS data were used to scale the available DACE data that is disaggregated by tillage regimes (i.e., cost data for different tillage practices are available for corn and soybean systems in the ERS Heartland region). For

example, to calculate the cost of no-till cotton production in the Fruitful Rim region, Equation 1 is used, which accounts for differences in the cost of production among the regions:

Equation 1:

$$\text{Fruitful Rim no-till cotton production cost} = \left[1 + \frac{\text{Fruitful Rim cotton cost} - \text{Heartland cotton cost}}{\text{Heartland cotton cost}}\right] \times \text{DACE Heartland no-till corn cost}$$

- Fruitful Rim and Heartland costs refer to USDA ERS resource regions, which are not contiguous with State boundaries. These resource regions were mapped to USDA Farm Production Regions used in the Census of Agriculture and throughout this report.[4]
- All crops are assumed to be rain-fed and not irrigated.
- The crop prices used are a 5-year average of the marketing year price received for each crop for 2006 to 2010 (USDA NASS, 2011b). The use of a 5-year average reduces the impact of a single year's prices on the results of the break-even prices.

Exhibit 2-5: Alternative Tillage System Estimated Costs for Soybeans in Illinois

Operations	Fuel Use	Fuel and Labor	Implement Overhead	Tractor Overhead	Total
	(gal/acre)	(2005 $/acre)	(2005 $/acre)	(2005 $/acre)	(2005 $/acre)
No-Till and Reduced (Strip) Tillage[a]					
Dry fertilizer	0.20	$0.61	$0.80	$0.50	$1.91
Spray	0.20	$1.11	$1.30	$0.90	$3.31
No-till drill	0.50	$2.84	$9.30	$3.20	$15.34
Spray	0.20	$1.11	$1.30	$0.90	$3.31
Spray (one-third amount)	0.10	$0.37	$0.43	$0.30	$1.10
Combine	1.00	$4.00	$3.20	$13.10	$20.30
Total	**2.00**	**$10.04**	**$16.33**	**$18.90**	**$45.27**
Conventional Tillage					
Dry fertilizer	0.20	$0.61	$0.80	$0.50	$1.91
Chisel plow	1.10	$4.85	$2.20	$4.20	$11.25
Field cultivate	0.70	$2.59	$1.80	$2.40	$6.79
Disk	0.60	$2.10	$3.50	$2.60	$8.20
Plant	0.40	$3.10	$4.40	$2.00	$9.50
Spray	0.20	$1.11	$1.30	$0.90	$3.31
Spray (one-third amount)	0.10	$0.37	$0.43	$0.30	$1.10
Combine	1.00	$4.00	$3.20	$13.10	$20.30
Total	**3.90**	**$18.73**	**$17.63**	**$26.00**	**$62.36**

[a] Soybean no-till and reduced (strip) tillage costs are the same according to (DACE, 2006) because they have lower fuel use costs when compared to conventional till systems (at least $9.50 per acre).

Source: DACE (2006).

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[4] USDA ERS Resource Regions include: Basin and Range, Eastern Uplands, Fruitful Rim, Heartland, Mississippi Portal, Northern Crescent, Northern Great Plains, Prairie Gateway, Southern Seaboard USDA ERS (2011a). USDA Farm Production Regions include Northeast, Lake States, Corn Belt, Northern Plains, Appalachia, Southeast, Delta, Southern Plains, Mountain, and Pacific.

Exhibit 2-6: Alternative Tillage System Estimated Costs for Corn in Illinois[a]

Operations	Fuel Use (gal/acre)	Fuel and Labor (2005 $/acre)	Implement Overhead (2005 $/acre)	Tractor Overhead (2005 $/acre)	Total (2005 $/acre)
No-Till					
Dry fertilizer	0.20	$0.61	$0.80	$0.50	$1.91
Spray	0.20	$1.11	$1.30	$0.90	$3.31
No-till plant	0.50	$3.13	$6.40	$2.10	$11.63
Nitrogen application	0.50	$2.00	$3.00	$1.90	$6.90
Second spray	0.20	$1.11	$1.30	$0.90	$3.31
Spray (one-third amount)	0.10	$0.37	$0.43	$0.30	$1.10
Combine	1.50	$5.99	$4.60	$14.10	$24.69
Total	**2.90**	**$14.32**	**$17.83**	**$20.70**	**$52.85**
Reduced Tillage					
Dry fertilizer	0.20	$0.61	$0.80	$0.50	$1.91
Anhydrous ammonia	0.60	$3.01	$3.96	$2.52	$9.49
Plant	0.40	$3.10	$4.40	$2.00	$9.50
Spray	0.20	$1.11	$1.30	$0.90	$3.31
Second spray	0.20	$1.11	$1.30	$0.90	$3.31
Spray (one-third amount)	0.10	$0.37	$0.43	$0.30	$1.10
Combine	1.50	$5.99	$4.60	$14.10	$24.69
Total	**2.90**	**$15.30**	**$16.79**	**$21.22**	**$53.31**
Conventional Tillage					
Dry fertilizer	0.20	$0.61	$0.80	$0.50	$1.91
Anhydrous ammonia	0.60	$2.51	$3.30	$2.10	$7.91
Field cultivate	0.70	$2.59	$1.80	$2.40	$6.79
Plant	0.40	$3.10	$4.40	$2.00	$9.50
Spray	0.20	$1.11	$1.30	$0.90	$3.31
Second spray (one-third amount)	0.10	$0.37	$0.43	$0.30	$1.10
Combine	1.50	$5.99	$4.60	$14.10	$24.69
Total	**3.40**	**$16.28**	**$16.63**	**$22.30**	**$55.21**

[a] These costs are also used for cotton, sorghum, and wheat.
Source: DACE (2006).

Estimates of the monetary costs and the benefits of switching from conventional to reduced tillage, conventional tillage to no-till, and reduced tillage to no-till are presented below. The underlying data and calculations for these cost profiles are discussed above. The changes in revenue are based on the changes in yield per acre in corn and soybeans as provided by Ogle (2011d), and the average crop price by region for 2010 (USDA NASS, 2011a) (see Appendix 2-A for crop prices). Exhibit 2-7 presents the cost impacts of the yield changes associated with the switch from conventional to reduced tillage. Exhibit 2-8 presents the incremental cost, the changes in yield, and the changes in revenue for switching from conventional tillage to no-till. Exhibit 2-9 presents the incremental cost, the changes in yield, and the changes in revenue for switching from reduced tillage to no-till. Positive changes in yield resulting from conversion from reduced till to no-till were not modeled in this report as an incentive would not be needed for landowners to implement this practice.

Exhibit 2-7: Incremental Cost, Changes in Yield, and Changes in Revenue for Switching from Conventional Tillage to Reduced Tillage

Crop	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Incremental Cost (2010 $/acre)[a]										
Corn	-$1.97	-$2.13	-$2.07	-$2.14	-$2.10	-$2.14	-$1.55	-$2.10	N/E	-$1.70
Cotton	-$1.11	-$3.67	-$3.52	N/A	-$1.11	N/A	-$1.11	-$4.46	-$3.03	-$2.28
Sorghum	-$0.73	-$1.00	-$0.73	-$0.73	-$0.73	-$0.73	-$0.57	-$0.77	-$0.73	-$0.72
Soybeans	-$15.87	-$19.14	N/E	-$17.67	-$18.69	-$17.67	N/E	-$18.69	-$14.93	-$17.91
Wheat	-$0.67	-$0.82	-$0.67	-$0.90	-$0.84	-$0.90	-$0.62	-$1.16	-$0.67	-$0.60
Changes in Yield (short tons/acre)[b]										
Corn	-0.11	-0.09	-0.07	-0.06	-0.03	-0.11	-0.04	-0.02	N/E	-0.08
Cotton	N/E	-0.03	-0.03	N/A	-0.03	N/A	-0.04	-0.02	+	-0.01
Sorghum	N/E	-0.06	-0.07	N/E	-0.04	N/E	-0.03	N/E	+	-0.04
Soybeans	-0.08	-0.03	N/E	-0.01	N/E	-0.08	N/E	N/E	+	-0.01
Wheat	-0.07	-0.04	-0.03	-0.04	-0.03	-0.07	-0.03	-0.02	+	-0.04
Changes in Revenue (2010 $/acre)[c]										
Corn	-$16.36	-$12.92	-$9.12	-$7.87	-$5.19	-$17.12	-$6.18	-$3.48	N/E	-$11.43
Cotton	N/E	-$36.60	-$38.64	N/A	-$41.86	N/A	-$53.74	-$32.35	+	-$13.12
Sorghum	N/E	-$7.65	-$8.07	N/E	-$6.33	N/E	-$4.38	N/E	+	-$5.87
Soybeans	-$24.77	-$10.71	N/E	-$3.45	N/E	-$24.69	N/E	N/E	+	-$3.32
Wheat	-$10.68	-$7.05	-$5.19	-$7.61	-$6.51	-$10.97	-$6.30	-$4.33	+	-$8.32

+ = Negligible change in yield or revenue
N/A = Not applicable
N/E = Not estimated
Source: [a] DACE (2006) and USDA ERS (2011a); [b] Ogle (2011d); [c] Ogle (2011d) and USDA NASS (2011a).

Exhibit 2-8: Incremental Cost, Changes in Yield, and Changes in Revenue for Switching from Conventional Tillage to No-Till

Crop	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Incremental Cost (2010 $/acre)[a]										
Corn	-$2.45	-$2.64	-$2.57	-$2.66	-$2.61	-$2.66	-$1.93	-$2.61	N/E	-$2.11
Cotton	-$1.38	-$4.56	-$4.37	N/A	-$1.38	N/A	-$1.38	-$5.53	N/E	-$2.84
Sorghum	-$0.90	-$1.24	-$0.90	-$0.90	-$0.90	-$0.90	-$0.70	-$0.96	N/E	-$0.90
Soybeans	-$15.87	-$19.14	-$18.78	-$17.67	-$18.69	-$17.67	-$14.66	-$18.69	N/E	-$17.91
Wheat	-$0.83	-$1.02	-$0.83	-$1.12	-$1.05	-$1.12	-$0.77	-$1.44	N/E	-$0.74
Changes in Yield (short tons/acre)[b]										
Corn	-0.19	-0.19	-0.12	-0.14	-0.02	-0.19	-0.09	-0.06	N/E	-0.07
Cotton	N/E	-0.06	-0.06	N/A	-0.02	N/A	-0.08	-0.07	N/E	-0.02
Sorghum	N/E	-0.12	-0.11	N/E	-0.03	N/E	-0.07	N/E	N/E	-0.07
Soybeans	-0.13	-0.08	-0.10	-0.08	N/E	-0.13	-0.04	N/E	N/E	-0.07
Wheat	-0.11	-0.09	-0.06	-0.13	-0.02	-0.11	-0.07	-0.06	N/E	-0.06

Crop	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Changes in Revenue (2010 $/acre)										
Corn	-$27.81	-$27.45	-$16.72	-$20.46	-$3.46	-$29.11	-$12.35	-$8.69	N/E	-$9.80
Cotton	N/E	-$61.00	-$64.40	N/A	-$27.91	N/A	-$94.04	-$97.06	N/E	-$26.23
Sorghum	N/E	-$16.82	-$13.46	N/E	-$4.75	N/E	-$8.76	N/E	N/E	-$8.81
Soybeans	-$42.46	-$24.98	-$29.70	-$24.12	N/E	-$42.33	-$13.62	N/E	N/E	-$19.90
Wheat	-$17.79	-$14.10	-$8.64	-$22.83	-$4.34	-$18.29	-$12.61	-$10.84	N/E	-$10.40

+ = Negligible change in yield or revenue
N/A = Not applicable
N/E = Not estimated
Source: [a] DACE (2006) and USDA ERS (2011a); [b] Ogle (2011d); [c] Ogle (2011d) and USDA NASS (2011a).

Exhibit 2-9: Incremental Cost, Changes in Yield, and Changes in Revenue for Switching from Reduced Tillage to No-Till

Crop	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Incremental Cost (2010 $/acre)[a]										
Corn	-$0.48	-$0.52	-$0.50	-$0.52	N/E	-$0.52	-$0.38	-$0.51	N/E	N/E
Cotton	-$0.27	-$0.89	-$0.85	N/A	N/E	N/A	-$0.27	-$1.08	-$0.73	-$0.55
Sorghum	-$0.18	-$0.24	-$0.18	-$0.18	N/E	-$0.18	-$0.14	-$0.19	N/E	-$0.17
Soybeans[b]	$0.00	$0.00	$0.00	$0.00	N/E	$0.00	$0.00	$0.00	N/E	$0.00
Wheat	-$0.16	-$0.20	-$0.16	-$0.22	N/E	-$0.22	-$0.15	-$0.28	N/E	-$0.15
Changes in Yield (short tons/acre)[c,d]										
Corn	-0.08	-0.10	-0.06	-0.09	N/E	-0.08	-0.04	-0.03	N/E	N/E
Cotton	N/E	-0.03	-0.02	N/A	N/E	N/A	-0.03	-0.03	+	-0.02
Sorghum	N/E	-0.07	-0.04	N/E	N/E	N/E	-0.03	N/E	N/E	-0.02
Soybeans	-0.06	-0.03	-0.04	-0.07	N/E	-0.06	-0.02	N/E	N/E	-0.06
Wheat	-0.04	-0.04	-0.02	-0.09	N/E	-0.04	-0.03	-0.03	N/E	-0.02
Changes in Revenue (2010 $/acre)[e]										
Corn	-$11.45	-$14.53	-$7.60	-$12.59	N/E	-$11.99	-$6.18	-$5.21	N/E	N/E
Cotton	N/E	-$36.60	-$25.76	N/A	N/E	N/A	-$40.30	-$48.53	N/E	-$26.23
Sorghum	N/E	-$9.17	-$5.38	N/E	N/E	N/E	-$4.38	N/E	N/E	-$2.94
Soybeans	-$17.69	-$10.71	-$13.20	-$20.67	N/E	-$17.64	-$6.81	N/E	N/E	-$16.58
Wheat	-$7.12	-$7.05	-$3.46	-$15.22	N/E	-$7.32	-$6.30	-$6.50	N/E	-$4.16

+ = Negligible change in yield or revenue
N/A = Not applicable
N/E = Not estimated

[a] Source: DACE (2006) and USDA ERS (2011a).

[b] The data do not indicate a change in costs for soybeans when switching from reduced tillage to no-tillage systems.

[c] The data indicate that declines in yield resulting from no-till management are most pronounced in cool, wet climatic conditions where the residue layer depresses the soil temperature, suppressing crop growth. However, instances of yield increases have also been observed due to improved soil structure and surface residue cover that enhances water infiltration, root growth, and reduces evaporative water losses from the soil (Ogle et al., 2012).

[d] Situations where yields increase are not modeled in this report as incentives would not be required for adoption of the practice (Ogle, (2011d).

[e] Source: Ogle (2011d) and USDA NASS (2011a).

2.1.1.4 Break-Even Prices

Exhibit 2-10 presents the break-even prices at which the cost of implementing a reduced tillage system equals the return, including the decrease in revenue resulting from a decrease in yield. These break-even prices are based on estimates of the following:

- Average annual soil carbon sequestration over a 20-year timeframe as provided by the DAYCENT model (Ogle, 2011a);
- Adoption cost;
- Yield changes obtained from simulations of the DAYCENT model (Ogle, (2011d); and
- Average crop price by region over the 2006–2010 period as provided by USDA NASS (2011a).

Only scenarios in which switching to a reduced tillage system decreases yields are considered. Without yield penalties, the break-even prices are consistently negative, implying that landowners would not need a financial incentive to adopt the practice. Despite negative break-even prices, landowners may still choose not to implement this practice due to limited time horizons, investments in fixed capital, or other factors that discourage switching to reduced tillage. In general, negative break-even values are a result of the estimated savings from reduced production costs (e.g., savings from reduced fuel usage) being marginally greater than the estimated losses in revenue due to yield reductions. For example, when switching from conventional to no-till for soybeans in the Northern Plans, as indicated in Exhibit 2-8, the savings from reduced production costs is $14.66 and reduced revenue from yield loss is $13.62.

Even with a decrease in yield, a negative break-even price was estimated for several region and crop type combinations. In particular, a negative break-even price was estimated for transitioning from conventional tillage to no-till for soybeans in the Northern Plains, and for transitioning from reduced tillage to no-till for cotton in the Southeast. For these situations, an incentive may not be needed for no-till; the cost-effectiveness of this option is supported by the relatively prevalent current use of no-till as indicated in Exhibit 2-3 for these region and crop type combinations. In addition, several studies address the cost-effectiveness of reduced tillage intensity. An Oklahoma State University study indicates that conversion to no-till can be cost-effective if farmers plan to (1) incorporate crop rotation, (2) double-crop, (3) grow crops on pastureland, and (4) leverage the labor savings from no-till management to generate additional income (Epplin, 2006). Decker et al. (2009) found that no-till generated greater net returns on larger farms with forage systems. Significant variability exists among farms; consequently, the costs of conversion to no-till are dependent upon farm size, soils, climate, crops grown, and the opportunity cost of the landowners' labor.

Exhibit 2-10: Break-Even Prices for Changes to Tillage Operations

Mitigation Practice	Region	Crop Type	Break-Even Price (2010 $/ mt CO_2-eq)
Conventional Tillage to No-Till	Northern Plains	Soybeans	<$0[a]
Reduced Tillage to No-Till	Southeast	Cotton	<$0
Conventional Tillage to No-Till	Mountain	Corn	$1
Conventional Tillage to No-Till	Southern Plains	Soybeans	$3
Reduced Tillage to No-Till	Delta	Wheat	$8
Reduced Tillage to No-Till	Delta	Corn	$11
Reduced Tillage to No-Till	Southern Plains	Sorghum	$11
Reduced Tillage to No-Till	Delta	Sorghum	$13
Conventional Tillage to Reduced Tillage	Mountain	Corn	$13
Conventional Tillage to No-Till	Southern Plains	Corn	$14
Reduced Tillage to No-Till	Northern Plains	Corn	$14

Mitigation Practice	Region	Crop Type	Break-Even Price (2010 $/ mt CO_2-eq)
Reduced Tillage to No-Till	Pacific	Corn	$16
Conventional Tillage to No-Till	Delta	Corn	$16
Conventional Tillage to No-Till	Mountain	Wheat	$16
Reduced Tillage to No-Till	Southern Plains	Wheat	$17
Conventional Tillage to No-Till	Lake States	Soybeans	$17
Conventional Tillage to No-Till	Delta	Wheat	$17
Conventional Tillage to No-Till	Northern Plains	Corn	$18
Conventional Tillage to No-Till	Mountain	Sorghum	$18
Reduced Tillage to No-Till	Northern Plains	Sorghum	$18
Reduced Tillage to No-Till	Lake States	Corn	$20
Conventional Tillage to No-Till	Pacific	Corn	$20
Conventional Tillage to No-Till	Lake States	Corn	$22
Conventional Tillage to No-Till	Delta	Soybeans	$23
Conventional Tillage to Reduced Tillage	Northern Plains	Corn	$23
Reduced Tillage to No-Till	Appalachia	Wheat	$24
Reduced Tillage to No-Till	Appalachia	Corn	$24
Reduced Tillage to No-Till	Northeast	Wheat	$24
Reduced Tillage to No-Till	Northeast	Corn	$25
Conventional Tillage to No-Till	Northern Plains	Sorghum	$26
Conventional Tillage to No-Till	Southern Plains	Sorghum	$27
Reduced Tillage to No-Till	Northern Plains	Wheat	$27
Conventional Tillage to No-Till	Delta	Sorghum	$27
Reduced Tillage to No-Till	Corn Belt	Corn	$30
Conventional Tillage to Reduced Tillage	Delta	Corn	$30
Conventional Tillage to No-Till	Corn Belt	Soybeans	$32
Conventional Tillage to Reduced Tillage	Lake States	Corn	$33
Reduced Tillage to No-Till	Northern Plains	Soybeans	$34
Conventional Tillage to No-Till	Corn Belt	Corn	$34
Reduced Tillage to No-Till	Delta	Soybeans	$36
Reduced Tillage to No-Till	Corn Belt	Wheat	$37
Reduced Tillage to No-Till	Lake States	Wheat	$38
Conventional Tillage to No-Till	Northern Plains	Wheat	$39
Conventional Tillage to No-Till	Appalachia	Corn	$42
Conventional Tillage to Reduced Tillage	Corn Belt	Corn	$43
Conventional Tillage to No-Till	Southern Plains	Wheat	$44
Conventional Tillage to No-Till	Northeast	Corn	$44
Conventional Tillage to No-Till	Lake States	Wheat	$47
Conventional Tillage to Reduced Tillage	Northern Plains	Sorghum	$49
Reduced Tillage to No-Till	Corn Belt	Sorghum	$51

Mitigation Practice	Region	Crop Type	Break-Even Price (2010 $/ mt CO_2-eq)
Conventional Tillage to Reduced Tillage	Mountain	Sorghum	$56
Conventional Tillage to No-Till	Corn Belt	Wheat	$57
Conventional Tillage to No-Till	Appalachia	Wheat	$57
Conventional Tillage to No-Till	Northeast	Wheat	$58
Reduced Tillage to No-Till	Lake States	Soybeans	$62
Reduced Tillage to No-Till	Pacific	Wheat	$63
Conventional Tillage to Reduced Tillage	Mountain	Wheat	$64
Reduced Tillage to No-Till	Delta	Cotton	$67
Reduced Tillage to No-Till	Northeast	Soybeans	$72
Reduced Tillage to No-Till	Appalachia	Soybeans	$72
Conventional Tillage to Reduced Tillage	Northern Plains	Wheat	$74
Conventional Tillage to No-Till	Corn Belt	Sorghum	$74
Reduced Tillage to No-Till	Corn Belt	Soybeans	$77
Conventional Tillage to Reduced Tillage	Southern Plains	Corn	$78
Reduced Tillage to No-Till	Southern Plains	Soybeans	$78
Conventional Tillage to Reduced Tillage	Delta	Wheat	$82
Conventional Tillage to No-Till	Southern Plains	Cotton	$93
Conventional Tillage to Reduced Tillage	Southern Plains	Sorghum	$93
Conventional Tillage to Reduced Tillage	Appalachia	Corn	$97
Conventional Tillage to Reduced Tillage	Lake States	Wheat	$101
Conventional Tillage to Reduced Tillage	Northeast	Corn	$101
Conventional Tillage to No-Till	Northeast	Soybeans	$104
Conventional Tillage to No-Till	Pacific	Wheat	$106
Conventional Tillage to Reduced Tillage	Delta	Sorghum	$111
Conventional Tillage to No-Till	Appalachia	Soybeans	$114
Reduced Tillage to No-Till	Southern Plains	Cotton	$126
Conventional Tillage to No-Till	Mountain	Cotton	$136
Conventional Tillage to No-Till	Delta	Cotton	$141
Conventional Tillage to Reduced Tillage	Corn Belt	Wheat	$188
Reduced Tillage to No-Till	Corn Belt	Cotton	$230
Conventional Tillage to Reduced Tillage	Southern Plains	Cotton	$280
Conventional Tillage to No-Till	Corn Belt	Cotton	$324
Conventional Tillage to Reduced Tillage	Mountain	Cotton	$466
Reduced Tillage to No-Till	Pacific	Cotton	$542
Conventional Tillage to Reduced Tillage	Delta	Cotton	$604
Conventional Tillage to Reduced Tillage	Corn Belt	Cotton	$1,700
Conventional Tillage to No-Till	Pacific	Cotton	$1,178[b]

[a] Negative break-even prices are a result of cost savings resulting from switching from conventional till to no-till, and switching from reduced till to no-till for soybeans in the Northern Plains and cotton in the Southeast.

[b] High break-even prices are primarily a result of relatively high yield reductions combined with the high price of cotton.

2.1.2 Qualitative Assessment of Other Potential Mitigation Strategies

Crop rotation changes, eliminating field residue burning, reducing lime application rates, and changing water and residue management practices in rice cultivation systems are frequently mentioned as potential GHG mitigation options associated with crop production systems. These options are discussed qualitatively in this section. Data are available for evaluating the break-even prices for some changes in crop rotations; hence, the discussion of this option is more detailed than the discussion of the other options. The remaining strategies have limited data available to quantify the GHG reduction, carbon sequestration potential, or costs, and, consequently, only brief descriptions of these options are provided.

2.1.2.1 Crop Rotation Changes

Crop rotation is a centuries-old practice of growing crops in a recurring sequence on the same field. It is often employed in combination with other conservation practices, such as reduced tillage intensity and nutrient management. Farmers use crop rotations for a variety of reasons, including improved nutrient management, reduced erosion, increased crop yields, pest and weed control, and soil health (Heimlich, 2003). Some rotation practices have been shown to increase soil carbon sequestration, particularly those that include a permanent conversion to reduced tillage intensity and/or a perennial crop rotation (Eagle et al., 2012; Liebig et al., 2012).

Summer fallow and winter cover crops are components of some crop rotations. Summer fallow is the practice of planting no crop on a field one year, followed by 1–2 years growing a crop. It is usually done in dry, wheat-growing areas such as the central Great Plains, and is intended to conserve soil moisture for the crop. Winter cover crops are grown mostly in wet, humid areas with sufficient rainfall to reduce erosion, improve soil health, and boost the yields of other crops (usually summer annual crops). Cover crops can be incorporated back into the soil as a green manure, or they can be harvested as a crop or forage.

Key factors that affect the feasibility of changing rotation patterns include climate, rainfall patterns, soil type and condition, and costs and returns from different crops. Many State NRCS offices have practice standards that are available for crop rotations and/or cover crops. These standards can inform farm-level decisions about crop and rotation selection. In general, the farmer is unlikely to face major changes in equipment needs unless the rotation changes are made at the same time as changes in tillage intensity.

Switching to crop rotation can result in higher yields than continuous monocropping (excluding areas that practice summer fallow). For example, grain yields following legumes can be 10–20% higher than continuous grain, independent of the amount of fertilizer used. A corn–wheat rotation provides higher yields than continuous corn with the same amount of fertilizer (Heimlich, 2003). Additional benefits include savings on feed when livestock are allowed to graze during certain periods of the rotation, and the potential for revenue gains from incorporating bioenergy feedstocks into the crop rotation. Field studies have demonstrated high variability in carbon sequestration potential when changing crop rotations.

The use of crop rotation can also result in reduced erosion, enhanced pest and weed control, and improved soil health (Heimlich, 2003). In addition, producers can benefit from improved soil quality and an improved balance of plant nutrients, and when incorporating legumes in a rotation, they can receive additional nitrogen through biological fixation. Crop rotations that include a fallow period can conserve water in semi-arid regions (USDA NRCS, 2011a).

The summer fallow period reduces the amount of crop residues entering the soil, increases the rate of carbon mineralization, and reduces soil carbon sequestration. For conventionally tilled wheat grown in areas with less than 325 mm of annual rainfall, summer fallow is a cost-effective strategy that accumulates water, nitrogen, and other nutrients. However, eliminating or reducing summer fallow has the potential to increase soil carbon storage, and is a viable option if alternative ways can be found to retain soil moisture, such as the use of no-till. Other potentially effective carbon sequestration options include increasing the number of years between fallow periods, increasing the diversity of rotation to include crops other than wheat, or including perennial crops in the rotation (Liebig et al., 2012). Summer fallow reduction/elimination is most effective in increasing carbon storage when combined with no-till (Denef et al., 2011; Eagle et al., 2012). Winter cover crops are easier to grow in regions where winter temperatures are higher, but their use is possible in most areas of the United States, except where soil moisture is a limiting factor (Denef et al., 2011; Eagle et al., 2012).

Using a winter cover crop can increase soil carbon sequestration by adding organic matter to the soil. If a legume such as red clover or hairy vetch is used, there is an additional benefit of added nitrogen in the soil through N-fixation, reducing the need for nitrogen fertilizers (and reducing N_2O emissions). Eagle et al. (2012) cite an average 0.07-mt CO_2-eq $ac^{-1}yr^{-1}$ reduction in N_2O emissions when annual crop rotations were diversified. The study goes on to state, however, that changes in crop rotations tend to have an insignificant or minimal impact on N_2O in most experiments analyzed. If a legume is incorporated into the rotation, a reduction in the nitrogen application rate could reduce N_2O emissions (this practice is presented later in the report); however, for the purposes of this analysis, only soil carbon sequestration potential is summarized below.

Data on the net GHG impact of crop rotations are available from an analysis of data from the U.S. GHG Inventory. In particular, data are readily available for five rotation changes as provided in Exhibit 2-11. As illustrated, the carbon sequestration varies by type of crop rotation. Other studies have identified lower carbon sequestration values closer to zero. In particular, from an analysis of 90 crop rotation change studies, Eagle et al. (2012) found an average soil carbon change near zero, although divergence from a monocropping system to some other rotation (excluding a corn–soybean rotation) resulted in an average gain of 0.04 mt CO_2-eq acre per year.

Exhibit 2-11: Annual Estimated Reductions in Atmospheric CO_2 in Response to Changes in Cropping Systems

Region	Current Practice	Alternate (Mitigation) Rotation	Carbon Sequestration (mt CO_2-eq/acre)[a]
Southeast	Continuous Corn	Corn with Cover Crop	0.55
Northern Plains	Spring Wheat/Fallow (RT, NT)	Spring Wheat/Winter Wheat/Corn/Sunflower (RT, NT)	0.38
Pacific	Wheat/Fallow (CT, NT)	Wheat/Pea (CT, NT)	0.21
Southeast	Cotton (NT)	Cotton with Cover Crop (crimson clover/rye) (NT)	0.17
Southern Plains	Wheat/Fallow (CT, RT, NT)	Continuous Wheat (CT, RT, NT)	0.11

Note: CT = Conventional tillage, RT = Reduced tillage, NT = No-till

[a] N_2O emissions or reductions are not included in these estimates.

Source: Data are from the U.S. National Inventory of GHG Emissions and Sinks and other sources as reported by the Greenhouse Gas Working Group (2010) cited in Ogle (2011b).

Crop rotations that result in increased carbon sequestration primarily entail two types: eliminating fallow or planting an alternative crop:

- Eliminating fallow is problematic as it is essential in some cases for increasing soil moisture and maintaining soil quality. Consequently, this type of crop rotation will only be applicable to limited land areas. Eliminating fallow will obviously be cost-effective over the short term for a landowner as he or she will receive additional crop revenue. In this situation, an incentive would not be needed for eliminating fallow (i.e., the break-even price would be negative).

- Planting an alternative crop will likely result in a loss of revenue and, hence, will be a barrier to adoption as landowners would need to transition from the optimal crop for their regional market, climate, and soil conditions. In addition, planting a cover crop will not compensate for the decrease in revenue from more profitable crops (e.g., cotton revenue in a cotton-to-cover crop rotation). Consequently, rotations involving the planting of an alternative crop would likely result in a prohibitively high break-even price.

Given the extreme situations for the incentive level (i.e., break-even prices are either highly negative [cost-effective] or positive [cost-prohibitive]), the break-even prices are not evaluated in this report. Although crop rotations can increase carbon sequestration, this practice is unlikely to be widely adopted in response to a GHG mitigation incentive.

2.1.2.2 Field Burning Elimination

While crop residues are burned in all regions of the country except New England, more than 50% of GHG emissions associated with residue burning occur in the Southeast, the Great Plains, the Pacific Coast, and the Southwest. In general, crop residue burning is not a major residue management strategy in the United States. Two exceptions are rice and sugarcane (see Exhibit 2-12).

Exhibit 2-12: U.S. Average Percentage of Crop Area Burned in 2010

Crop Type	2010
Corn	+
Cotton	1%
Lentils	1%
Rice	10%
Soybeans	+
Sugarcane	32%
Wheat	2%

\+ = Less than 0.5%
Source: EPA (2012).

Eliminating residue burning has been proposed as a GHG mitigation option because burning residues emit CH_4 and N_2O, as well as biogenic CO_2. In practice, the GHG mitigation potential of eliminating crop residue burning is likely very limited. First, total annual emissions of CH_4 and N_2O from all crop residue burning are on the order of 0.3 to 0.4 Tg CO_2-eq. Additionally, farmers typically burn residues to control diseases, weeds, and insects, as well as to reduce the need for tillage. For example, rice straw is burned to control fungal diseases, dispose of straw (which has limited value), and facilitate soil tillage and seedbed preparation (CalRice, 2011). Sugarcane is burned before harvest to dispose of leaves, which otherwise make harvesting difficult.

In considering whether to accept an incentive to eliminate residue burning, farmers will factor in the value of these production benefits. Ultimately, there are good economic reasons why farmers burn residues (e.g., disease control) and the loss of these benefits would affect the farmers' response to any GHG mitigation incentive.

2.1.2.3 Reduced Lime Application

Farmers apply crushed limestone and dolomite (lime) to soils to mitigate soil acidity; sometimes the soil's acidity is due partly to nitrification from the application of nitrogen fertilizers. Most liming in the United States occurs in the Southeast, with about 75% occurring in the Mississippi River basin (West and McBride, 2005). When lime is applied to soils, CO_2 is released. Reducing lime application to agricultural soils reduces the associated CO_2 emissions, but the resulting increase in soil acidity would generally reduce crop yields. Reducing lime may need to be part of a more comprehensive soil and nutrient management scheme that could include more careful placement or lower application rates of nitrogen fertilizer. In addition, recent research suggests that emissions from lime applications in the United States may be lower than previously thought due to the form of acidic reaction taking place in soils (West and McBride, 2005). In 2010, CO_2 emissions from agricultural liming were 3.9 Tg CO_2-eq, which represented a 16% decrease in emissions from 1990 to 2010 (EPA, 2012). This decrease was driven by reduced lime application to soils over the 20-year time period. Limited data are available on this practice as a GHG reduction measure.

2.1.2.4 Changes in Rice Cultivation Practices

In 2009, methane emissions from U.S. wetland rice cultivation totaled 7.3 Tg CO_2-eq—or about 1% of total U.S. CH_4 emissions (EPA, 2011). A number of rice management practices have been proposed to reduce these emissions, but the GHG mitigation potential is not currently well understood. For example, mid-season drainage has been shown to reduce CH_4 emissions in some studies (Li et al., 2004; Wassmann et al., 2000); however, in regions with high soil carbon, N_2O emissions rose significantly following drainage (Li et al., 2005). In a meta-analysis by Ogle et al. (2010), key management options affecting CH_4 emissions from rice production included water table management (i.e., midseason drainage and/or a fallow period that reduces emissions) and organic amendment additions.

Van Kessel and Horwath (2012) noted that straw incorporation, while it leads to an increase in CH_4 emissions, could also sequester soil carbon and preserve soil nitrogen. The authors also note, however, that increased weed and disease pressure may result from straw incorporation (Van Kessel and Horwath, 2012). Ultimately, this practice must be better understood before it can be recommended as a GHG mitigation option.

Finally, rice seed varieties that produce higher yields are a potential option for reducing GHG emissions. More efficient use of carbon to produce grain instead of root and shoot production could decrease CH_4 emissions (Eagle et al., 2012). However, results vary widely, and are likely affected by differences in the ability of rice aerenchyma tissue to transport CH_4 from the roots or oxygen to the roots, soil redox potential, and the availability of substrate for methanogens (Denef et al., 2011). In addition, CH_4 emissions from flooded rice fields are influenced by fertilization, residue management, soil temperature, soil type, rice variety, and cultivation practices (Ogle et al., 2010).

2.2 Nutrient Management

The primary nutrients applied to U.S. cropland are nitrogen (N), phosphorous (P), and potassium (K). Farm use of phosphorous and potassium does not directly result in GHG emissions; however, these nutrients—when available to plants—can result in improved nitrogen use efficiency and have the potential to reduce N_2O emissions by the reduction of nitrate (NO_3) levels. Improved use of nitrogen to reduce direct N_2O emissions through adjustments in the nitrogen fertilizer rate, timing, source,[5] and application techniques are considered in this section. These adjustments form the basis of nutrient management practices and are summarized in Textbox 2- 4. Textbox 2- 5 illustrates two additional tools for managing NUE at the farm level. These tools are not evaluated quantitatively in this report, but provide landowners with options for managing nitrogen levels and evaluating alternative management scenarios.

Nutrient Management GHG Mitigation Options

- Reduce Application Rate
- Shift from Fall to Spring Fertilizer Application
- Inhibitor Application
    - Nitrification Inhibitors
    - Urease Inhibitors
- Use Variable Rate Technology

Nutrient management, for the purposes of this report, is the management of nitrogen applied to or released in agricultural soils. Nitrification and denitrification processes are the primary sources of N_2O emitted from soils. Denitrification is usually the dominant source in the relatively moist soils found in the eastern and central United States. Nitrification can also be a major source of N_2O emissions, particularly following application of ammoniacal fertilizers in semi-arid areas (Liebig et al., 2012).

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[5] While certain studies (Fujinuma et al., 2011; Venterea et al., 2005; Venterea et al., 2010) have shown that N_2O emissions from anhydrous ammonia are often greater than that of other nitrogen fertilizers in certain production regions, nitrogen formulation differences are not evaluated quantitatively in this report (with the exception of inhibitors) due to limited data availability.

Textbox 2-4: Nutrient Management Practices

Fertilizer Application

- **Fertilizer Application Rate:** Reductions in the rate (i.e., the amount per acre) of synthetic fertilizer application can lead to N_2O emissions reductions. In some cases, reductions in fertilizer application can be made without reducing the crop yield.
- **Timing of Fertilizer Application:** Crop nitrogen uptake generally follows the growth patterns of plants. Uptake capacity is low at the beginning of the growing season, increases during vegetative growth, and diminishes as the crop nears maturity. Synchronizing the timing of nitrogen application with plant nitrogen demand can reduce nitrogen losses, including N_2O emissions in some situations. The reduction in nitrogen losses may be limited in semi-arid climates with low leaching potential.
- **Placement:** Where and how nitrogen is applied can affect N_2O emissions. Injecting fertilizer deep (at or below 4 inches) into the soil instead of broadcast application can reduce emissions, volatilization, and leaching, although the results vary (Ogle et al., 2010).
- **Nitrogen Formulation:** Different formulations of nitrogen produce different amounts of N_2O. Generally, nitrate-based fertilizers have been shown to produce smaller amounts of N_2O than ammonium-based fertilizers (Bouwman et al., 2002a), although the mitigation potential varies.
- **Nitrogen Release Rate:** Slow-release fertilizers discharge soluble nitrogen (NH_4 and NO_3) over several weeks/months, increasing the amount of fertilizer recovered by the plant and improving the synchronization between plant uptake and nitrogen availability. These products have been shown to increase the recovery of applied nitrogen by 33% worldwide in cereal grains and reduce the need for additional applications, while reducing the risk to seedlings (Delgado and Follett, 2010).

Inhibitor Application

- Nitrification and urease inhibitors are toxic to nitrifying bacteria and inhibit nitrification temporarily when added to the soil (Delgado and Follett, 2010). Nitrification inhibitors are a chemical compound that slow the rate of ammonium conversion to nitrate by inhibiting the metabolism of *Nitrosomonas* bacteria (Nelson and Huber, 2001). The nitrification inhibitor N-Serve® was selected for analysis in this report.
- Urease inhibitors impede the urease enzyme that catalyzes the hydrolysis of urea into CO_2 and ammonia. Agrotain® was selected for analysis in this report.

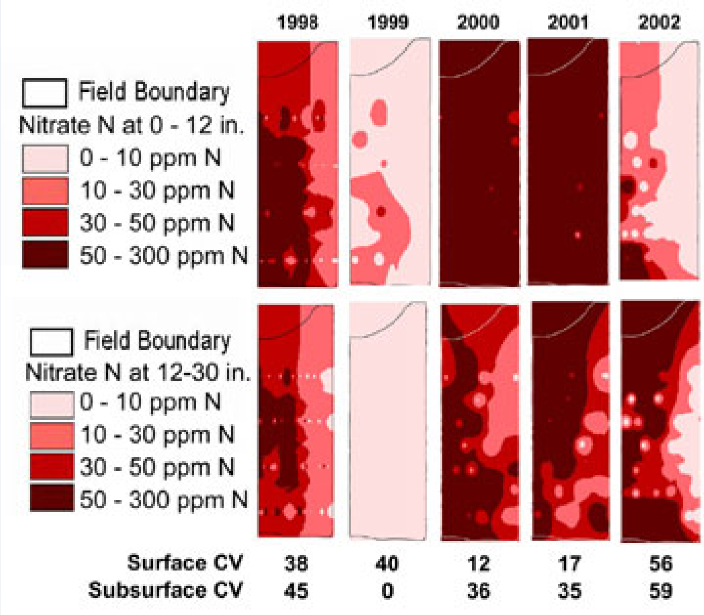
Variable Rate Technology

- Variable rate technology or site-specific management allows more precise input application based on soil and field characteristics. Variable rate technology relies on global positioning systems (GPS) and geographical information systems (GIS) that enable producers to identify field locations so that inputs may be customized. A GIS allows users to store and retrieve input and output data layers for future input allocation decisions (Surjandari and Batte, 2003). An automated variable rate technology is GreenSeeker™. This technology measures a crop's vegetative index, predicts yield potential, and then delivers the optimum rate of nitrogen at a ¼- to ½-acre scale (N Tech Industries, 2011).

Textbox 2-5: Additional Nutrient Use Efficiency Tools

Late Spring Nitrate Test (LSNT) is a type of base map used to determine nitrogen needs for different sections of a given parcel of land. By using a map based on soil sampling by zone, landowners can adjust input rates to meet crop needs. Because nitrogen is mobile, LSNT maps for nitrogen are less effective at pinpointing nitrogen needs compared with phosphorus and potassium. The graphic below illustrates the results of a typical LSNT test over a 4-year period. The darker areas indicate areas of higher nitrogen concentration. Using these maps, farmers can better match nitrogen applications to crop nitrogen needs. In a study by Jaynes et al. (2004), adoption of LSNT management for nitrogen fertilizer application was predicted to result in a 30% or greater decrease in nitrate concentrations in surface water.

Late Spring Nitrate Test Result



Source: Davenport (2010).

Dynamic Base (Adapt-N) is a Cornell University Web-based model that is used for managing nitrogen. It allows users to input climatic conditions, soil, tillage, nitrogen source, timing, and weather interactions. The model relies on three components: nitrogen transformations and water transport, crop growth and nitrogen uptake simulation, and weather data from the Northeast Regional Climate Center at Cornell (Milkonian et al., 2007). Weather data are currently available only for the Northeastern region and Iowa, which limits the model's applicability to other regions (Cornell University, 2011). The adjacent graphic presents a screenshot of the Adapt-N Dynamic Base model and some of the features that it contains.

Adapt-N Dynamic Base Model

Provide in-season N recommendations for corn production based on simple soils, management and crop inputs.

Key feature: accounts for changes in soil N due to early season weather and adjusts the in-season N recommendations accordingly.

Source: Van Es et al. (2010).

The key purposes of nutrient management are to (1) budget and supply nutrients for plant production; (2) ensure the proper use of manure or organic byproducts as a plant nutrient source; (3) minimize agricultural nonpoint source pollution of surface and groundwater resources; (4) protect air quality by reducing nitrogen emissions (ammonia, NO_x, and N_2O) and the formation of atmospheric particulates; and (5) maintain or improve the physical, chemical, and biological condition of the soil (USDA NRCS, 2011a).

The USDA NRCS Environmental Quality Incentives Program (EQIP) provides technical and financial assistance to farms to encourage the adoption of best management practicies (BMPs) related to nutrient use. Nutrient management plans are a key component of EQIP (Ribaudo et al., 2011). Typically, a nutrient management plan includes general information about the land, an environmental assessment, a nutrient assessment with planned applications for the year, a management assessment, and additional inputs for certain types of producers. Nutrient management plans often require that application rates be developed based on an assessment of plant available nitrogen in the soil through Land Grant University soil and tissue tests. Plans must also specify how BMPs will budget and supply nutrients for plant production while minimizing the flow of nutrients into surface and groundwater resources (USDA NRCS, 2010c).

BMPs for field-level nitrogen use have been developed to help farmers match the delivery of nutrients to specific crop and field situations. Nutrient use efficiency (NUE) is the proportion of all nitrogen inputs that are removed in harvested crop biomass, contained in recycled crop residues, and incorporated into soil organic and inorganic nitrogen pools. A higher NUE value implies less nitrogen loss into the environment (Ribaudo et al., 2011). Exhibit 2-13 shows the percentage of acres where USDA ERS estimates that BMPs regarding the rate, timing, and application method for nitrogen fertilizers are not being met (Ribaudo et al., 2011). Conceptually, these percentages reflect the potential cropland area where changes in application rate, timing, and application method could be adopted without decreasing crop yields.

Exhibit 2-13: Shares of Treated Acres and Applied Nitrogen Not Meeting Rate, Timing, or Method Criteria by Crop

Crop	Criteria		
	Did not meet rate[a]	Did not meet timing[b]	Did not meet method[c]
	(percentage of treated acres)		
Barley	14	20	25
Corn	25	34	37
Cotton	47	18	32
Oats	33	28	42
Peanuts	0	16	39
Sorghum	24	16	27
Soybeans	3	28	45
Wheat	34	11	37
Average	**32**	**24**	**37**

[a] "Did not meet rate" indicates that managers applied nitrogen (commercial and manure) at a rate of 40% more than that removed with the crop at harvest based on the stated yield goal, including any carryover from the previous crop (Ribaudo et al., 2011; USDA NRCS, 2010a).

[b] "Did not meet timing" indicates that managers applied nitrogen in the fall for a crop planted in the spring (Ribaudo et al., 2011).

[c] "Did not meet method" indicates that managers broadcast fertilizer onto the soil rather than injecting it (placing fertilizer directly into the soil) or incorporating it (applying it to the surface and then disking the fertilizer into the soil) into the soil.

Source: Ribaudo et al. (2011).

Four potential GHG mitigation practices associated with managing nitrogen in crop production systems are presented in this section. For each practice, the following information is provided: a technology characterization, an assessment of current and potential adoption rates, estimated farm-level GHG benefits relative to a typical management practice, a description of other farm-level environmental and production impacts (relative to the typical management practice), a cost profile for implementing the mitigation option, and estimated break-even prices. The break-even prices reflect the CO_2 incentive level (stated in dollars per mt CO_2-eq) that various representative farm operations would need to achieve to make adoption of the practice pay for itself.

2.2.1 Reduce Fertilizer Application Rate

2.2.1.1 Technology Characterization

Applying the optimum amount of nitrogen to a crop is a delicate balance. Nitrogen is typically the limiting nutrient in row crop systems (Millar et al., 2010). As a result, most acres planted with row crops receive supplemental nitrogen through either commercial fertilizer or manure. Once applied, however, nitrogen can oxidize to the atmosphere, run off to adjacent lands and surface waters, or leach into groundwater supplies. These pathways off of the field can lead to negative environmental outcomes, including N_2O and ammonia emissions, contamination and eutrophication of surface waters, and contamination of groundwater supplies. Among the factors affecting the mobility of nitrogen are recent and current weather conditions, various soil properties, and past and present field management practices. These factors make it difficult to know, at the time of application, the amount of nitrogen to put on a given field to meet crop nutrient needs.

Key Features of Reducing Fertilizer Application Rate

- Decreases per-acre fertilizer costs.
- Applicable GHG mitigation option for all crops.
- Most effective at GHG mitigation in warm, wet climates on soils with high organic matter content or where tillage has occurred.
- Additional equipment is not required to reduce nitrogen application.
- Has the lowest level of technology compared to other nutrient management GHG mitigation practices.
- Decreases nitrogen runoff into adjacent land and bodies of water, nitrogen leaching into groundwater, and trace gas and ammonia emissions.
- Has the potential to decrease yields.

Excessive application decreases financial returns and increases the potential for nitrogen leaching into the environment. Insufficient application can reduce yields and net farm income (Ribaudo et al., 2011). A number of studies have concluded that many farmers apply nitrogen in excess of crop nutrient needs (Bausch and Delgado, 2005; Millar et al., 2010; Ribaudo et al., 2011).

Current and Potential Adoption

NRCS nutrient management guidance suggests that nitrogen application rates match Land Grant University recommendations and consider current soil test results, realistic yield goals, and management capabilities (USDA NRCS, 2011a). Ribaudo et al. (2011) propose that farmers apply "no more nitrogen (commercial and manure) than 40% more than that removed with the crop at harvest, based on the stated yield goal, including any carryover from the previous crop" (p. 9). Based on these criteria, Ribaudo et al. (2011) determined that nitrogen is being over- or under-applied on about 53 million acres (or 32% of all acres treated with nitrogen) in the United States (see Exhibit 2-13).[6] In 2006, the Corn Belt, Lake States, and Northern Plains had the highest nitrogen applications above the rate criteria cited in Ribaudo et al. (2011). Nitrogen applications in excess of or below crop growth needs reduce net farm income (through either higher fertilizer costs or lower yields). This suggests that farmers who perceive that they can apply less nitrogen without incurring a yield penalty will likely do so without any additional incentive. It also suggests that farmers who are applying nitrogen in excess of plant nutrient needs expect, at least on average, that yields will decrease if they reduce the nitrogen. One possibility is that some farmers accept additional fertilizer costs in some years to ensure that growing crops have adequate nutrients in all years. Another possibility is that some farmers apply fertilizers based on the expectations of favorable weather conditions for crop production. When actual weather conditions are less favorable, nitrogen is applied in excess of plant needs. In assessing reductions in nitrogen applications as a farm-level GHG mitigation option, it is reasonable to assume that farmers will be more receptive to smaller rather than larger reductions, and that farmers will consider a yield penalty as a cost of adoption.

Other studies have demonstrated that nitrogen application can by reduced by more than 50% without significant yield impacts (Bausch and Delgado, 2005; Millar et al., 2010). This report assumes a 10% reduction in nitrogen application rate to balance landowner concerns for maintaining crop yields while also minimizing the impacts to the environment. Exhibit 2.A-1 details the number of acres growing major crops in the United States in 2007 (USDA NASS, 2008). Exhibit 2-14 identifies the percentage of acres that are treated with nitrogen (USDA NASS, 2008).

Exhibit 2-14: Acres Treated with Nitrogen[a]

Crop	Acres Treated with Nitrogen by Region (percent)										
	All	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn	95	98	96	98	94	82	94	94	82	98	94
Cotton	91	97	98	97	N/A	89	N/A	85	89	91	85
Sorghum	82	82	100	82	82	62	82	70	82	82	67
Soybeans	19	18	12	18	21	19	21	32	19	18	32
Wheat	86	86	96	86	93	87	93	85	87	86	85

Farms Treated with Nitrogen[a] (percent)				
Crop	Farm Size			
	Large (>800 acres)	Mid (300–800 acres)	Small (<300 acres)	All Farms
Corn	95	94	96	95
Cotton	93	86	93	91
Soybeans	17	17	22	19
Wheat	90	83	79	86

[a] Sorghum data are not available at the farm-size level.
N/A = Not applicable
Source: USDA ERS (2011c).

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[6] Viewed by commodity, the percentage of acres not meeting the rate criteria is highest for cotton (47%) and ranges from 24% to 34% for corn, oats, sorghum, and wheat (Ribaudo et al., 2011).

Production and Environmental Impacts

Production Impacts. Where per-acre nitrogen applications can be reduced without affecting crop yields, there will be a per-acre cost savings associated with reduced fertilizer purchases (Bausch and Delgado, 2005; Millar et al., 2010).

Other Environmental Impacts. Decreased nitrogen application rates will decrease nitrogen runoff and leaching into nearby surface water and groundwater. In many areas, this decrease will help ease problems with eutrophication of surface water bodies and nitrogen contamination of groundwater resources (Hoeft et al., 2000). In addition, if reduced yields are observed, producers may compensate by shifting crop production to less efficient or marginal land, leading to further degradation (Eagle et al., 2012).

Barriers to Adoption

The key challenge to reducing nitrogen application rates is the potential and the perceived potential for incurring yield reductions.

2.2.1.2 GHG Impacts[7]

Various studies have found that nitrogen fertilizer application rates correlate well with N_2O emissions (Millar et al., 2010).[8] Despite a close correlation, the relationship between nitrogen application and N_2O emissions is not necessarily linear (Hoben et al., 2011; McSwiney and Robertson, 2005). In particular, Bouwman et al. (2002b) found that the relationship of N_2O emissions to nitrogen application rate increases proportionally with the nitrogen application rate.

To illustrate the range in estimates and the inherent uncertainty, low and high emissions reduction scenarios were developed. The low-end emissions reduction scenario is based on outputs generated by the DAYCENT model that is used in the U.S. Inventory of GHG Emissions and Sinks to estimate N_2O emissions from soil management (Ogle, 2011b). The high emissions reduction scenario is based on a synthesis of the literature conducted by the Nicholas Institute (Eagle et al., 2012).[9] Emissions reduction estimates in the Nicholas Institute report are for a 15% reduction in nitrogen application; consequently, the data points were multiplied by two-thirds to represent a 10% reduction in nitrogen application for the sake of comparison. Exhibit 2-15 presents the low and high emissions reduction scenarios by USDA region. The emissions reductions shown in the Low N_2O Emissions Reduction Scenario were found to be similar to those presented in a meta-analysis by (Ogle et al., 2010). This study estimates that an average of 1.19% of nitrogen added to soils is released as N_2O. Similarly, a report by the Council for Agricultural Science and Technology (CAST) indicates that because cropped soils emit N_2O at a rate of 0.2–3% of their nitrogen inputs, decreasing nitrogen inputs in cropping systems could decrease N_2O emissions directly by approximately 1.25% of nitrogen inputs saved (Paustian, et al., 2004). At the field scale, these scenarios illustrate that (1) N_2O emissions will vary across locations at a given time period and across time periods at a given location; and (2) point estimates of N_2O emissions associated with applied nitrogen will be inherently uncertain.

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[7] N_2O emissions from soils are driven by the availability of oxygen and mineral nitrogen in the soil, as well as the carbon substrate. These emissions are influenced by moisture conditions, soil structure and texture, soil organic matter dynamics, and nitrogen management. Consequently, N_2O emissions are dynamic in time and space.

[8] Additional studies with similar findings include Bouwman et al. (2002b); Halvorson et al. (2008); and Mosier et al. (2006).

[9] Based on a collection of 32 data points for a 15% fertilizer nitrogen rate reduction, the average decrease in N_2O emissions is 0.11 mt CO_2-eq/acre (Eagle et al., 2012).

Exhibit 2-15: N_2O Emissions Reduction Potential for a 10% Nitrogen Reduction[a]

Crop	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Low N_2O Emissions Reduction Scenario (mt CO_2-eq/acre)										
Corn	0.01	0.03	0.02	0.02	0.01	0.01	0.01	+	0.02	0.01
Cotton	+	0.01	0.02	N/A	+	N/A	0.01	+	0.01	+
Sorghum	+	0.01	0.01	+	+	+	+	+	0.01	+
Soybeans	+	+	+	+	+	+	0.03	+	+	+
Wheat	0.01	0.02	0.01	0.02	+	0.01	0.01	+	0.01	0.01
High N_2O Emissions Reduction Scenario (mt CO_2-eq/acre)										
All Crops	0.08	0.16	0.08	0.15	0.02	0.08	0.005[b]	0.08	0.08	0.08

[a] + = Negligible reduction in emissions.

[b] The high emissions reduction scenario defined in Eagle et al. (2012) is not always higher than the low emissions reduction values defined in Ogle (2011b). As indicated, the high emissions reduction scenario has a lower emissions reduction potential for the Northern Plains (i.e., 0.005 mt CO_2-eq/acre) (Bemer, 2006) than the low emissions reduction scenario (i.e., 0.01 mt CO_2-eq ac^{-1}yr^{-1}) (Ogle, 2011b).

Sources: The low emissions reduction scenario (Ogle, (2011b) is based on outputs from the DAYCENT model. The high emissions reduction scenario is from Eagle et al. (2012). The values in Eagle et al. were multiplied by 0.67 to adjust from a 15% to a 10% nitrogen reduction. The national average of 0.08 mt CO_2-eq/acre was used for regions that lack relevant studies.

2.2.1.3 Cost Profile

Exhibit 2-18 provides a cost profile for reducing per-acre nitrogen use for acres where there would be a yield penalty. The key calculations for estimating net costs are summarized below. The resulting break-even prices are presented in Exhibit 2-19.

Estimate Change in Yield Associated with Reducing Fertilizer Application by 10%. Changes in crop yield resulted in a loss in crop revenue across all crops and regions when fertilizer rates were reduced by 10%. Key assumptions include the following:

- Estimated yield changes presented in Exhibit 2-16 are in response to a 10% fertilizer reduction.
- Fertilizer application rates are presented in Exhibit 2-17. Fertilizer and crop prices are shown in Appendix 2-A.
- All crops are rain-fed.

Exhibit 2-16: Estimated Changes in Annual Crop Yields in Response to a 10% Reduction in Nitrogen Application Rate

Crop	Changes in Annual Crop Yield by Region (metric tons dry matter/acre)									
	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn	-0.03	-0.07	-0.06	-0.04	+	-0.03	-0.07	+	-0.04	-0.06
Cotton	+	-0.01	-0.02	N/A	+	N/A	-0.05	+	-0.01	+

Crop	Changes in Annual Crop Yield by Region (metric tons dry matter/acre)									
	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Sorghum	+	-0.03	-0.01	+	-0.01	+	-0.03	+	-0.02	-0.03
Soybeans	-0.01	+	-0.04	-0.01	+	-0.01	-0.02	+	-0.01	-0.02
Wheat	-0.01	-0.02	-0.02	-0.03	-0.01	-0.01	-0.03	-0.01	-0.02	-0.04

+ = Negligible
N/A = Not applicable
Source: Ogle (2011d).

Estimate Change in Costs and Revenues Associated with Reducing Fertilizer Application by 10%. As yield changes are all negative or "no change," crop revenue values are negative in the cost profile, representing a loss to the farmer. The costs are negative and reflect a cost savings to the farmer due to purchasing less nitrogen fertilizer. The cost profiles developed below reflect the differences in costs between the current application of nitrogen as shown in Exhibit 2-17 and applying 10% less nitrogen (on a per-acre basis). Fertilizer costs associated with the 10% reduction in fertilizer application rates were estimated using Equation 2 below.

Equation 2:

$$\text{Change in Fertilizer Cost} = \text{N Application Rate} \times \text{Change in N Application Rate} \times \frac{\text{Fertilizer Price}}{\text{Fertilizer N Content}}$$

Where:

Change in N Application Rate = -10%

Units:

- Change in Fertilizer Cost: $/acre
- N Application Rate: lbs/acre
- Fertilizer Price: $/ton of fertilizer
- Fertilizer N Content: lbs of N per ton of specified fertilizer

The cost profiles shown in Exhibit 2-18 assume the following:

- Nitrogen use per acre is presented in Exhibit 2-17. The nitrogen application rate was multiplied by -10% to generate the reduction in nitrogen rate value.
- Current fertilizer prices as presented in Exhibit 2.A-4 are based on USDA data. The reduced fertilizer rate was multiplied by the price of the fertilizer and divided by the fertilizer nitrogen content of either anhydrous ammonia or urea.
- Corn, sorghum, and soybeans use anhydrous ammonia; cotton uses urea; and wheat uses a 50:50 mix of anhydrous ammonia and urea. Fertilizer cost savings are based on the cost of these fertilizers for each crop in each region (USDA ERS, 2011b) and Equation 2.
- Nitrogen content varies by type of fertilizer (listed as Fertilizer N Content in Equation 2) and is based on data from Abaye et al. (2006), and is provided inExhibit 2.A- 6.
- There is no change in labor or capital costs for reducing fertilizer application rates.
- Per-acre fertilizer application costs do not vary by farm size.

Additionally, crop prices and yields were used to calculate crop revenue losses (Exhibit 2-16, Exhibit 2.A-5).

Exhibit 2-17: Nitrogen Use per Acre by Region for Major Crops

Crop	Nitrogen Use by Region (lbs nitrogen/acre/year)									
	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn	62	125	116	80	107	62	80	107	116	98
Cotton	62	62	80	62	62	62	62	62	80	36
Sorghum	36	62	62	45	54	36	45	54	62	54
Soybean	18	18	18	18	18	18	18	18	27	18
Wheat	54	80	54	71	45	54	45	54	54	62

Source: Ogle (2011c).

Exhibit 2-18: Cost Profile for Reduced Fertilizer Application Accounting for Changes in Yield

		(2010 $/acre)									
Cost Category[a,b]		Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn	Fertilizer Costs	-$2.45	-$4.89	-$4.54	-$3.15	-$4.19	-$2.45	-$3.15	-$4.19	-$4.54	-$3.84
	Crop Revenue	-$4.39	-$10.11	-$8.15	-$5.63	$0.00	-$4.60	-$9.67	$0.00	-$5.83	-$8.77
Cotton	Fertilizer Costs	-$3.28	-$3.28	-$4.22	N/A	-$3.28	N/A	-$3.28	-$3.28	-$4.22	-$1.88
	Crop Revenue	$0.00	-$12.56	-$26.49	N/A	$0.00	N/A	-$69.05	$0.00	-$13.71	$0.00
Sorghum	Fertilizer Costs	-$1.40	-$2.45	-$2.45	-$1.75	-$2.10	-$1.40	-$1.75	-$2.10	-$2.45	-$2.10
	Crop Revenue	$0.00	-$4.20	-$1.23	$0.00	-$1.45	$0.00	-$4.02	$0.00	-$2.50	-$4.03
Soybean	Fertilizer Costs	-$0.70	-$0.70	-$0.70	-$0.70	-$0.70	-$0.70	-$0.70	-$0.70	-$1.05	-$0.70
	Crop Revenue	-$3.31	$0.00	-$12.33	-$3.22	$0.00	-$3.30	-$6.37	$0.00	-$3.28	-$6.20
Wheat	Fertilizer Costs	-$1.83	-$2.88	-$1.83	-$2.53	-$1.48	-$1.83	-$1.48	-$1.83	-$1.83	-$2.18
	Crop Revenue	-$1.63	-$3.23	-$3.16	-$5.23	-$1.99	-$1.68	-$5.78	-$1.99	-$3.18	-$7.63

[a] Negative fertilizer costs indicate a *savings* to the farmer resulting from less fertilizer purchased.

[b] Negative crop revenue indicates a *loss* to the farmer resulting from reduced yield.

Source: Calculated using sources listed above.

2.2.1.4 Break-Even Prices

Break-even prices for a 10% reduction in nitrogen fertilizer are presented in Exhibit 2-19. Conceptually, break-even prices reflect the carbon incentive level where a given GHG mitigation option becomes economically viable to the farmer (i.e., the point at which the net present value of the benefits equals the net present value of the costs). Break-even prices were developed that account for changes in yield, which were primarily negative or showed negligible change (see Exhibit 2-16). Instances where the savings from reduced fertilizer application outweighed the revenue loss from yield reductions are indicated as <$0 in Exhibit 2-19 (e.g., corn in the Mountain region, sorghum in the Delta region, wheat in the Appalachian and Northeast regions). For these situations that represent a net savings, farmers would likely not need a financial incentive to implement this practice. Negative break-even prices are close to zero due to the savings from reduced fertilizer use being approximately equal to the yield revenue losses.[10]

Break-even prices are presented for low and high emissions reduction scenarios in Exhibit 2-19. Although break-even prices in certain instances are negative, landowners may not implement this practice due to the perceived risk of yield impacts, lack of familiarity with the practice, or other factors that discourage reduced fertilizer application. A high break-even price indicates that the savings from reduced fertilizer use are much less than the yield revenue losses. The highest break-even prices were observed in the Northern Plains (corn, wheat, and soybeans) and cotton in the Southeast and Delta regions.

Exhibit 2-19: Break-Even Prices for 10% Reduced Fertilizer Application Rate Accounting for Decreases in Yield

Low Emissions Reduction Scenario		
Region	**Crop Type**	**Break-Even Price (2010 $/ mt CO_2-eq)**
Mountain	Corn	<$0[a]
Delta	Sorghum	<$0
Appalachia	Wheat	<$0
Northeast	Wheat	<$0
Corn Belt	Wheat	$17
Southeast	Corn	$64
Lake States	Corn	$124
Delta	Wheat	$133
Lake States	Wheat	$135
Southeast	Wheat	$135
Corn Belt	Corn	$174
Corn Belt	Sorghum	$175
Delta	Corn	$180
Northern Plains	Soybeans	$189
Appalachia	Corn	$194
Northeast	Corn	$215

High Emissions Reduction Scenario		
Region	**Crop Type**	**Break-Even Price (2010 $/ mt CO_2-eq)**
Mountain	Corn	<$0
Delta	Sorghum	<$0
Appalachia	Wheat	<$0
Northeast	Wheat	<$0
Corn Belt	Wheat	$2
Corn Belt	Sorghum	$11
Lake States	Corn	$17
Southeast	Corn	$17
Delta	Wheat	$18
Southeast	Wheat	$18
Lake States	Wheat	$18
Appalachia	Corn	$26
Northeast	Corn	$28
Corn Belt	Corn	$32
Delta	Corn	$48
Southern Plains	Corn	$65

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[10] Studies support the feasibility of reducing nitrogen rates without incurring adverse impacts on yield. Millar et al. (2010) argue, based on their study of seven midwestern States, that nitrogen rates could be lowered from greater than 223 lbs nitrogen per acre to 175 lbs nitrogen per acre and still be within the high economically profitable nitrogen rate range for corn according to the Maximum Return to Nitrogen (MRTN) approach.

Low Emissions Reduction Scenario		
Region	**Crop Type**	**Break-Even Price (2010 $/ mt CO_2-eq)**
Northern Plains	Wheat	$429
Southern Plains	Corn	$492
Southern Plains	Wheat	$545
Northern Plains	Corn	$652
Southeast	Cotton	$949
Delta	Cotton	$1,114

High Emissions Reduction Scenario		
Region	**Crop Type**	**Break-Even Price (2010 $/ mt CO_2-eq)**
Southern Plains	Wheat	$72
Southeast	Cotton	$126
Delta	Cotton	$295
Northern Plains	Wheat	$796
Northern Plains	Soybeans	$1,050
Northern Plains	Corn	$1,209[b]

[a] <$0 = Break-even price is negative due to the fertilizer savings per acre being greater than the revenue losses per acre. That is, there were no estimated yield changes for corn in the Mountain region, and relatively small yield decreases for sorghum and wheat when compared to the corresponding fertilizer savings for these crops and regions.

[b] In this instance, break-even prices in the Northern Plains tend to be higher for the high emissions reduction scenario than for the low emissions reduction scenario (i.e., $796 versus $429 per mt CO_2-eq). Exhibit 2-15 presents the N_2O emissions reductions and illustrates that not all high emissions reductions are greater than the lower emissions reduction scenarios, and hence the break-even price is not always lower for the high emissions reduction scenario.

2.2.2 Shift Nitrogen Application from Fall to Spring (Single Application)

2.2.2.1 Technology Characterization

Where commercial nitrogen fertilizers are applied to fields in the fall and crops are planted in the spring, significant quantities of applied nitrogen can be lost via nitrification, denitrification, and leaching before the crops can use it for plant growth. The magnitude of these nitrogen losses (some of which occur as N_2O emissions to the atmosphere) will depend on a variety of field conditions, including soil characteristics (e.g., temperature, moisture, pH level), weather variables (before, during, and after application), and farm management factors (e.g., placement and form of fertilizer, rotation, tillage system, irrigation technology). Under appropriate field conditions, shifting from fall to spring applications can improve synchronization of the supply of applied nitrogen with the nitrogen needs of growing crops.[11] Where this occurs,

Key Features of Adjusting Fertilizer Timing

- Additional equipment may be required to apply fertilizer in the spring.
- Applicable as a mitigation option for corn, sorghum, wheat, cotton, and soybeans.
- Most effective at GHG mitigation in warm, wet climates, on soils with high organic matter content, or where irrigation occurs.
- All common types of nitrogen fertilizers can be used (e.g., anhydrous ammonia, aqua ammonia, nitrogen solutions).
- Decreases nitrogen runoff into surface water and leaching into groundwater, and reduces trace gas and ammonia emissions.
- Potential cost increases associated with additional workload, higher fertilizer prices, weather-related risk, possible soil compaction, and potential damage to crops (Ribaudo et al., 2011).

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[11] A similar nitrogen management option, split-spring application, applies nitrogen in two parts: one early in the planting season and a second application some weeks later. Compared to a single application, studies have not identified significant GHG benefits for a split application. As such, the GHG mitigation potential of shifting from a fall split-spring application appears to be limited.

nitrogen use efficiency (i.e., the share of applied nitrogen utilized by growing crops) will increase and nitrogen losses (including N_2O emissions) associated with nitrification, denitrification, and leaching will decrease. Additionally, there may be the potential for higher yields and/or lower fertilizer requirements (Hoeft et al., 2000).

As long as field conditions allow adequate nitrogen applied in the fall to remain in the field throughout the winter and early spring, farmers may view the risk of potential nitrogen losses associated with fall application as acceptable when viewed against the potential benefits of not having to apply nitrogen in the spring. First, farm workloads are typically lower in the fall than in the spring. Fall nitrogen applications can free farm labor and equipment for other tasks in the spring. Additionally, lower farm-sector demands for inputs and services (e.g., equipment rental, labor, fertilizer, fertilizer services) in the fall can translate to lower input prices and production costs. Finally, fall nitrogen applications can address several production risks associated with unfavorable spring weather, including the risk that heavy spring precipitation and waterlogged field conditions will delay nitrogen application and planting dates, increase problems with soil compaction, and cause damage to seedlings if nitrogen applied as ammonia does not have adequate time and soil moisture to transform to ammonium and nitrate (Ribaudo et al., 2011). Seasonal price differences and increased labor costs are reflected in the cost profile for this practice.

Current and Potential Adoption

Nitrification does not occur under frozen or anaerobic (waterlogged) soil conditions, and is significantly slowed by soil temperatures below 50°F and/or soil pH levels below 5.5. Denitrification is halted by soil temperatures below 35° F, is slowed by soil pH levels lower than 5.0, and is halted by aerobic soil conditions that preserve the nitrogen in the soil for plant uptake in the spring (Fernández, 2012; University of Hawaii, 2012). Where these conditions are met and farmers apply nitrogen in the fall, the potential exists to incentivize switching to spring nitrogen application as a farm-level GHG mitigation activity. Conversely, warm winter temperatures, soil pH levels above 5.5, sandy soil conditions, and soils that drain easily (naturally or artificially) all facilitate nitrogen loss associated with fall-applied nitrogen. Under these conditions, farmers have likely already adopted spring nitrogen applications to better synchronize nitrogen availability with plant uptake.

Based on USDA ARMS data, approximately 16% of U.S. wheat acreage, 62% of corn acreage, 45% of cotton acreage, 67% of sorghum acreage, and 9% of soybean acreage are fertilized with nitrogen in the spring (USDA ERS, 2011c). Ribaudo et al. (2011) indicates that, on average, 24% of crop acreage are not meeting the timing criteria, that is, managers applied nitrogen in the fall for a crop planted in the spring (see Exhibit 2-13). Exhibit 2-20 presents estimates of the percentage of acreage by region, crop, and farm size now using spring fertilizer application in the United States. As indicated, for corn, cotton, and sorghum, spring application is relatively widespread, hence modest potential exists for wheat and soybeans.

Exhibit 2-20: Number of Acres with Spring Application

Crop	Acres Using Spring Fertilizer Application (percent)										
	All	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn	62	72	67	72	48	51	48	64	51	72	64
Cotton	45	44	63	44	N/A	23	N/A	46	23	45	46
Sorghum	67	67	64	67	67	69	67	53	67	67	51
Soybeans	9	13	6	10	10	9	10	13	9	13	13
Wheat	16	16	5	45	45	24	45	12	24	16	12

Crop	Farms Practicing Spring Application[a] (percent)			
	Farm Size			
	Large (>800 acres)	Mid (300–800 acres)	Small (<300 acres)	All Farms
Corn	58	63	64	62
Cotton	48	36	45	45
Soybeans	6	9	12	9
Wheat	18	13	14	16

[a] Sorghum data not available at the farm level.
N/A = Not applicable
Source: USDA ERS (2011c).

Production and Environmental Impacts

Production Impacts. Spring application can improve nitrogen use efficiency. More efficient use of nitrogen could increase crop yields and/or decrease fertilizer input requirements (Hoeft et al., 2000). With the transition from fall to spring application, there is the risk of lower yields if planting dates are delayed. For example, spring precipitation can delay planting or lead to soil compaction if equipment is taken into fields with overly moist soil conditions. In addition, if anhydrous ammonia is applied in the spring, there is the potential for seedling injury.[12] Higher fuel, fertilizer, and equipment costs could be incurred during spring application compared with fall application due to increased demand for field equipment, fertilizer inputs, and higher opportunity costs for labor and capital equipment during the spring.

Other Environmental Impacts. Reductions in nutrient flows to surface water and groundwater resources may be observed with adjustments to fertilizer timing. With spring application, there is less potential for loss compared with fall application as there is less time for nitrification to occur before plants start to absorb the nitrogen (Hoeft et al., 2000).

Barriers to Adoption

For individual farmers, shifting from fall to spring nitrogen applications may result in increased spring workload requirements, higher fertilizer prices, weather-related risk of not applying at the right time, increased application costs, possible soil compaction, and potential damage to crops (Ribaudo et al., 2011). These risks may discourage some farmers from adopting this practice even if a GHG mitigation incentive is available.

2.2.2.2 GHG Impacts

While limited research exists on the GHG mitigation potential of seasonal shifts in the timing of nitrogen applications, studies have found lower N_2O emissions associated with spring application of nitrogen fertilizer compared with fall application (Hao et al., 2001). A 10% reduction from current N_2O flux was estimated for fertilizer timing adjustments in Paustian, et al. (2004). The GHG mitigation potential for switching from fall to spring application using anhydrous ammonia was estimated at 0.06 mt CO_2-eq $ac^{-1}yr^{-1}$ in Burton et al. (2008). A report by Rochette et al. (2004) found that N_2O impacts resulting from changing the timing of application of organic fertilizers varied and could not be generalized due to interactions among crop, climate, and soil factors. Subsequently, in a meta-analysis by Ogle et al. (2010), 15 studies were statistically analyzed with the results

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[12] Free ammonia (NH_3) is toxic to emerging seedlings and their roots. The conversion of NH_3 to ammonium requires hydrogen ions from the soil cation exchange site, which increase the soil pH at the injection site. Soil moisture content, texture, and temperature all affect the length of time that ammonia persists in the soil (Schwab, 2012). The increased potential for a higher pH during a spring application results in a higher risk of seedling injury.

proving inconclusive. For this report, emissions reductions based on the DAYCENT model were used. Exhibit 2-21 presents the emissions reduction by crop type and USDA production region (Ogle, 2011b).

Exhibit 2-21: Estimates of Emissions Reduction Potential for Spring Nitrogen Application[a]

Crop	Estimates of Emissions Reduction Potential (mt CO_2-eq/acre)									
	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northern Plains	Northeast	Pacific	Southeast	Southern Plains
Corn	0.04	0.08	0.01	0.06	0.01	0.02	0.04	+	+	+
Cotton	+	0.04	+	N/A	0.01	0.02	N/A	+	+	+
Hay	0.01	0.01	0.01	0.02	0.01	0.02	0.01	+	+	0.03
Sorghum	+	0.04	0.01	+	0.01	0.01	+	+	+	+
Soybeans	0.03	0.01	+	0.03	+	0.03	0.03	+	+	0.02
Wheat	0.03	0.05	0.01	0.06	0.01	0.02	0.03	+	+	+

[a] Estimated N_2O emissions reductions include both direct and indirect N_2O emissions (Ogle, 2011b).
+ = Small reduction in emissions
N/A = Not applicable
Source: Ogle (2011b).

2.2.2.3 Cost Profile

The cost profiles developed here represent the costs of applying nitrogen in the spring above and beyond the costs of applying nitrogen in the fall. To calculate the cost profiles for spring applications, the following steps were undertaken: (1) estimate the fertilizer cost changes associated with spring applications, and (2) estimate the change in fertilizer application costs for spring applications.

Estimate Fertilizer Cost Changes Associated with Spring Application. Fertilizer costs for switching from fall to spring nitrogen application were estimated using USDA NASS data and are based on the percentage change in fall to spring fertilizer price over 5 years (1990–1994) (USDA ERS, 2011b). As this cost profile represents the marginal difference between fall and spring fertilizer application, capital costs remain the same and are not included. Equation 3 presents the method for estimating fertilizer costs associated with spring fertilizer application.

Equation 3:

$$\text{Change in Fertilizer Cost} = \text{N Application Rate} \times \text{Fall to Spring 5-year Average Price Difference} \times \frac{\text{Fertilizer Price}}{\text{Fertilizer N Content}}$$

Units:

- Change in Fertilizer Cost: $/acre
- N Application Rate: lbs/acre
- Fall to Spring 5-year Average Price Difference: % change
- Fertilizer Price: $/ton of fertilizer
- Fertilizer N Content: lbs of N per ton of specified fertilizer

The cost profile is based on the following assumptions:

- No change in the amount of nitrogen applied.
- Corn, sorghum, and soybeans use anhydrous ammonia; cotton uses urea; and wheat uses a 50:50 mix of anhydrous ammonia and urea.

- The average fertilizer price differences are based on the difference between fall prices and spring prices (USDA ERS, 2011b).
- Changes in fertilizer costs are based on the percentage change in fertilizer price (See Exhibit 2.A-4) for each crop in each region and the results of Equation 3 (USDA ERS, 2011b).
- Fertilizer application rates are based on the data in Exhibit 2-17 (Ogle, 2011c).
- Fertilizer nitrogen content varies depending on the type of fertilizer applied (i.e., anhydrous ammonia, urea).
- Fertilizer N Content is based on data from the Mid-Atlantic Nutrient Management Handbook (Abaye et al., 2006) (Exhibit 2.A- 6).
- No variation in costs by farm size.
- No changes in per-acre crop yields.[13]

Estimate Fertilizer Application Cost Changes Associated with Spring Application Relative to Fall Applications. Fertilizer application costs are expected to rise with spring application due to higher opportunity costs in the spring relative to the fall. The change in fertilizer application costs for spring application is the sum of the custom fertilizer application costs (i.e., the cost of the machinery[14]) along with the regional hourly wage multiplied by the time for nitrogen application. Equation 4 indicates the variables used to estimate the costs for applying fertilizer in the spring.

Equation 4:

$$\text{Change in fertilizer application costs} = \text{Custom Fertilizer Application} + \text{USDA Region Mean Labor Rate} \times \text{Nitrogen Application Time}$$

Units:

- Change in Fertilizer Application Costs: \$/acre
- Custom Fertilizer Application: \$/acre
- USDA Region Mean Labor Rate: \$/hour
- Nitrogen Application Time: hour/acre

The fertilizer application cost component of spring application is based on the following assumptions:

- Custom application costs per acre for anhydrous ammonia and urea (Stein, 2010) were added to the labor costs associated with custom application.
- Custom application costs and associated labor for anhydrous ammonia were applied to corn, sorghum, wheat, and soybeans, and urea dry bulk spreading custom application and labor costs were applied to cotton, and wheat (Stein, 2010).
- Labor costs for custom application consist of the nitrogen application time (0.08 hrs/acre) (Massey, 1997) multiplied by average USDA regional hourly labor rates based on USDA NASS (2011c) survey data.

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[13] Positive yield gains were generated by the DAYCENT model for some crops and regions with this practice; however, they were not included in the estimation due to the assumption that farmers will already be applying this practice where it is economically profitable.

[14] Custom costs per acre represent the rate obtained from surveys of actual farm data for 2009 and 2010. Depending on actual crop and soil conditions, the size of the field, and the location, higher and lower rates would apply. Custom application estimates include the cost for the use of the machine, with the values adjusted higher to reflect the change in power fuel costs (Stein, 2010).

Exhibit 2-22: Cost Profile for Spring Fertilizer Application

Crops[a]	Cost Category	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
		(2010 $/acre)									
Corn[b]	Fertilizer Costs	$1.21	$2.41	$2.24	$1.55	$2.07	$1.21	$1.55	$2.07	$2.24	$1.90
	Fertilizer Application Costs	$10.83	$10.92	$10.74	$10.88	$10.83	$10.90	$10.93	$10.86	$10.76	$10.79
Cotton[c]	Fertilizer Costs	-$0.19	-$0.19	-$0.25	N/A	-$0.19	N/A	-$0.19	-$0.19	-$0.25	-$0.11
	Fertilizer Application Costs	$5.63	$5.72	$5.54	N/A	$5.63	N/A	$5.73	$5.66	$5.56	$5.59
Sorghum	Fertilizer Costs	$0.69	$1.21	$1.21	$0.86	$1.03	$0.69	$0.86	$1.03	$1.21	$1.03
	Fertilizer Application Costs	$10.83	$10.92	$10.74	$10.88	$10.83	$10.90	$10.93	$10.86	$10.76	$10.79
Soybeans	Fertilizer Costs	$0.34	$0.34	$0.34	$0.34	$0.34	$0.34	$0.34	$0.34	$0.52	$0.34
	Fertilizer Application Costs	$10.83	$10.92	$10.74	$10.88	$10.83	$10.90	$10.93	$10.86	$10.76	$10.79
Wheat	Fertilizer Costs	$0.43	$0.65	$0.43	$0.57	$0.36	$0.43	$0.36	$0.43	$0.43	$0.50
	Fertilizer Application Costs	$8.23	$8.32	$8.14	$8.28	$8.23	$8.30	$8.33	$8.26	$8.16	$8.19

[a] All crops are assumed to be rain-fed.

[b] Corn = "Corn for grain"; Sorghum = "Sorghum for grain"

[c] Cotton fertilizer prices are negative or a savings based on the assumption that urea with 44–46% nitrogen is applied to cotton. The 5-year percentage change in price from fall to spring for urea was -0.62% (i.e., decrease in fertilizer costs), while the 5-year percentage change for anhydrous ammonia was 4.93% when comparing fall prices with spring prices (USDA NASS, 2011a).

2.2.2.4 Break-Even Prices

Break-even prices for switching from fall nitrogen application to spring nitrogen application are presented in Exhibit 2-23. By construction, the break-even prices are positive since only increases in fertilizer and labor costs are considered. Break-even prices will be lower in cases where shifting to spring applications results in higher yields.

Exhibit 2-23: Break-Even Prices for Spring Fertilizer Application, Not Accounting for Changes in Yield

Region	Crop Type	Break-Even Price (2010$ /mt CO_2-eq)
Lake States	Wheat	$148
Corn Belt	Corn	$167
Corn Belt	Wheat	$179
Lake States	Corn	$207

Region	Crop Type	Break-Even Price (2010 $/mt CO_2-eq)
Northern Plains	Soybeans	$376
Northern Plains	Wheat	$435
Mountain	Cotton	$543
Southern Plains	Soybeans	$557

Region	Crop Type	Break-Even Price (2010$ /mt CO_2-eq)
Appalachia	Wheat	$289
Northeast	Wheat	$291
Appalachia	Corn	$301
Northeast	Corn	$303
Corn Belt	Sorghum	$303
Appalachia	Soybeans	$372
Lake States	Soybeans	$374
Northeast	Soybeans	$375

Region	Crop Type	Break-Even Price (2010 $/mt CO_2-eq)
Northern Plains	Corn	$624
Delta	Wheat	$857
Mountain	Wheat	$859
Corn Belt	Soybeans	$1,126
Northern Plains	Sorghum	$1,179
Delta	Sorghum	$1,194
Mountain	Corn	$1,290
Delta	Corn	$1,298

2.2.3 Inhibitor Application

2.2.3.1 Technology Characterization

Inhibitor application includes, for the purposes of this report, nitrification and urease inhibitors. Most nitrogen in commercial fertilizers applied to U.S. cropland is in the form of ammonium, urea, or anhydrous ammonia. In the field, urea and ammonia transform relatively quickly into ammonium. Ammonium, in turn, volatilizes relatively quickly into nitrate in a process called nitrification. While nitrate is the most usable form of nitrogen for many crops, it is very mobile in most soils and thus subject to leaching, and, under very wet (anaerobic) conditions, volatilization into nitrogen gas (a process called denitrification). Nitrification, denitrification, and leaching all result in losses of applied nitrogen from the field, some in the form of N_2O emissions to the atmosphere. The rate and degree of loss depends on many site-specific variables, including soil characteristics (e.g., temperature, moisture, pH level), weather conditions (before, during, and soon after application), and various farm management factors (e.g., timing, placement, and form of fertilizer; tillage system; irrigation technology).

Nitrification and urease inhibitors are chemical compounds that, when applied with nitrogen fertilizers, temporarily stop, or significantly slow, the transformation of applied nitrogen into nitrate. For surface applications, the inhibitors and nitrogen must be incorporated into the soil within a few days (via precipitation, irrigation, or tilling). Once incorporated, the ammonium or urea bonds with the soil, making the nitrogen resistant to volatilization and leaching as long as the inhibitor remains active (Nelson and Huber, 2001).

Key Features of Inhibitors

- Nitrification and urease inhibitors are most successful at reducing N_2O emissions associated with nitrogen fertilizers applied prior to cold winters or heavy spring rains.
- Nitrification inhibitors can be applied with anhydrous ammonia.
- Urease inhibitors can be applied with urea.
- These products help to improve nitrogen uptake in plants by synchronizing nitrogen availability with crop demand (Delgado and Follett, 2010).

Exhibit 2-24: Inhibitors Can Be Applied with Nitrogen Solution Fertilizers

Source: USDA NRCS (2011c).

In the nitrification process, ammonium is first oxidized to nitrite by the *Nitrosomonas* bacteria; the nitrite is then oxidized to nitrate by the *Nitrobacter* bacteria. Nitrification inhibitors work by interfering with the metabolism of the *Nitrosomas* bacteria (Nelson and Huber, 2001). The most common nitrification inhibitors used by U.S. farmers is N-Serve® (active ingredient nitrapyrin). N-Serve® can keep applied nitrogen in ammonium form for 2–6 weeks (Laboski, 2006).

Urease inhibitors interfere with the urease enzyme that converts urea to ammonia (which then transforms to ammonium), and can be used with surface-applied urea products (USDA NRCS, 2011c). Urease inhibitors can reduce the loss of ammonia into the atmosphere resulting from the hydrolization of surface-applied urea (USDA NRCS, 2011b). Phenyl phosphorodiamidate (PPDA) and N-(n-butyl) thiophosphoric triamide (NBPT) or Agrotain® are two of the more widely used urease inhibitors in the United States (Chien et al., 2009).

For spring applications, farmers can use inhibitors to keep applied nitrogen locked in the soil as urea or ammonium through the period of heavy precipitation before crop growth begins to accelerate. Conversely, inhibitors will be less effective as a GHG mitigation activity in areas with warm winter soil temperatures and/or dry soil conditions. Inhibitors will likely have little effect on N_2O emissions where farmers apply nitrogen in excess of crop nutrient needs, because there will be no improvement in nitrogen use efficiency (Nelson and Huber, 2001). Exhibit 2-25 provides an overview of various inhibitors along with their corresponding nitrogen content and inhibitor duration.

Exhibit 2-25: Nitrogen Source, Content, Process, and Inhibitor Duration for Some Nitrogen Sources

Nitrogen Source	Nitrogen Content (%)	Nitrogen Process	Inhibitor Duration (weeks)
Nitrapyrin	ND	Nitrification/Denitrification	2–6
DCD	ND	Nitrification/Denitrification	12–14
NBPT	ND	Volatilization	2
Urea-formaldehyde	>35	Volatilization/Leaching	10–30+
Isobutylidene diurea	31	Volatilization/Leaching	10–16
Triazone	28	Volatilization/Leaching	6–9
Crotonylidene diurea	34	Volatilization/Leaching	6–12
Melamine	50–60	Volatilization/Leaching	ND

ND = No data
Source: Delgado and Follett (2010).

Current and Potential Adoption

USDA ARMS survey data for various years suggests that inhibitors are currently used on about 8% of U.S. corn acreage and 5% of U.S. cotton and wheat acreage. Regionally, inhibitor use is highest in the Corn Belt, where inhibitors are applied to about 13% of corn acreage, 22% of cotton acreage, and 10% of wheat acreage (USDA ERS, 2011c). Under field conditions where inhibitors increase the share of applied nitrogen that is ultimately taken up by growing crops, they also decrease N_2O emissions associated with nitrification, denitrification, and/or leaching. Where such conditions occur with relative certainty, adopting inhibitors can be considered as a potential farm-level GHG mitigation practice. Exhibit 2-26 summarizes current nitrification inhibitor adoption by production region, crop type, and farm size, based on USDA data. Inhibitors are effective with surface-applied urea, surface-applied ammonium, or injected anhydrous ammonia. Consequently, inhibitors could be applied where they are not currently being applied with a relatively large adoption potential.

Exhibit 2-26: Use of Nitrification Inhibitors

USDA Production Region	Acreage Using Inhibitors (percent)				
	Corn (2005)	Cotton (2007)	Sorghum (2003)	Soybeans (2006)	Wheat (2009)
Corn Belt	13	22	5	0	10
Lake States/Northeast	8	N/A	2	0	6
Northern Plains/Southern Plains	2	2	3	0	4
Appalachia/Southeast/Delta	6	8	2	0	5
Pacific/Mountain	8	5	2	0	5
All	8	5	2	0	5

Crop	Acreage Using Inhibitors (percent)[a]			
	Farm Size (acres)			
	Large (>800)	Mid (300–800)	Small (<300)	Total
Corn	11	10	5	8
Cotton	5	8	3	5
Soybeans	0	0	0	0
Wheat	3	7	5	5

[a] Sorghum data not available at the farm level.
N/A = Not applicable
Source: USDA ERS (2011c).

Production and Environmental Impacts

Production Impacts. The potential benefits of inhibitors are dependent on a number of factors, including soil type, climate, cultural practices, and nitrogen management program. In some cases, nitrification inhibitors can result in yield increases. Studies indicate that the highest yield increases resulting from inhibitor use occur on either excessively drained or poorly drained soils—conditions that promote nitrogen loses due to leaching and denitrification, respectively (Nelson and Huber, 2001). Conditions where nitrogen inhibitors have limited effectiveness include sandy soils with a low cation exchange capacity during low rainfall years (Nelson and Huber, 2001). Other potential benefits of nitrification inhibitors are increases in the protein concentration of corn grain and a reduction in the severity of *Diplodia* and *Gibberella* stalk rots in corn (Nelson and Huber, 2001).

Other Environmental Impacts. Stabilized sources of nitrogen have the potential to reduce ammonia emissions and leaching under certain conditions. Field-specific emissions reduction depends on interactions between fertilizer source, timing, and placement, and with soil conditions, moisture, and management practices.

Barriers to Adoption

Only a few inhibitors have been approved to be marketed in the United States. Inhibitors increase the cost of fertilizer by at least 9% according to a study by Snyder et al. (2009) as cited in Eagle et al. (2012). As a result, supplies of inhibitors are somewhat limited. Mainly due to their limited supply and adoption, farmers may not have adequate information or exposure.

2.2.3.2 GHG Impacts

Studies that have estimated the impact of nitrification and urease inhibitors on N_2O emissions associated with nitrogen fertilizer use find that emissions vary significantly based on the same factors that affect the rate of nitrogen loss (i.e., climate, soil type, and precipitation events). A literature review by Akiyama et al. (2010)

found that nitrification inhibitors reduced N_2O emissions by an average of 38% compared with conventional fertilizers. Similarly, in a meta-analysis by Ogle et al. (2010), the addition of inhibitors reduced N_2O emissions by 32% ± 9% relative to crops without inhibitors. To reflect the range of published results, low and high emissions reduction scenarios for inhibitors were developed (see Exhibit 2-27). For corn, soybeans, sorghum, and wheat, these scenarios were estimated as follows:

- **Low Emissions Reduction Scenario.** Estimates as derived from the DAYCENT model were used (Ogle, 2011b).
- **High Emissions Reduction Scenario.** The N_2O emissions were estimated by multiplying the nitrogen application rates in each region and cropping system (Ogle, 2011b) by the N_2O emissions factor of 1.19% (Ogle et al., 2010). The resulting N_2O emissions were reduced by 38% to represent emissions reductions for nitrification inhibitors (Akiyama et al., 2010).

For the low emissions reduction scenario for cotton, cotton was assumed to be treated with urease inhibitors. A 0.5% emissions reduction was used based on research indicating that the urease inhibitor AgrotainPlus®, when coupled with urea-ammonium nitrate (UAN), reduced N_2O emissions by 0.5% over UAN applications alone in irrigated no-till corn (Halvorson and Del Grosso, 2012). The high emissions reduction scenario values for cotton were based on the DAYCENT model simulations.

Exhibit 2-27: Estimated N_2O Emissions Reductions for Nitrification and Urease Inhibitors[a]

Crop	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Low Emissions Reduction Scenario (mt CO_2-eq/acre)										
Corn	0.09	0.12	0.09	0.10	0.02	0.09	0.05	0.02	0.07	0.04
Cotton[a]	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Sorghum	+	0.09	0.05	+	0.02	+	0.04	+	0.05	0.02
Soybeans	0.09	0.09	0.07	0.08	+	0.09	0.07	+	0.04	0.05
Wheat	0.04	0.05	0.05	0.10	0.02	0.04	0.03	0.02	0.05	0.03
High Emissions Reduction Scenario (mt CO_2-eq/acre)										
Corn	0.06	0.12	0.12	0.08	0.11	0.06	0.08	0.11	0.12	0.06
Cotton[b]	+	0.06	0.07	N/A	0.02	N/A	0.04	0.02	0.05	0.03
Sorghum	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02
Soybeans	0.05	0.08	0.05	0.07	0.04	0.05	0.04	0.05	0.05	0.05
Wheat	0.06	0.12	0.12	0.08	0.11	0.06	0.08	0.11	0.12	0.06

+ = Negligible reduction in emissions

N/A = Not applicable

[a] Two different methods were used to develop the high and low emissions reduction scenarios; consequently, in some cases, the low emissions reductions are greater than the high emissions reduction scenarios. However, these scenarios provide an indication of the potential range of emissions reductions.

[b] For low emissions reductions, estimates for cotton are based on Halvorson and Del Grosso (2012); high emissions reductions are based on (Ogle, 2011b).

Source: For all crops except cotton, the Low Emissions Reduction Scenario is based on Ogle (2011b) and High Emissions Reduction Scenario based on Akiyama (2010).

2.2.3.3 Cost Profile

The application of inhibitors depends on the type of fertilizer. Nitrification inhibitors are typically used with injected ammonia and ammonium fertilizers, and urease inhibitors are used with surface-applied urea products. In developing a per-acre cost profile for nitrification inhibitors and urease inhibitors, costs were based on quotes for N-Serve® and Agrotain®.

Nitrification inhibitor per-acre cost represents the cost of adding N-Serve® to the anhydrous ammonia application to the field. The cost of Agrotain® per acre is estimated to be $0.07 per pound of nitrogen applied per crop per year (Agrotain, 2012). To estimate the cost of Agrotain® per acre, the unit cost of $0.07 (per lbs N/acre) was multiplied by the nitrogen application rate (lbs N/acre) (see Exhibit 2-17) for cotton in each USDA production region. As nitrification inhibitors are typically applied with anhydrous ammonia, N-Serve® costs were associated with corn, sorghum, soybeans, and wheat. Urease inhibitors are applied with urea, hence Agrotain® costs were estimated for cotton (Hoeft et al., 2000). Exhibit 2-28 presents the costs per acre by crop and USDA production region. The costs presented below reflect the following assumptions:

- No change in nitrogen application per acre.
- Corn, sorghum, soybeans and wheat use anhydrous ammonia and, therefore, were selected for nitrification inhibitor application (Hoeft et al., 2000).
- Cotton was selected for urease inhibitor application (Hoeft et al., 2000).
- Only additional cost is for the inhibitor.
- No change in labor and capital costs with respect to applying fertilizer only.
- No variation in costs by farm size.

Exhibit 2-28: Cost Profile for Inhibitor Application (2011 $/acre)

Crop	Inhibitor	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
		(2011 $/acre)									
Corn, Sorghum, Soybeans, Wheat	N-Serve®	$7.50									
Cotton	Agrotain®	$4.06	$4.06	$5.22	N/A	$4.06	N/A	$4.06	$4.06	$5.22	$2.32

Source: N-Serve® data source (Randall and Sawyer, 2006); Agrotain® data source (Agrotain, 2012).

2.2.3.4 Break-Even Prices

Break-even prices for the application of inhibitors with nitrogen application (assuming no yield impacts) are presented in Exhibit 2-29 below. Break-even prices are biased upward for situations where there are positive yield impacts associated with using nitrification inhibitors. In such cases, farmers would likely start adopting this practice at a lower price. Each break-even price reflects the carbon value that would allow the associated representative farm to pay for the costs of adding a nitrification or urease inhibitor to its input mix.

Exhibit 2-29: Break-Even Prices for Inhibitor Application, Not Accounting for Changes in Yield

Inhibitors (Low Emissions Reduction Scenario)		
Region	**Crop Type**	**Break-Even Price (2010 \$/mt CO_2-eq)**
Corn Belt	Corn	\$63
Lake States	Wheat	\$75
Lake States	Corn	\$75
Appalachia	Soybeans	\$83
Corn Belt	Sorghum	\$83
Northeast	Corn	\$83
Appalachia	Corn	\$83
Delta	Corn	\$83
Corn Belt	Soybeans	\$83
Northeast	Soybeans	\$83
Lake States	Soybeans	\$94
Southeast	Corn	\$107
Delta	Soybeans	\$107
Northern Plains	Soybeans	\$107
Corn Belt	Wheat	\$150
Southeast	Wheat	\$150
Delta	Wheat	\$150
Northern Plains	Corn	\$150
Delta	Sorghum	\$150
Southern Plains	Soybeans	\$150
Northeast	Wheat	\$188
Appalachia	Wheat	\$188
Southeast	Soybeans	\$188
Southern Plains	Corn	\$188
Northern Plains	Sorghum	\$188
Northern Plains	Wheat	\$250
Southern Plains	Wheat	\$250
Mountain	Wheat	\$375
Pacific	Wheat	\$375
Mountain	Corn	\$375
Pacific	Corn	\$375

Inhibitors (High Emissions Reduction Scenario)		
Region	**Crop Type**	**Break-Even Price (2010 \$/mt CO_2-eq)**
Corn Belt	Corn	\$60
Delta	Corn	\$65
Southern Plains	Corn	\$65
Southeast	Corn	\$70
Mountain	Corn	\$70
Delta	Cotton	\$75
Southern Plains	Cotton	\$77
Corn Belt	Wheat	\$93
Lake States	Corn	\$93
Pacific	Corn	\$93
Southeast	Cotton	\$104
Lake States	Wheat	\$105
Corn Belt	Sorghum	\$120
Northeast	Corn	\$120
Appalachia	Corn	\$120
Northern Plains	Corn	\$120
Delta	Sorghum	\$120
Southern Plains	Sorghum	\$120
Southeast	Wheat	\$140
Northeast	Wheat	\$140
Appalachia	Wheat	\$140
Delta	Wheat	\$140
Northern Plains	Wheat	\$140
Southern Plains	Wheat	\$140
Mountain	Sorghum	\$140
Mountain	Wheat	\$168
Pacific	Wheat	\$168
Mountain	Cotton	\$203
Pacific	Cotton	\$203
Northern Plains	Sorghum	\$210
Southern	Soybeans	\$280

Inhibitors (Low Emissions Reduction Scenario)		
Region	**Crop Type**	**Break-Even Price (2010 \$/mt CO_2-eq)**
Mountain	Sorghum	\$375
Southern Plains	Sorghum	\$375
Southern Plains	Cotton	\$2,197[a]
Delta	Cotton	\$4,944
Mountain	Cotton	\$4,944
Pacific	Cotton	\$4,944
Southeast	Cotton	\$6,357

Inhibitors (High Emissions Reduction Scenario)		
Region	**Crop Type**	**Break-Even Price (2010 \$/mt CO_2-eq)**
Plains		
Appalachia	Soybeans	\$421
Lake States	Soybeans	\$421
Southeast	Soybeans	\$421
Corn Belt	Soybeans	\$421
Delta	Soybeans	\$421
Northern Plains	Soybeans	\$421
Northeast	Soybeans	\$421

[a] Values for cotton are relatively high due to the limited effectiveness of the urease inhibitors applied to cotton in the low emissions reduction scenario.

2.2.4 *Variable Rate Technology*

2.2.4.1 Technology Characterization

Precision agriculture is “an information and technology-based crop management system to identify, analyze, and manage spatial and temporal variability within fields” (Heimlich, 2003). Variable rate technology (VRT), a subset of precision agriculture, allows farmers to more precisely control the rate of crop inputs to account for differing conditions within a given field. VRT uses adjustable rate controls on application equipment to apply different amounts of inputs on specific sites at specific times (Alabama Precision Ag Extension, 2011). VRT can include the use of Global Positioning System (GPS), yield, and fertilizer application monitoring, and the use of field markers and/or laser sighting to reduce fertilizer application overlap. For the purposes of this report, the use of GreenSeeker^{TM} technology is modeled.

Key Features of Variable Rate Technology

- Allows for more precise application of inputs based on soil and field characteristics (Surjandari and Batte, 2003).
- Can reduce nutrient flow into surface water and groundwater resources by decreasing application rates.
- Reduced application rates can decrease fertilizer costs.
- GreenSeeker^{TM} Technology requires upfront capital costs.
- Additional training and equipment may be required.

GreenSeeker^{TM} technology employs high-level optical sensing to observe crop status and regulate nitrogen input. Nitrogen is recommended based on yield potential and crop responsiveness to nitrogen (N Tech Industries, 2011). The optical sensors are mounted on the application equipment and communicate with a controller to regulate application rates for different zones. This high level of precision allows farmers to determine crop status and apply appropriate amounts of nitrogen to meet crop needs in real time. The high cost of equipment, however, may limit the current adoption potential of this technology.

Current and Potential Adoption

Precision agriculture technologies can be applied across all regions, crop types, soil conditions, and farm sizes. Of the landowners who adopt VRT, 70–80% purchase the technology and 20% hire custom VRT application through fertilizer dealers who own GreenSeeker™ technology (Linhart, 2011).

Exhibit 2-31 summarizes the current adoption by production region, crop type, and farm size based on USDA ARMS data. VRT technology has a relatively high adoption potential as it is not widely practiced. Wheat and corn production have the highest current adoption rates when compared to other crops, cconsequently the break-even costs analysis for VRT technology focuses on these two crop types.

Exhibit 2-30: GreenSeeker™ Active Nitrogen Sensor

Source: GreenSeeker (2011).

Exhibit 2-31: VRT Adoption by Production Region, and Crop Type

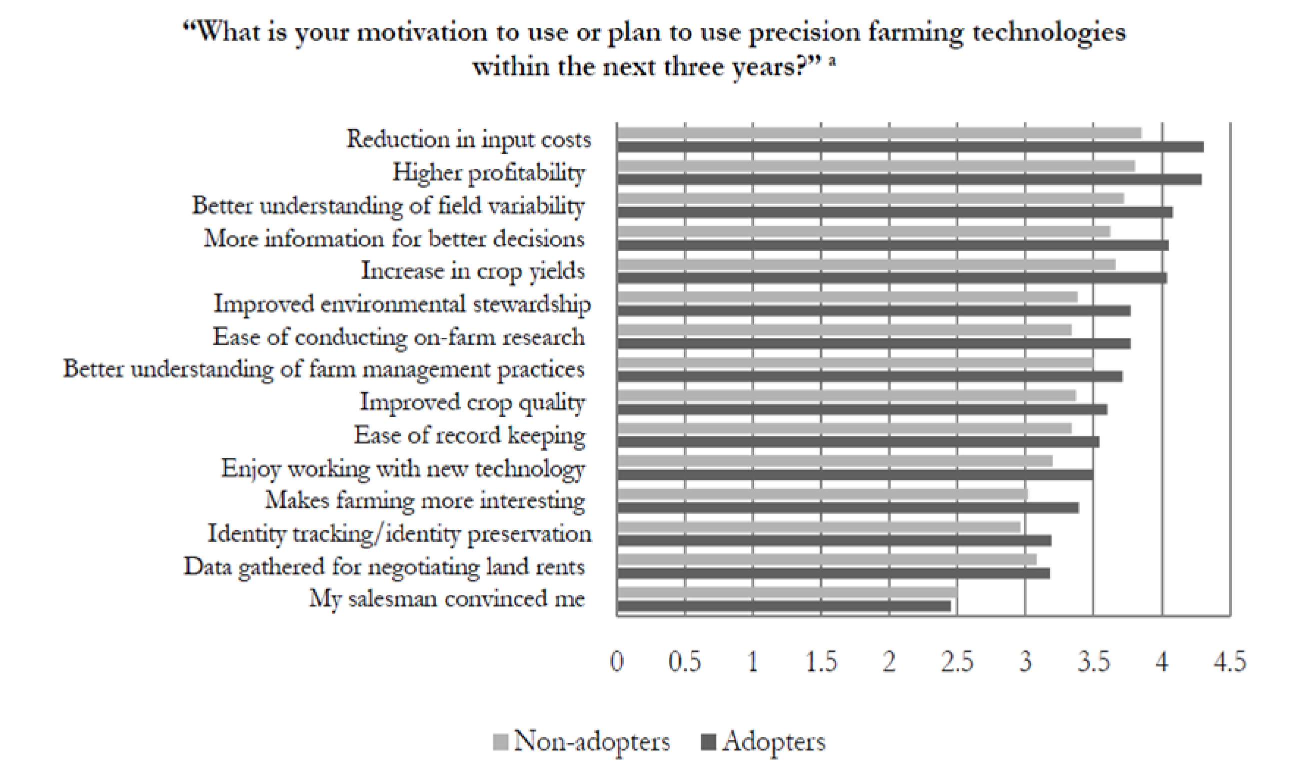
USDA Production Region	Acres Using VRT for Nitrogen Application (percent)				
	Corn (2005)	Cotton (2007)	Sorghum (2003)	Soybeans (2006)	Wheat (2009)
All	5	3	5	1	11
Appalachia	3	2	5	1	11
Corn Belt	6	3	5	2	7
Delta	5	6	5	1	11
Lake States	2	N/A	5	1	14
Mountain	5	3	9	1	12
Northeast	5	N/A	5	1	11
Northern Plains	5	3	5	0	6
Pacific	5	3	5	1	38
Southeast	5	3	5	1	11
Southern Plains	5	3	5	1	10

N/A = Not applicable
Source: USDA ERS (2011c).

Production and Environmental Impacts

Production Impacts. Variable rate technology has been found to produce economic benefits through increased yields, improved crop quality, and decreased fertilizer applications (Delgado and Follett, 2010). In particular, Virginia Tech researchers noted an 8% increase in wheat yields and a 5% increase in corn yield when GreenSeeker™ technology was used in Virginia (Chester River Association, 2010). In a Maryland study, GreenSeeker™ technology was applied and compared to a variety of nitrogen application rates in a 126-plot replication design. In the corn plots, the GreenSeeker™ technology applied nearly 24 lbs/acre less nitrogen than the conventional method with a nearly equivalent yield (CSWCD, 2010). Although limited data exist on yield impacts, survey data gathered in Ohio on the adoption of precision agriculture indicate that key motivators include reduction in input costs, higher profitability, and an understanding of field variability (see Exhibit 2-32) (Diekmann and Batte, 2010). The study indicated that approximately 39% of all surveyed farmers have adopted at least one precision farming component, and 3.6% expect to adopt precision farming technology within the next 3 years (Diekmann and Batte, 2010). While data availability is limited, studies have indicated the potential for yield gains and farmer interest in VRT.

Exhibit 2-32: Surveyed Ohio Farmers' Motivations for Adopting Precision Agriculture



[a] Respondents were asked: "Think about the precision farming technology available today. Please indicate your level of agreement with the following statements." Items were measured on a five-point Likert scale, 1 = Strongly disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly agree. Respondents who reported to be unfamiliar with precision framing technology were excluded. Adopters are those farmers who already practice some form of precision agriculture; non-adopters do not do so.
Source: Diekmann and Batte (2010).

Other Environmental Impacts. The use of precision agriculture can reduce nutrient flow into surface water and groundwater resources. VRT has the potential to detect the sources of spatial and temporal variation in the soil and crop properties that regulate plant available nitrogen, which are not accounted for with current more uniform application practices. This detection capability can, in turn, improve NUE, reduce nitrogen inputs, and/or lower residual nitrates (Delgado and Follett, 2010).

Barriers to Adoption

The use of precision agriculture technologies are not, at present, widespread in the United States. The reasons for this include lack of information, high capital costs, and time spent on training and data collection. When considering the adoption of precision agriculture, fertilizer prices, production acreage, and crop values are key factors.

2.2.4.2 GHG Impacts

Limited data exist on the GHG mitigation potential of VRT. In a study by Sehy, Ruser, and Munch (2003), the use of VRT and GPS decreased N_2O emissions by up to 34% in low-yielding areas. Due to limited data availability, two emissions reduction scenarios were evaluated in this report. A value of 34% was used for the high emissions reduction scenario and an assumed value of 15% was used for the low emissions reduction scenario to evaluate a range of GHG impacts.

2.2.4.3 Cost Profile

The cost profile for GreenSeeker$^{\text{TM}}$ assumes no changes in crop yield. In alternative scenarios, an increase or decrease in yield could occur, depending on a number of variables. Although these yield changes are not modeled due to limited data availability, a landowner who benefits from fertilizer savings and yield gains would not require additional incentives, although yield losses would require additional incentives. Additional revenue gains could be realized with decreased need for fuel, labor, or other chemicals.

GreenSeeker$^{\text{TM}}$ technology detects the crop status and adjusts nitrogen application rates accordingly. The technology recommends nitrogen application rates based on yield potential and the responsiveness of the crop to additional nitrogen (GreenSeeker, 2011). The one-time capital cost of GreenSeeker$^{\text{TM}}$ technology ranges from $20,000 to $22,000, depending on whether farmers already have electronic flow control technology on their fertilizer application equipment (Linhart, 2011). The high value of the range ($22,000) was used for the cost profile with the assumption that farmers do not have flow control technology. The cost of fertilizer inputs vary per acre and are based on nitrogen reductions of 10% for wheat and 21% for corn (Chester River Association, 2010). The cost profiles presented in Exhibit 2-33 represent the differences between fertilizer application with and without GreenSeeker$^{\text{TM}}$ technology for each crop. Custom application costs are not included in this profile, because 70–80% of farmers who currently use GreenSeeker$^{\text{TM}}$ technology purchase it (Gerhardt, 2011).

The costs shown in Exhibit 2-32 are based on the following assumptions:

- Fertilizer savings are calculated on a per-acre basis using Equation 5.

  Equation 5:

  $$\text{Change in Fertilizer Costs} = \text{N Application Rate} \times \text{Change in N Application Rate} \times \frac{\text{Fertilizer Price}}{\text{Fertilizer N Content}}$$

  Where:

  Change in N Application Rate = -10% for wheat; -21% for corn

  Units:

    – Change in Fertilizer Cost: $/acre
    – N Application Rate: lbs/acre
    – Change in N Application Rate: %
    – Fertilizer Price: $/ton of fertilizer
    – Fertilizer N Content: lbs of N per ton of specified fertilizer

  – See Exhibit 2-17 for fertilizer application rates (Ogle, 2011b).

  – Fertilizer prices for anhydrous ammonia are shown in Exhibit 2.A-4 and based on data from USDA ERS (2011b).

  – Fertilizer nitrogen content varies depending on the type of fertilizer applied (i.e., anhydrous ammonia) see Exhibit 2.A- 6(Abaye et al., 2006).

- Farmers have fertilizer equipment but do not have electronic flow control.
- Farmers make a one-time capital investment in the GreenSeeker$^{\text{TM}}$ technology.
- Fertilizer is spray-applied and not side-dressed for select crops.
- No change in labor costs.
- No change in yield.

Exhibit 2-33: Cost Profile for Use of GreenSeeker™ Technology

Cost	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
	(2010 $)									
Fertilizer Corn[a]	-$5.14	-$10.28	-$9.54	-$6.61	-$8.81	-$5.14	-$6.61	-$8.81	-$9.54	-$8.07
Fertilizer Wheat	-$2.10	-$3.15	-$2.10	-$2.80	-$1.75	-$2.10	-$1.75	-$2.10	-$2.10	-$2.45
GreenSeeker™ Technology Cost per Farm[b]	**Capital Costs per Acre for a Small Farm (250 acres)**			**Capital Costs per Acre for a Medium Farm (550 acres)**				**Capital Costs per Acre for a Large Farm (1000 acres)**		
$22,000	$88			$40				$22		

[a] Fertilizer costs are on a per-acre basis.

[b] A technology lifetime of 10 years was assumed (i.e., capital costs were annualized over 10 years) for all capital costs.

Negative input amounts in the cost profiles are fertilizer cost savings when less fertilizer is required for application.

Source: Abaye et al. (2006); Chester River Association (2010); Linhart (2011); Ogle (2011c); USDA ERS (2011b).

2.2.4.4 Break-Even Prices

Break-even prices for the adoption of VRT GreenSeeker™ technology are shown in Exhibit 2-34. Because of a lack of data, yield gains are not modeled; however, fertilizer savings are modeled. High and low emissions reduction scenarios were applied to illustrate the range in reduction potential. Low emissions reduction scenarios assumed a 15% reduction, and high emissions reduction scenarios assumed a 34% reduction in N_2O emissions (Sehy et al., 2003). VRT GreenSeeker™ technology is more effective for large- and medium-sized farms compared with smaller farm sizes because the capital costs are spread over more acreage and fertilizer savings are realized over a larger area, allowing for quicker cost recovery.

Exhibit 2-34: Break-Even Prices for Precision Agriculture Low Emissions Reduction Scenario

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Break-Even Price[a] (2010 $/ mt CO_2-eq)
GreenSeeker™	Southeast	Corn	1000-acre farm	Low	<$0[a]
GreenSeeker™	Delta	Corn	1000-acre farm	Low	<$0
GreenSeeker™	Southeast	Corn	550-acre farm	Low	<$0
GreenSeeker™	Corn Belt	Corn	1000-acre farm	Low	<$0
GreenSeeker™	Delta	Corn	550-acre farm	Low	<$0
GreenSeeker™	Mountain	Corn	1000-acre farm	Low	<$0
GreenSeeker™	Corn Belt	Corn	550-acre farm	Low	<$0
GreenSeeker™	Northern Plains	Corn	1000-acre farm	Low	<$0
GreenSeeker™	Lake States	Corn	1000-acre farm	Low	<$0
GreenSeeker™	Appalachia	Corn	1000-acre farm	Low	<$0
GreenSeeker™	Southern Plains	Corn	1000-acre farm	Low	<$0
GreenSeeker™	Mountain	Corn	550-acre farm	Low	<$0
GreenSeeker™	Pacific	Corn	1000-acre farm	Low	<$0
GreenSeeker™	Northeast	Corn	1000-acre farm	Low	<$0
GreenSeeker™	Northern Plains	Corn	550-acre farm	Low	<$0
GreenSeeker™	Southern Plains	Corn	550-acre farm	Low	<$0

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Break-Even Price[a] (2010 \$/ mt CO_2-eq)
GreenSeeker™	Pacific	Corn	550-acre farm	Low	<\$0
GreenSeeker™	Lake States	Corn	550-acre farm	Low	<\$0
GreenSeeker™	Corn Belt	Wheat	1000-acre farm	Low	<\$0
GreenSeeker™	Northeast	Corn	550-acre farm	Low	\$4
GreenSeeker™	Lake States	Wheat	1000-acre farm	Low	\$5
GreenSeeker™	Appalachia	Corn	550-acre farm	Low	\$5
GreenSeeker™	Pacific	Corn	250-acre farm	Low	\$18
GreenSeeker™	Appalachia	Wheat	1000-acre farm	Low	\$21
GreenSeeker™	Corn Belt	Corn	250-acre farm	Low	\$23
GreenSeeker™	Southern Plains	Wheat	1000-acre farm	Low	\$23
GreenSeeker™	Northeast	Wheat	1000-acre farm	Low	\$25
GreenSeeker™	Delta	Wheat	1000-acre farm	Low	\$25
GreenSeeker™	Southeast	Wheat	1000-acre farm	Low	\$29
GreenSeeker™	Pacific	Wheat	1000-acre farm	Low	\$30
GreenSeeker™	Southern Plains	Corn	250-acre farm	Low	\$33
GreenSeeker™	Mountain	Corn	250-acre farm	Low	\$39
GreenSeeker™	Corn Belt	Wheat	550-acre farm	Low	\$40
GreenSeeker™	Northern Plains	Wheat	1000-acre farm	Low	\$45
GreenSeeker™	Mountain	Wheat	1000-acre farm	Low	\$49
GreenSeeker™	Delta	Corn	250-acre farm	Low	\$55
GreenSeeker™	Southeast	Corn	250-acre farm	Low	\$70
GreenSeeker™	Lake States	Wheat	550-acre farm	Low	\$71
GreenSeeker™	Lake States	Corn	250-acre farm	Low	\$79
GreenSeeker™	Appalachia	Wheat	550-acre farm	Low	\$80
GreenSeeker™	Northeast	Wheat	550-acre farm	Low	\$95
GreenSeeker™	Delta	Wheat	550-acre farm	Low	\$96
GreenSeeker™	Northern Plains	Corn	250-acre farm	Low	\$102
GreenSeeker™	Northeast	Corn	250-acre farm	Low	\$106
GreenSeeker™	Southeast	Wheat	550-acre farm	Low	\$112
GreenSeeker™	Pacific	Wheat	550-acre farm	Low	\$113
GreenSeeker™	Southern Plains	Wheat	550-acre farm	Low	\$131
GreenSeeker™	Northern Plains	Wheat	550-acre farm	Low	\$133
GreenSeeker™	Appalachia	Corn	250-acre farm	Low	\$139
GreenSeeker™	Mountain	Wheat	550-acre farm	Low	\$147
GreenSeeker™	Corn Belt	Wheat	250-acre farm	Low	\$156
GreenSeeker™	Appalachia	Wheat	250-acre farm	Low	\$237
GreenSeeker™	Lake States	Wheat	250-acre farm	Low	\$249
GreenSeeker™	Northeast	Wheat	250-acre farm	Low	\$281
GreenSeeker™	Delta	Wheat	250-acre farm	Low	\$285
GreenSeeker™	Southeast	Wheat	250-acre farm	Low	\$331
GreenSeeker™	Pacific	Wheat	250-acre farm	Low	\$336
GreenSeeker™	Northern Plains	Wheat	250-acre farm	Low	\$370
GreenSeeker™	Mountain	Wheat	250-acre farm	Low	\$408
GreenSeeker™	Southern Plains	Wheat	250-acre farm	Low	\$420

[a] Negative values were generated primarily for large farms (550 acres or larger) when using the VRT GreenSeeker™. This is a result of the costs being distributed over a larger acreage and fertilizer savings.

Exhibit 2-35: Break-Even Prices for Precision Agriculture High Emissions Reduction Scenario

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Break-Even Price[a] (2010 $/ mt CO_2-eq)
GreenSeeker™	Southeast	Corn	1000-acre farm	High	<$0[a]
GreenSeeker™	Delta	Corn	1000-acre farm	High	<$0
GreenSeeker™	Southeast	Corn	550-acre farm	High	<$0
GreenSeeker™	Corn Belt	Corn	1000-acre farm	High	<$0
GreenSeeker™	Delta	Corn	550-acre farm	High	<$0
GreenSeeker™	Mountain	Corn	1000-acre farm	High	<$0
GreenSeeker™	Corn Belt	Corn	550-acre farm	High	<$0
GreenSeeker™	Northern Plains	Corn	1000-acre farm	High	<$0
GreenSeeker™	Lake States	Corn	1000-acre farm	High	<$0
GreenSeeker™	Appalachia	Corn	1000-acre farm	High	<$0
GreenSeeker™	Southern Plains	Corn	1000-acre farm	High	<$0
GreenSeeker™	Mountain	Corn	550-acre farm	High	<$0
GreenSeeker™	Pacific	Corn	1000-acre farm	High	<$0
GreenSeeker™	Northeast	Corn	1000-acre farm	High	<$0
GreenSeeker™	Northern Plains	Corn	550-acre farm	High	<$0
GreenSeeker™	Southern Plains	Corn	550-acre farm	High	<$0
GreenSeeker™	Pacific	Corn	550-acre farm	High	<$0
GreenSeeker™	Lake States	Corn	550-acre farm	High	<$0
GreenSeeker™	Corn Belt	Wheat	1000-acre farm	High	<$0
GreenSeeker™	Northeast	Corn	550-acre farm	High	$2
GreenSeeker™	Lake States	Wheat	1000-acre farm	High	$2
GreenSeeker™	Appalachia	Corn	550-acre farm	High	$2
GreenSeeker™	Pacific	Corn	250-acre farm	High	$8
GreenSeeker™	Appalachia	Wheat	1000-acre farm	High	$9
GreenSeeker™	Corn Belt	Corn	250-acre farm	High	$10
GreenSeeker™	Southern Plains	Wheat	1000-acre farm	High	$10
GreenSeeker™	Northeast	Wheat	1000-acre farm	High	$11
GreenSeeker™	Delta	Wheat	1000-acre farm	High	$11
GreenSeeker™	Southeast	Wheat	1000-acre farm	High	$13
GreenSeeker™	Pacific	Wheat	1000-acre farm	High	$13
GreenSeeker™	Southern Plains	Corn	250-acre farm	High	$15
GreenSeeker™	Mountain	Corn	250-acre farm	High	$17
GreenSeeker™	Corn Belt	Wheat	550-acre farm	High	$18
GreenSeeker™	Northern Plains	Wheat	1000-acre farm	High	$20
GreenSeeker™	Mountain	Wheat	1000-acre farm	High	$22
GreenSeeker™	Delta	Corn	250-acre farm	High	$24
GreenSeeker™	Southeast	Corn	250-acre farm	High	$31
GreenSeeker™	Lake States	Wheat	550-acre farm	High	$31
GreenSeeker™	Lake States	Corn	250-acre farm	High	$35
GreenSeeker™	Appalachia	Wheat	550-acre farm	High	$35
GreenSeeker™	Northeast	Wheat	550-acre farm	High	$42
GreenSeeker™	Delta	Wheat	550-acre farm	High	$42
GreenSeeker™	Northern Plains	Corn	250-acre farm	High	$45
GreenSeeker™	Northeast	Corn	250-acre farm	High	$47

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Break-Even Price[a] (2010 \$/ mt CO_2-eq)
GreenSeeker	Southeast	Wheat	550-acre farm	High	\$49
GreenSeeker™	Pacific	Wheat	550-acre farm	High	\$50
GreenSeeker™	Southern Plains	Wheat	550-acre farm	High	\$58
GreenSeeker™	Northern Plains	Wheat	550-acre farm	High	\$59
GreenSeeker™	Appalachia	Corn	250-acre farm	High	\$61
GreenSeeker™	Mountain	Wheat	550-acre farm	High	\$65
GreenSeeker™	Corn Belt	Wheat	250-acre farm	High	\$69
GreenSeeker™	Appalachia	Wheat	250-acre farm	High	\$105
GreenSeeker™	Lake States	Wheat	250-acre farm	High	\$110
GreenSeeker™	Northeast	Wheat	250-acre farm	High	\$124
GreenSeeker™	Delta	Wheat	250-acre farm	High	\$126
GreenSeeker™	Southeast	Wheat	250-acre farm	High	\$146
GreenSeeker™	Pacific	Wheat	250-acre farm	High	\$148
GreenSeeker™	Northern Plains	Wheat	250-acre farm	High	\$163
GreenSeeker™	Mountain	Wheat	250-acre farm	High	\$180
GreenSeeker™	Southern Plains	Wheat	250-acre farm	High	\$185

[a] Negative values were generated primarily for large farms (550 acres or larger) when using the VRT GreenSeeker™. This is a result of the costs being distributed over a larger acreage and fertilizer savings.

2.2.5 Qualitative Assessment of Crop Production Mitigation Practices

Discussions of four additional fertilizer management practices are included qualitatively because data on the adoption cost and/or GHG mitigation potential were insufficient to estimate representative break-even costs. With increased research and/or technical innovation, these practices could become feasible GHG mitigation opportunities in the future.

2.2.5.1 Fertilizer Injection

Fertilizer injection refers to a practice in which nitrogen fertilizer is "injected or knifed-in usually between 4.5 to 9.5 inches below the soil surface. High-pressure liquid nitrogen such as anhydrous ammonia is the most common form of nitrogen injected into the soil. Nitrogen solutions in low-pressure liquid form are also injected into the soil" (Heimlich, 2003). Some studies (Ogle et al., 2010) show that deeper injection (at or below 4 inches) results in reduced N_2O emissions, while shallower injection of fertilizers may not reduce emissions. Other studies show the greatest reductions with shallower placement (Denef et al., 2011). The amount of emissions reduction depends on crop, climate, and soil type, and empirical results are highly variable.

Injection requires specialized equipment that is adjusted for the crop row spacing, and can be applied to all cropping systems. Fertilizer injection can reduce fertilizer requirements in some scenarios, and is applicable in all climate and soil systems. Studies have shown that injecting anhydrous ammonia into the soil profile near the crop rows can decrease nitrogen leaching and volatilization by up to 35% (Paustian et al., 2004). Consequently, decreased runoff into groundwater and surface water may result from fertilizer injection. High variability in results across and within studies highlights the need for further research to determine the impacts of fertilizer placement on N_2O emissions.

2.2.5.2 Form of Nitrogen Fertilizer

Nitrogen comes in a variety of different chemical and physical formulations. While a number of different types of synthetic nitrogen fertilizers are available to landowners, those most commonly applied to row crops in the United States include urea, anhydrous ammonia, urea ammonium nitrate, ammonium nitrate, and ammonium sulfate (Millar et al., 2010). All forms of nitrogen are likely to produce similar yields if managed properly (Hoeft et al., 2000). On the other hand, the type of fertilizer used can have an impact on the resulting N_2O emissions. N_2O emissions were 2–4 times greater from plots where anhydrous ammonia was applied compared with urea ammonium nitrate and broadcast urea (Venterea et al., 2005; Venterea et al., 2010). In a meta-analysis of global annual N_2O and NO emissions from fertilized fields, Bouwman et al. (2002a) found that nitrate-based fertilizers produced significantly lower N_2O emissions than ammonium-based fertilizers.

In Colorado, urea had consistently higher N_2O emissions than urea ammonium nitrate, polymer-coated urea, and stabilized nitrogen sources (Halvorson et al., 2011; Halvorson and Del Grosso, 2012; Halvorson et al., 2010). Differences are more apparent in semi-arid climates than in wet, humid climates. Polymer-coated urea has the benefit of a single application at planting instead of several urea applications during the growing season. In a study by Halvorson et al. (2011), N_2O flux peaks occurred 4–6 weeks after application and were found to be generally lower than conventional urea in strip-tilled corn. In a similar study, polymer-coated urea reduced N_2O emissions by 49% compared with urea under no-till continuous corn (Halvorson et al., 2010). While polymer-coated urea (PCU) generated reductions in N_2O emissions compared with granular urea in these studies, PCUs are not evaluated quantitatively due to a need for more data to evaluate their effectiveness across regions and soil types (see Akiyama et al., 2010).

Despite these apparent differences in emissions across the range of synthetic nitrogen fertilizers, studies are confounded by inconsistencies in methodologies, climate, and placement, among other variables. Some studies have found no differences in emissions from different fertilizers (Millar et al., 2010). At present, research indicates that the form of nitrogen fertilizer can affect N_2O emissions from croplands, but the quantitative difference among the forms is unclear and variable, depending on the soil and climatic conditions.

2.2.5.3 Substitution of Manure for Synthetic Nitrogen Fertilizers

Appropriate manure management is essential to protecting surrounding ecosystems. When handled and applied properly, manure can be a highly valuable source for crop nutrients, improving soil tilth and water-retention ability. The nitrogen in manure must be mineralized before it becomes available to the plants, potentially resulting in a lag in nitrogen availability, and a reduction in nitrogen use efficiency (Ribaudo et al., 2011). Nitrogen availability in the first year of application is estimated to be 20–30% for surface broadcast, 40–50% for knife-injected, and 55–65% for sweep-injected manure (Hoeft et al., 2000). When evaluating the value of manure, land managers consider a number of variables, including nutrient content, nutrient loss during storage and handling, rate of application, inherent fertility level of the soil, uniformity of application, and the cropping system to which it is being applied (Hoeft et al., 2000).

While manure is an important source of nitrogen, it also has potentially negative environmental impacts. If manure is applied improperly, nutrients can leach into nearby waterways and ecosystems. Repeated applications of manure can lead to excesses phosphorus loading on fields. Variables such as manure type, soil, and weather conditions also make nitrate management a challenge, increasing the risk of loss into the environment (Ribaudo et al., 2011). In a meta-analysis of 15 studies evaluating N_2O emissions from manure management, results demonstrated that higher N_2O emissions occur in the more aerobic systems, although inconsistencies in data collection methods hampered direct comparisons of results (Ogle et al., 2010). N_2O mitigation potential is not as well understood, with high variability across soil conditions (Eagle et al., 2012).

2.2.5.4 Biochar Amendments to Soils

Biochar is the product of pyrolysis, or the incomplete combustion of biomass into charred and highly recalcitrant organic matter (Denef et al., 2011). Applying biochar to soils can greatly increase the amount of carbon sequestered in soils, and can stabilize existing stores of carbon in soils (Gaunt and Driver, 2010). Biochar is also much more stable than other sources of soil carbon, potentially remaining in soil hundreds or thousands of years, as opposed to 5–10 years for decomposed biomass (Lehmann, 2007). Biochar can provide long-term carbon sequestration and may reduce N_2O emissions by absorbing soil water, thereby increasing the oxygen concentration of the surrounding soil (Liebig et al., 2012). Agricultural biomass sources for biochar include crop residues, animal manure, and milling residues. In a study by Ro et al. (2010), a pilot-scale pyrolysis reactor system was employed to produce combustible gas and biochar from animal manures consisting of chicken litter, swine solids, and a mixture of swine solids and rye grass. They found that 50% of the feedstock energy was retained in the biochar and 25% in the produced gases. They also found that manure biochar has higher concentrations of phosphorous and potassium than that of original manure feedstocks. Mixing dried biomass, such as rye grass, with dewatered swine solids nearly eliminates the need for external energy (Ro et al., 2010); this option could represent a significant mitigation opportunity. Currently, the production of biochar is too costly to be feasible on a commercial scale. In addition, a complete understanding of the full range of economic and environmental impacts associated with large-scale field applications is not yet available (CAST, 2011).

2.4 Summary of Break-Even Prices for Crop Production Systems Mitigation Options

As indicated in the assumptions used for estimating the break-even price for each mitigation option, several of the mitigation options explicitly address the change in yield. Exhibit 2-36 summarizes the approach used for each mitigation option. The reasoning for the approach for addressing yield is summarized below for the two approaches:

- **Assumed Reduction in Crop Yield:** Several of the mitigation options are based on the fundamental principle of reducing the frequency or magnitude of a particular management practice (i.e., reduced tillage or fertilizer application). The inherent risk in these types of mitigation options is a reduction in yield. Hence, this potential reduction in yield is evaluated as part of the break-even price. The omission of these impacts would result in negative break-even prices, indicating that the landowner would implement them without an incentive, which is likely not the case due to the risk of loss of yield.
- **Assumed No Change in Crop Yield:** Although several of the mitigation options could result in increases in yield (e.g., switch from fall to spring nitrogen application, nitrification and urease inhibitors, precision agriculture), the financial impact of these yield increases are not evaluated as part of the break-even price because the net impact would reduce the incentive level. In particular, incorporating these increases in yield as part of the break-even price could lead to negative incentive levels (i.e., the landowner would implement the mitigation option without an incentive because it would be financially beneficial). Additionally, landowners may seek to withhold these types of benefits in setting an incentive level given the uncertainty of the potential increase in yield, thereby minimizing their risk of revenue loss.

The next two sections summarize the key finding and break-even prices for field management and nutrient management.

Exhibit 2-36: Mitigation Practices and Associated Yield Scenarios Modeled

Mitigation Practice	Decrease in Yield	No Change in Yield
Field Management		
Switching from Conventional to Reduced Tillage	✓	
Switching from Conventional to No-Till	✓	
Switching from Reduced Till to No-Till	✓	
Nutrient Management		
10% Reduction in Nitrogen Application	✓	
Switch from Fall to Spring Nitrogen Application		✓
Nitrification and Urease Inhibitors[a]		✓
Precision Agriculture		✓

[a] Nitrification inhibitors were applied to corn, sorghum, wheat, and soybeans; urease inhibitors were applied to cotton.

2.4.1 Field Management and Tillage Operations

Data were only readily available to estimate break-even prices for tillage practices; hence, this section focuses on this one option. Among changes in tillage systems, conversion to no-till generally has the lowest break-even price. This includes switching from conventional tillage and reduced tillage to no-till. This result was particularly true for corn, soybean, and wheat crops. Overall, these low break-even prices are due to a combination of relatively high cost savings and low yield losses, combined with a relatively high soil carbon sequestration potential. The relatively high break-even prices associated with conversion from conventional tillage to reduce tillage are due to the lower carbon sequestration benefits compared with other mitigation practices examined. Exhibit 2-37 presents the complete table of break-even prices for tillage mitigation practices across all USDA production regions, sorted from lowest to highest.

Exhibit 2-37: Summary of Break-Even Prices for Field Management Mitigation Practices Including Changes in Yield

Mitigation Practice	Region	Crop Type	Break-Even Price[a] (2010 \$/mt CO_2-eq)
Conventional Tillage to No-Till	Northern Plains	Soybeans	<$0
Reduced Tillage to No-Till	Southeast	Cotton	<$0
Conventional Tillage to No-Till	Mountain	Corn	$1
Conventional Tillage to No-Till	Southern Plains	Soybeans	$3
Reduced Tillage to No-Till	Delta	Wheat	$8
Reduced Tillage to No-Till	Delta	Corn	$11
Reduced Tillage to No-Till	Southern Plains	Sorghum	$11
Reduced Tillage to No-Till	Delta	Sorghum	$13
Conventional Tillage to Reduced Tillage	Mountain	Corn	$13
Conventional Tillage to No-Till	Southern Plains	Corn	$14
Reduced Tillage to No-Till	Northern Plains	Corn	$14
Reduced Tillage to No-Till	Pacific	Corn	$16
Conventional Tillage to No-Till	Delta	Corn	$16
Conventional Tillage to No-Till	Mountain	Wheat	$16
Reduced Tillage to No-Till	Southern Plains	Wheat	$17
Conventional Tillage to No-Till	Lake States	Soybeans	$17
Conventional Tillage to No-Till	Delta	Wheat	$17
Conventional Tillage to No-Till	Northern Plains	Corn	$18
Conventional Tillage to No-Till	Mountain	Sorghum	$18
Reduced Tillage to No-Till	Northern Plains	Sorghum	$18
Reduced Tillage to No-Till	Lake States	Corn	$20
Conventional Tillage to No-Till	Pacific	Corn	$20
Conventional Tillage to No-Till	Lake States	Corn	$22
Conventional Tillage to No-Till	Delta	Soybeans	$23
Conventional Tillage to Reduced Tillage	Northern Plains	Corn	$23
Reduced Tillage to No-Till	Appalachia	Wheat	$24
Reduced Tillage to No-Till	Appalachia	Corn	$24

Mitigation Practice	Region	Crop Type	Break-Even Price[a] (2010 $/mt CO_2-eq)
Reduced Tillage to No-Till	Northeast	Wheat	$24
Reduced Tillage to No-Till	Northeast	Corn	$25
Conventional Tillage to No-Till	Northern Plains	Sorghum	$26
Conventional Tillage to No-Till	Southern Plains	Sorghum	$27
Reduced Tillage to No-Till	Northern Plains	Wheat	$27
Conventional Tillage to No-Till	Delta	Sorghum	$27
Reduced Tillage to No-Till	Corn Belt	Corn	$30
Conventional Tillage to Reduced Tillage	Delta	Corn	$30
Conventional Tillage to No-Till	Corn Belt	Soybeans	$32
Conventional Tillage to Reduced Tillage	Lake States	Corn	$33
Reduced Tillage to No-Till	Northern Plains	Soybeans	$34
Conventional Tillage to No-Till	Corn Belt	Corn	$34
Reduced Tillage to No-Till	Delta	Soybeans	$36
Reduced Tillage to No-Till	Corn Belt	Wheat	$37
Reduced Tillage to No-Till	Lake States	Wheat	$38
Conventional Tillage to No-Till	Northern Plains	Wheat	$39
Conventional Tillage to No-Till	Appalachia	Corn	$42
Conventional Tillage to Reduced Tillage	Corn Belt	Corn	$43
Conventional Tillage to No-Till	Southern Plains	Wheat	$44
Conventional Tillage to No-Till	Northeast	Corn	$44
Conventional Tillage to No-Till	Lake States	Wheat	$47
Conventional Tillage to Reduced Tillage	Northern Plains	Sorghum	$49
Reduced Tillage to No-Till	Corn Belt	Sorghum	$51
Conventional Tillage to Reduced Tillage	Mountain	Sorghum	$56
Conventional Tillage to No-Till	Corn Belt	Wheat	$57
Conventional Tillage to No-Till	Appalachia	Wheat	$57
Conventional Tillage to No-Till	Northeast	Wheat	$58
Reduced Tillage to No-Till	Lake States	Soybeans	$62
Reduced Tillage to No-Till	Pacific	Wheat	$63
Conventional Tillage to Reduced Tillage	Mountain	Wheat	$64
Reduced Tillage to No-Till	Delta	Cotton	$67
Reduced Tillage to No-Till	Northeast	Soybeans	$72
Reduced Tillage to No-Till	Appalachia	Soybeans	$72
Conventional Tillage to Reduced Tillage	Northern Plains	Wheat	$74
Conventional Tillage to No-Till	Corn Belt	Sorghum	$74
Reduced Tillage to No-Till	Corn Belt	Soybeans	$77
Conventional Tillage to Reduced Tillage	Southern Plains	Corn	$78
Reduced Tillage to No-Till	Southern Plains	Soybeans	$78
Conventional Tillage to Reduced Tillage	Delta	Wheat	$82

Mitigation Practice	Region	Crop Type	Break-Even Price[a] (2010 \$/mt CO_2-eq)
Conventional Tillage to No-Till	Southern Plains	Cotton	\$93
Conventional Tillage to Reduced Tillage	Southern Plains	Sorghum	\$93
Conventional Tillage to Reduced Tillage	Appalachia	Corn	\$97
Conventional Tillage to Reduced Tillage	Lake States	Wheat	\$101
Conventional Tillage to Reduced Tillage	Northeast	Corn	\$101
Conventional Tillage to No-Till	Northeast	Soybeans	\$104
Conventional Tillage to No-Till	Pacific	Wheat	\$106
Conventional Tillage to Reduced Tillage	Delta	Sorghum	\$111
Conventional Tillage to No-Till	Appalachia	Soybeans	\$114
Reduced Tillage to No-Till	Southern Plains	Cotton	\$126
Conventional Tillage to No-Till	Mountain	Cotton	\$136
Conventional Tillage to No-Till	Delta	Cotton	\$141
Conventional Tillage to Reduced Tillage	Corn Belt	Wheat	\$188
Reduced Tillage to No-Till	Corn Belt	Cotton	\$230
Conventional Tillage to Reduced Tillage	Southern Plains	Cotton	\$280
Conventional Tillage to No-Till	Corn Belt	Cotton	\$324
Conventional Tillage to Reduced Tillage	Mountain	Cotton	\$466
Reduced Tillage to No-Till	Pacific	Cotton	\$542
Conventional Tillage to Reduced Tillage	Delta	Cotton	\$604
Conventional Tillage to No-Till	Pacific	Cotton	\$1,178[b]
Conventional Tillage to Reduced Tillage	Corn Belt	Cotton	\$1,700

[a] Negative break-even prices are a result of cost savings resulting from switching from conventional till to no-till, and switching from reduced till to no-till for soybeans in the Northern Plains and Cotton in the Southeast.
[b] High break-even prices are primarily a result of relatively high yield reductions combined with the high price of cotton.

2.4.2 Nutrient Management

Variable Rate Technology was the most cost-effective farm-level approaches to mitigating GHG emissions related to the application of nitrogen fertilizers. Negative break-even prices were generated primarily for large farms (550 acres or larger) when using the VRT GreenSeeker^{TM} technology, indicating that this option is cost-effective for large farms. With precision agriculture, larger farms have the advantage of covering the initial capital costs over a larger acreage than those managed by smaller farms; consequently, larger farms have the lowest break-even prices for GreenSeeker^{TM} technology.

Incentivizing reductions in nitrogen application rates would need to account for the risk of the potential for reduced yield. Although limited to a few situations, negative nitrogen reduction break-even prices are a result of the savings from reduced fertilizer use being somewhat larger than the associated revenue losses (due to lower yields) in certain regions. Low break-even prices for a 10% reduction in the nitrogen application rate for corn and sorghum in the Mountain and Delta regions are due to the cost savings from reduced fertilizer application being relatively greater than the revenue losses resulting from either no change in yield (for corn) or small changes in yield in the Delta region. The break-even prices for nitrification inhibitors start at approximately \$60/mt CO_2-eq, with relatively lower break-even prices associated with corn compared to other crops due to the effectiveness of nitrification inhibitors at reducing N_2O emissions for corn. In general, the next most cost-effective practice is switching from fall to spring application, with the break-even price starting at approximately \$148/mt CO_2-eq. Urease inhibitors for cotton crops have the highest price incentive level due to the urease inhibitor's limited mitigation potential. Exhibit 2-38 presents the complete table of break-even prices for nutrient management mitigation practices across all USDA production regions, sorted from lowest to highest.

Exhibit 2-38: Summary of Break-Even Prices for Nutrient Management Mitigation Practices

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Includes Yield Changes	Break-Even Price[a] (2010 $/ mt CO_2-eq)
Nitrogen Reduction	Southern Plains	Corn	All farms	Low	Y	<$0
Nitrogen Reduction	Mountain	Corn	All farms	High	Y	<$0
GreenSeeker™	Southeast	Corn	1000-acre farm	Low	N	<$0
GreenSeeker™	Delta	Corn	1000-acre farm	Low	N	<$0
GreenSeeker™	Southeast	Corn	550-acre farm	Low	N	<$0
Nitrogen Reduction	Mountain	Corn	All farms	Low	Y	<$0
GreenSeeker™	Corn Belt	Corn	1000-acre farm	Low	N	<$0
GreenSeeker™	Delta	Corn	550-acre farm	Low	N	<$0
GreenSeeker™	Southeast	Corn	1000-acre farm	High	N	<$0
GreenSeeker™	Mountain	Corn	1000-acre farm	Low	N	<$0
GreenSeeker™	Corn Belt	Corn	550-acre farm	Low	N	<$0
GreenSeeker™	Northern Plains	Corn	1000-acre farm	Low	N	<$0
GreenSeeker™	Delta	Corn	1000-acre farm	High	N	<$0
GreenSeeker™	Southeast	Corn	550-acre farm	High	N	<$0
GreenSeeker™	Lake States	Corn	1000-acre farm	Low	N	<$0
GreenSeeker™	Corn Belt	Corn	1000-acre farm	High	N	<$0
GreenSeeker™	Appalachia	Corn	1000-acre farm	Low	N	<$0
GreenSeeker™	Southern Plains	Corn	1000-acre farm	Low	N	<$0
GreenSeeker™	Delta	Corn	550-acre farm	High	N	<$0
GreenSeeker™	Mountain	Corn	550-acre farm	Low	N	<$0
GreenSeeker™	Pacific	Corn	1000-acre farm	Low	N	<$0
GreenSeeker™	Northeast	Corn	1000-acre farm	Low	N	<$0
GreenSeeker™	Mountain	Corn	1000-acre farm	High	N	<$0
GreenSeeker™	Corn Belt	Corn	550-acre farm	High	N	<$0
GreenSeeker™	Northern Plains	Corn	1000-acre farm	High	N	<$0
GreenSeeker™	Lake States	Corn	1000-acre farm	High	N	<$0
GreenSeeker™	Northern Plains	Corn	550-acre farm	Low	N	<$0
GreenSeeker™	Southern Plains	Corn	550-acre farm	Low	N	<$0

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Includes Yield Changes	Break-Even Price[a] (2010 $/ mt CO_2-eq)
Nitrogen Reduction	Lake States	Corn	All farms	Low	Y	<$0
GreenSeeker™	Pacific	Corn	550-acre farm	Low	N	<$0
GreenSeeker™	Appalachia	Corn	1000-acre farm	High	N	<$0
GreenSeeker™	Southern Plains	Corn	1000-acre farm	High	N	<$0
GreenSeeker™	Mountain	Corn	550-acre farm	High	N	<$0
GreenSeeker™	Lake States	Corn	550-acre farm	Low	N	<$0
Nitrogen Reduction	Delta	Sorghum	All farms	High	Y	<$0
Nitrogen Reduction	Delta	Sorghum	All farms	Low	Y	<$0
GreenSeeker™	Pacific	Corn	1000-acre farm	High	N	<$0
GreenSeeker™	Northeast	Corn	1000-acre farm	High	N	<$0
GreenSeeker™	Northern Plains	Corn	550-acre farm	High	N	<$0
GreenSeeker™	Southern Plains	Corn	550-acre farm	High	N	<$0
GreenSeeker™	Pacific	Corn	550-acre farm	High	N	<$0
GreenSeeker™	Lake States	Corn	550-acre farm	High	N	<$0
GreenSeeker™	Corn Belt	Wheat	1000-acre farm	Low	N	<$0
Nitrogen Reduction	Appalachia	Wheat	All farms	High	Y	<$0
Nitrogen Reduction	Northeast	Wheat	All farms	High	Y	<$0
GreenSeeker™	Corn Belt	Wheat	1000-acre farm	High	N	<$0
GreenSeeker™	Northeast	Corn	550-acre farm	High	N	$2
GreenSeeker™	Lake States	Wheat	1000-acre farm	High	N	$2
Nitrogen Reduction	Corn Belt	Wheat	All farms	High	Y	$2
GreenSeeker™	Appalachia	Corn	550-acre farm	High	N	$2
GreenSeeker™	Northeast	Corn	550-acre farm	Low	N	$4
GreenSeeker™	Lake States	Wheat	1000-acre farm	Low	N	$5
GreenSeeker™	Appalachia	Corn	550-acre farm	Low	N	$5
GreenSeeker™	Pacific	Corn	250-acre farm	High	N	$8
GreenSeeker™	Appalachia	Wheat	1000-acre farm	High	N	$9
GreenSeeker™	Corn Belt	Corn	250-acre farm	High	N	$10
GreenSeeker™	Southern Plains	Wheat	1000-acre farm	High	N	$10
Nitrogen Reduction	Corn Belt	Sorghum	All farms	High	Y	$11
GreenSeeker™	Northeast	Wheat	1000-acre farm	High	N	$11
GreenSeeker™	Delta	Wheat	1000-acre farm	High	N	$11
GreenSeeker™	Southeast	Wheat	1000-acre farm	High	N	$13

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Includes Yield Changes	Break-Even Price[a] (2010 $/ mt CO_2-eq)
GreenSeeker™	Pacific	Wheat	1000-acre farm	High	N	$13
GreenSeeker™	Southern Plains	Corn	250-acre farm	High	N	$15
Nitrogen Reduction	Lake States	Corn	All farms	High	Y	$17
Nitrogen Reduction	Southeast	Corn	All farms	High	Y	$17
Nitrogen Reduction	Northeast	Wheat	All farms	Low	Y	$17
GreenSeeker™	Mountain	Corn	250-acre farm	High	N	$17
Nitrogen Reduction	Delta	Wheat	All farms	High	Y	$18
GreenSeeker™	Corn Belt	Wheat	550-acre farm	High	N	$18
Nitrogen Reduction	Southeast	Wheat	All farms	High	Y	$18
GreenSeeker™	Pacific	Corn	250-acre farm	Low	N	$18
Nitrogen Reduction	Lake States	Wheat	All farms	High	Y	$18
GreenSeeker™	Northern Plains	Wheat	1000-acre farm	High	N	$20
GreenSeeker™	Appalachia	Wheat	1000-acre farm	Low	N	$21
GreenSeeker™	Mountain	Wheat	1000-acre farm	High	N	$22
GreenSeeker™	Corn Belt	Corn	250-acre farm	Low	N	$23
GreenSeeker™	Southern Plains	Wheat	1000-acre farm	Low	N	$23
GreenSeeker™	Delta	Corn	250-acre farm	High	N	$24
GreenSeeker™	Northeast	Wheat	1000-acre farm	Low	N	$25
GreenSeeker™	Delta	Wheat	1000-acre farm	Low	N	$25
Nitrogen Reduction	Appalachia	Corn	All farms	High	Y	$26
Nitrogen Reduction	Northeast	Corn	All farms	High	Y	$28
GreenSeeker™	Southeast	Wheat	1000-acre farm	Low	N	$29
GreenSeeker™	Pacific	Wheat	1000-acre farm	Low	N	$30
GreenSeeker™	Southeast	Corn	250-acre farm	High	N	$31
GreenSeeker™	Lake States	Wheat	550-acre farm	High	N	$31
Nitrogen Reduction	Corn Belt	Corn	All farms	High	Y	$32
GreenSeeker™	Southern Plains	Corn	250-acre farm	Low	N	$33
GreenSeeker™	Lake States	Corn	250-acre farm	High	N	$35
GreenSeeker™	Appalachia	Wheat	550-acre farm	High	N	$35
GreenSeeker™	Mountain	Corn	250-acre farm	Low	N	$39
GreenSeeker™	Corn Belt	Wheat	550-acre farm	Low	N	$40
GreenSeeker™	Northeast	Wheat	550-acre farm	High	N	$42
GreenSeeker™	Delta	Wheat	550-acre farm	High	N	$42

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Includes Yield Changes	Break-Even Price[a] (2010 $/ mt CO_2-eq)
GreenSeeker™	Northern Plains	Wheat	1000-acre farm	Low	N	$45
GreenSeeker™	Northern Plains	Corn	250-acre farm	High	N	$45
GreenSeeker™	Northeast	Corn	250-acre farm	High	N	$47
Nitrogen Reduction	Delta	Corn	All farms	High	Y	$48
GreenSeeker™	Mountain	Wheat	1000-acre farm	Low	N	$49
GreenSeeker™	Southeast	Wheat	550-acre farm	High	N	$49
GreenSeeker™	Pacific	Wheat	550-acre farm	High	N	$50
GreenSeeker™	Delta	Corn	250-acre farm	Low	N	$55
GreenSeeker™	Southern Plains	Wheat	550-acre farm	High	N	$58
GreenSeeker™	Northern Plains	Wheat	550-acre farm	High	N	$59
Nitrogen Inhibitors	Corn Belt	Corn	All farms	High	N	$60
GreenSeeker™	Appalachia	Corn	250-acre farm	High	N	$61
Nitrogen Inhibitors	Corn Belt	Corn	All farms	Low	N	$63
Nitrogen Reduction	Appalachia	Corn	All farms	Low	Y	$64
Nitrogen Inhibitors	Delta	Corn	All farms	High	N	$65
Nitrogen Inhibitors	Southern Plains	Corn	All farms	High	N	$65
GreenSeeker™	Mountain	Wheat	550-acre farm	High	N	$65
Nitrogen Reduction	Southern Plains	Corn	All farms	High	Y	$65
GreenSeeker™	Corn Belt	Wheat	250-acre farm	High	N	$69
GreenSeeker™	Southeast	Corn	250-acre farm	Low	N	$70
Nitrogen Inhibitors	Southeast	Corn	All farms	High	N	$70
Nitrogen Inhibitors	Mountain	Corn	All farms	High	N	$70
GreenSeeker™	Lake States	Wheat	550-acre farm	Low	N	$71
Nitrogen Reduction	Southern Plains	Wheat	All farms	High	Y	$72
Urease Inhibitor	Delta	Cotton	All farms	High	N	$75
Nitrogen Inhibitors	Lake States	Wheat	All farms	Low	N	$75
Nitrogen Inhibitors	Lake States	Corn	All farms	Low	N	$75
Urease Inhibitor	Southern Plains	Cotton	All farms	High	N	$77
GreenSeeker™	Lake States	Corn	250-acre farm	Low	N	$79
GreenSeeker™	Appalachia	Wheat	550-acre farm	Low	N	$80
Nitrogen Inhibitors	Appalachia	Soybeans	All farms	Low	N	$83
Nitrogen Inhibitors	Corn Belt	Sorghum	All farms	Low	N	$83
Nitrogen Inhibitors	Northeast	Corn	All farms	Low	N	$83

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Includes Yield Changes	Break-Even Price[a] (2010 $/ mt CO_2-eq)
Nitrogen Inhibitors	Appalachia	Corn	All farms	Low	N	$83
Nitrogen Inhibitors	Delta	Corn	All farms	Low	N	$83
Nitrogen Inhibitors	Corn Belt	Soybeans	All farms	Low	N	$83
Nitrogen Inhibitors	Northeast	Soybeans	All farms	Low	N	$83
Nitrogen Inhibitors	Corn Belt	Wheat	All farms	High	N	$93
Nitrogen Inhibitors	Lake States	Corn	All farms	High	N	$93
Nitrogen Inhibitors	Pacific	Corn	All farms	High	N	$93
Nitrogen Inhibitors	Lake States	Soybeans	All farms	Low	N	$94
GreenSeeker™	Northeast	Wheat	550-acre farm	Low	N	$95
GreenSeeker™	Delta	Wheat	550-acre farm	Low	N	$96
GreenSeeker™	Northern Plains	Corn	250-acre farm	Low	N	$102
Urease Inhibitor	Southeast	Cotton	All farms	High	N	$104
GreenSeeker™	Appalachia	Wheat	250-acre farm	High	N	$105
Nitrogen Inhibitors	Lake States	Wheat	All farms	High	N	$105
GreenSeeker™	Northeast	Corn	250-acre farm	Low	N	$106
Nitrogen Inhibitors	Southeast	Corn	All farms	Low	N	$107
Nitrogen Inhibitors	Delta	Soybeans	All farms	Low	N	$107
Nitrogen Inhibitors	Northern Plains	Soybeans	All farms	Low	N	$107
GreenSeeker™	Lake States	Wheat	250-acre farm	High	N	$110
GreenSeeker™	Southeast	Wheat	550-acre farm	Low	N	$112
GreenSeeker™	Pacific	Wheat	550-acre farm	Low	N	$113
Nitrogen Inhibitors	Corn Belt	Sorghum	All farms	High	N	$120
Nitrogen Inhibitors	Northeast	Corn	All farms	High	N	$120
Nitrogen Inhibitors	Appalachia	Corn	All farms	High	N	$120
Nitrogen Inhibitors	Northern Plains	Corn	All farms	High	N	$120
Nitrogen Inhibitors	Delta	Sorghum	All farms	High	N	$120
Nitrogen Inhibitors	Southern Plains	Sorghum	All farms	High	N	$120
GreenSeeker™	Northeast	Wheat	250-acre farm	High	N	$124
Nitrogen Reduction	Southern Plains	Corn	All farms	Low	Y	$124
Nitrogen Reduction	Southeast	Cotton	All farms	High	Y	$126
GreenSeeker™	Delta	Wheat	250-acre farm	High	N	$126
GreenSeeker™	Southern Plains	Wheat	550-acre farm	Low	N	$131
Nitrogen Reduction	Pacific	Corn	All farms	Low	Y	$133

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Includes Yield Changes	Break-Even Price[a] (2010 $/mt CO_2-eq)
GreenSeeker™	Northern Plains	Wheat	550-acre farm	Low	N	$133
Nitrogen Reduction	Mountain	Corn	All farms	Low	Y	$135
Nitrogen Reduction	Northeast	Corn	All farms	Low	Y	$135
GreenSeeker™	Appalachia	Corn	250-acre farm	Low	N	$139
Nitrogen Inhibitors	Southeast	Wheat	All farms	High	N	$140
Nitrogen Inhibitors	Northeast	Wheat	All farms	High	N	$140
Nitrogen Inhibitors	Appalachia	Wheat	All farms	High	N	$140
Nitrogen Inhibitors	Delta	Wheat	All farms	High	N	$140
Nitrogen Inhibitors	Northern Plains	Wheat	All farms	High	N	$140
Nitrogen Inhibitors	Southern Plains	Wheat	All farms	High	N	$140
Nitrogen Inhibitors	Mountain	Sorghum	All farms	High	N	$140
GreenSeeker™	Southeast	Wheat	250-acre farm	High	N	$146
GreenSeeker™	Mountain	Wheat	550-acre farm	Low	N	$147
Fall to Spring N Application	Lake States	Wheat	1000-acre farm	N/A	N	$148
GreenSeeker™	Pacific	Wheat	250-acre farm	High	N	$148
Nitrogen Inhibitors	Corn Belt	Wheat	All farms	Low	N	$150
Nitrogen Inhibitors	Southeast	Wheat	All farms	Low	N	$150
Nitrogen Inhibitors	Delta	Wheat	All farms	Low	N	$150
Nitrogen Inhibitors	Northern Plains	Corn	All farms	Low	N	$150
Nitrogen Inhibitors	Delta	Sorghum	All farms	Low	N	$150
Nitrogen Inhibitors	Southern Plains	Soybeans	All farms	Low	N	$150
GreenSeeker™	Corn Belt	Wheat	250-acre farm	Low	N	$156
GreenSeeker™	Northern Plains	Wheat	250-acre farm	High	N	$163
Fall to Spring N Application	Corn Belt	Corn	1000-acre farm	N/A	N	$167
Nitrogen Inhibitors	Mountain	Wheat	All farms	High	N	$168
Nitrogen Inhibitors	Pacific	Wheat	All farms	High	N	$168
Nitrogen Reduction	Pacific	Corn	All farms	Low	Y	$174
Nitrogen Reduction	Northeast	Corn	All farms	Low	Y	$175
Fall to Spring N Application	Corn Belt	Wheat	550-acre farm	N/A	N	$179
GreenSeeker™	Mountain	Wheat	250-acre farm	High	N	$180
Nitrogen Reduction	Northern Plains	Corn	All farms	Low	Y	$180
GreenSeeker™	Southern Plains	Wheat	250-acre farm	High	N	$185

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Includes Yield Changes	Break-Even Price[a] (2010 $/ mt CO_2-eq)
Nitrogen Inhibitors	Northeast	Wheat	All farms	Low	N	$188
Nitrogen Inhibitors	Appalachia	Wheat	All farms	Low	N	$188
Nitrogen Inhibitors	Southeast	Soybeans	All farms	Low	N	$188
Nitrogen Inhibitors	Southern Plains	Corn	All farms	Low	N	$188
Nitrogen Inhibitors	Northern Plains	Sorghum	All farms	Low	N	$188
Nitrogen Reduction	Southern Plains	Corn	All farms	Low	Y	$189
Nitrogen Reduction	Pacific	Corn	All farms	Low	Y	$194
Urease Inhibitor	Mountain	Cotton	All farms	High	N	$203
Urease Inhibitor	Pacific	Cotton	All farms	High	N	$203
Fall to Spring N Application	Lake States	Corn	1000-acre farm	N/A	N	$207
Nitrogen Inhibitors	Northern Plains	Sorghum	All farms	High	N	$210
Nitrogen Reduction	Northern Plains	Corn	All farms	Low	Y	$215
GreenSeeker™	Appalachia	Wheat	250-acre farm	Low	N	$237
GreenSeeker™	Lake States	Wheat	250-acre farm	Low	N	$249
Nitrogen Inhibitors	Northern Plains	Wheat	All farms	Low	N	$250
Nitrogen Inhibitors	Southern Plains	Wheat	All farms	Low	N	$250
Nitrogen Inhibitors	Southern Plains	Soybeans	All farms	High	N	$280
GreenSeeker™	Northeast	Wheat	250-acre farm	Low	N	$281
GreenSeeker™	Delta	Wheat	250-acre farm	Low	N	$285
Fall to Spring N Application	Appalachia	Wheat	550-acre farm	N/A	N	$289
Fall to Spring N Application	Northeast	Wheat	550-acre farm	N/A	N	$291
Nitrogen Reduction	Delta	Cotton	All farms	High	Y	$295
Fall to Spring N Application	Appalachia	Corn	1000-acre farm	N/A	N	$301
Fall to Spring N Application	Northeast	Corn	All farms	N/A	N	$303
Fall to Spring N Application	Corn Belt	Sorghum	550-acre farm	N/A	N	$303
GreenSeeker™	Southeast	Wheat	250-acre farm	Low	N	$331
GreenSeeker™	Pacific	Wheat	250-acre farm	Low	N	$336
GreenSeeker™	Northern Plains	Wheat	250-acre farm	Low	N	$370
Fall to Spring N Application	Appalachia	Soybeans	All farms	N/A	N	$372
Fall to Spring N	Lake States	Soybeans	All farms	N/A	N	$374

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Includes Yield Changes	Break-Even Price[a] (2010 $/ mt CO_2-eq)
Application						
Fall to Spring N Application	Northeast	Soybeans	250-acre farm	N/A	N	$375
Nitrogen Inhibitors	Mountain	Wheat	All farms	Low	N	$375
Nitrogen Inhibitors	Pacific	Wheat	All farms	Low	N	$375
Nitrogen Inhibitors	Mountain	Corn	All farms	Low	N	$375
Nitrogen Inhibitors	Pacific	Corn	All farms	Low	N	$375
Nitrogen Inhibitors	Mountain	Sorghum	All farms	Low	N	$375
Nitrogen Inhibitors	Southern Plains	Sorghum	All farms	Low	N	$375
Fall to Spring N Application	Northern Plains	Soybeans	1000-acre farm	N/A	N	$376
GreenSeeker™	Mountain	Wheat	250-acre farm	Low	N	$408
GreenSeeker™	Southern Plains	Wheat	250-acre farm	Low	N	$420
Nitrogen Inhibitors	Appalachia	Soybeans	All farms	High	N	$421
Nitrogen Inhibitors	Lake States	Soybeans	All farms	High	N	$421
Nitrogen Inhibitors	Southeast	Soybeans	All farms	High	N	$421
Nitrogen Inhibitors	Corn Belt	Soybeans	All farms	High	N	$421
Nitrogen Inhibitors	Delta	Soybeans	All farms	High	N	$421
Nitrogen Inhibitors	Northern Plains	Soybeans	All farms	High	N	$421
Nitrogen Inhibitors	Northeast	Soybeans	All farms	High	N	$421
Nitrogen Reduction	Southern Plains	Corn	All farms	Low	Y	$429
Fall to Spring N Application	Northern Plains	Wheat	All farms	N/A	N	$435
Nitrogen Reduction	Lake States	Corn	All farms	Low	Y	$492
Fall to Spring N Application	Mountain	Cotton	All farms	N/A	N	$543
Nitrogen Reduction	Pacific	Corn	All farms	Low	Y	$545
Fall to Spring N Application	Southern Plains	Soybeans	250-acre farm	N/A	N	$557
Fall to Spring N Application	Northern Plains	Corn	250-acre farm	N/A	N	$624
Nitrogen Reduction	Lake States	Corn	All farms	Low	Y	$652
Nitrogen Reduction	Northern Plains	Wheat	All farms	High	Y	$796
Fall to Spring N Application	Delta	Wheat	1000-acre farm	N/A	N	$857
Fall to Spring N Application	Mountain	Wheat	All farms	N/A	N	$859

Mitigation Practice	Region	Crop Type	Farm Size	Emissions Reduction Scenario	Includes Yield Changes	Break-Even Price[a] (2010 $/mt CO_2-eq)
Nitrogen Reduction	Appalachia	Wheat	All farms	Low	Y	$949
Nitrogen Reduction	Northern Plains	Soybeans	All farms	High	Y	$1,050
Nitrogen Reduction	Northeast	Wheat	All farms	Low	Y	$1,114
Fall to Spring N Application	Corn Belt	Soybeans	All farms	N/A	N	$1,126
Fall to Spring N Application	Northern Plains	Sorghum	1000-acre farm	N/A	N	$1,179
Fall to Spring N Application	Delta	Sorghum	1000-acre farm	N/A	N	$1,194
Nitrogen Reduction	Northern Plains	Corn	All farms	High	Y	$1,209
Fall to Spring N Application	Mountain	Corn	1000-acre farm	N/A	N	$1,290
Fall to Spring N Application	Delta	Corn	All farms	N/A	N	$1,298
Urease Inhibitor	Southern Plains	Cotton	All farms	Low	N	$2,197
Urease Inhibitor	Delta	Cotton	All farms	Low	N	$4,944
Urease Inhibitor	Mountain	Cotton	All farms	Low	N	$4,944
Urease Inhibitor	Pacific	Cotton	All farms	Low	N	$4,944
Urease Inhibitor	Southeast	Cotton	All farms	Low	N	$6,357[a]

[a] Values for cotton are relatively high due to the limited effectiveness of the urease inhibitors applied to cotton in the low emissions reduction scenario (Halvorson and Del Grosso, 2012).

APPENDIX 2-A

This appendix presents the national data used for estimating current and potential adoption for mitigation options and the associated costs. The following data are provided:

- Exhibit 2.A-1: Census of Agriculture: Number of Acres Growing Major Crops, 2007
- Exhibit 2.A-2: Census of Agriculture: Number of Farms Growing Major Crops, 2007
- Exhibit 2.A-3: Census of Agriculture: Number of Farms Growing Major Crops, by Number of Acres Harvested, 2007
- Exhibit 2.A-4: Average U.S. Farm Prices of Selected Nitrogen Fertilizers
- Exhibit 2.A-5: Five-Year Average (2006–2010) Crop Price Received
- Exhibit 2.A- 6: Nitrogen Content of Selected Fertilizers

Exhibit 2.A-1: Census of Agriculture: Number of Acres Growing Major Crops, 2007

Crop	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn for Grain	3,487,042	40,163,530	2,180,634	13,402,516	1,350,328	2,274,384	19,676,473	347,016	1,132,141	2,234,478
Cotton	1,089,360	377,960	1,844,265	0	213,507	0	40,924	471,378	1,617,342	4,838,502
Hay (Alfalfa)	417,684	2,126,587	17,827	3,160,892	5,757,697	1,057,120	5,333,264	1,864,471	20,202	488,753
Sorghum for Grain	31,829	194,338	578,717	936	245,947	9,708	2,991,940	10,996	57,848	2,647,463
Soybeans for Beans	3,947,953	30,599,417	4,844,378	9,352,470	3,357	1,255,516	12,723,136	725	914,420	274,331
Wheat for Grain	1,212,226	2,896,983	1,243,625	2,522,182	9,285,904	487,679	22,262,322	3,305,567	451,084	7,265,339

Source: USDA NASS (2008).

Exhibit 2.A-2: Census of Agriculture: Number of Farms Growing Major Crops, 2007

Crop	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn for Grain	21,786	152,566	4,817	72,249	4,438	24,875	52,055	1,418	8,100	5,456
Cotton	2,283	511	2,540	0	500	0	106	855	4,165	7,645
Hay (Alfalfa)	17,199	69,311	489	67,639	45,306	26,296	46,101	11,455	758	6,172
Sorghum for Grain	420	1,950	1,614	40	679	245	13,674	61	618	6,941
Soybeans for Beans	16,211	139,722	8,654	52,014	43	11,266	45,493	10	4,513	1,184
Wheat for Grain	7,426	34,176	3,933	18,412	13,732	7,823	50,133	5,209	2,657	17,309

Source: USDA NASS (2008).

Exhibit 2.A-3: Census of Agriculture: Number of Farms Growing Major Crops, by Number of Acres Harvested, 2007

Crop and Farm Size	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn for Grain and for Silage/Greenchop										
1 to 24 acres	8,577	24,794	819	15,361	708	11,250	2,944	187	2,773	595
25 to 99 acres	6,202	44,029	713	25,633	1,242	8,055	11,823	425	2,439	1,111
100 to 249 acres	3,263	35,510	924	16,404	1,097	3,290	14,340	393	1,639	1,306
250 to 499 acres	1,896	24,799	878	8,314	611	1,397	10,878	234	752	1,048
500 to 999 acres	1,199	16,093	845	4,498	479	636	7,666	131	353	831
1,000 acres or more	649	7,341	638	2,039	301	247	4,404	48	144	565
Cotton										
1 to 24 acres	176	10	160	0	44	0	5	29	267	270
25 to 99 acres	461	64	329	0	95	0	15	147	852	1,080
100 to 249 acres	406	71	336	0	124	0	33	232	1,104	1,580
250 to 499 acres	502	100	487	0	100	0	27	197	888	1,437
500 to 999 acres	463	129	581	0	79	0	14	170	683	1,639
1,000 acres or more	275	137	647	0	58	0	12	80	371	1,639
Sorghum for Grain										
1 to 24 acres	161	374	99	31	53	127	1,195	11	163	395
25 to 99 acres	167	910	330	7	154	92	4,774	16	260	1,625
100 to 249 acres	59	508	435	2	168	23	4,027	25	139	1,916
250 to 499 acres	29	130	369	0	158	3	2,218	5	44	1,421
500 to 999 acres	4	24	262	0	88	0	1,043	2	11	1,009
1,000 acres or more	0	4	119	0	58	0	417	2	1	575
Soybeans for Beans										
1 to 24 acres	3,039	19,331	536	8,069	7	3,667	3,028	2	671	108
25 to 99 acres	5,347	45,217	1,622	19,855	19	4,430	12,568	5	1,478	394
100 to 249 acres	3,325	35,618	1,701	12,851	16	1,892	13,658	3	1,290	344
250 to 499 acres	2,138	23,192	1,580	6,760	1	759	9,162	0	599	190
500 to 999 acres	1,550	12,492	1,635	3,464	0	391	5,114	0	345	106
1,000 acres or more	812	3,872	1,580	1,015	0	127	1,963	0	130	42
Wheat for Grain										
1 to 24 acres	1,706	10,182	223	5,027	926	3,874	2,896	375	427	1,067
25 to 99 acres	2,548	15,287	905	7,856	2,611	2,596	11,594	1,067	929	4,016
100 to 249 acres	1,653	6,307	1,106	3,105	2,715	961	12,400	1,080	760	4,616
250 to 499 acres	963	1,816	941	1,239	2,089	291	9,483	814	348	3,183
500 to 999 acres	435	480	541	779	2,350	83	7,740	778	148	2,455
1,000 acres or more	121	104	217	406	3,041	18	6,020	1,095	45	1,972

Source: USDA NASS (2008).

Exhibit 2.A-4: Average U.S. Farm Prices of Selected Nitrogen Fertilizers

Year	Month	Anhydrous Ammonia	Nitrogen Solutions (30%)	Urea 44–46% Nitrogen	Ammonium Nitrate	Sulfate of Ammonium
		(2010 $/short ton)				
2007	April	$549.15	$290.85	$475.65	$401.10	$302.40
2009	March	$693.60	$326.40	$495.72	$446.76	$385.56
2010	March	$499.00	$283.00	$448.00	$398.00	$326.00
2011	March	$726.53	$340.47	$510.22	$464.63	$410.31
2012	March	$743.85	$354.35	$526.30	$480.70	$428.45
5-year Average		**$642.43**	**$300.08**	**$473.12**	**$415.29**	**$337.99**

Source: USDA ERS (2011b).

Exhibit 2.A-5: Five-Year Average (2006–2010) Crop Price Received

Crop	Crop Price Received (2010 $/short ton dry matter)									
	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn	$132.72	$130.98	$123.25	$127.68	$140.43	$139.07	$125.28	$141.06	$132.28	$132.57
Cotton	$1,189.42	$1,139.24	$1,201.65	$0.00	$1,300.72	$0.00	$1,252.93	$1,508.81	$1,243.70	$1,223.58
Sorghum	$120.82	$126.93	$111.72	$0.00	$131.68	$110.73	$121.42	$131.12	$113.55	$121.97
Soybeans	$300.19	$302.67	$279.74	$292.21	$0.00	$299.34	$288.73	$0.00	$297.86	$281.39
Wheat	$147.76	$146.33	$143.53	$158.04	$180.42	$152.05	$174.73	$180.14	$144.40	$173.02

Source: USDA NASS (2008).

Exhibit 2.A- 6: Nitrogen Content of Selected Fertilizers

Fertilizer Type	% Nitrogen
Ammonium Bicarbonate	16
Ammonium Chloride	26
Ammonium Nitrate	33.5
Ammonium Sulphate	20.5
Anhydrous Ammonia[a]	82
Aqua Ammonia	22.3
Calcium Cyanamide	20.5
Calcium Nitrate	15.5
Cal-Nitro	26
Diammonium Phosphate	18
Low-Pressure N Solutions	39
Non-Pressure N Solutions	30
Potassium Nitrate	13
Sodium Nitrate	16
Urea[b]	45
Urea-Ammonium Nitrate (liquid solution)	28–32

[a,b] For the purposes of this report, anhydrous ammonia (82% nitrogen) is assumed to be applied to corn, sorghum, wheat, and soybeans. Urea (45% nitrogen) is applied to wheat and cotton.

Source: Abaye et al. (2006).

CHAPTER 2: REFERENCES

Abaye, A.O., T.J. Basden, D. Beegle, G.D. Binford, et al. 2006. *The Mid-Atlantic Nutrient Management Handbook*: The Mid-Atlantic Regional Water Program. http://www.mawaterquality.org/publications/pubs/manhcomplete.pdf.

Agrotain. 2012. *Frequently Asked Questions: What does Agrotain cost?* http://www.agrotain.com/faq#4.

Akiyama, H., X. Yan, and K. Yagi. 2010. Evaluation of Effectiveness of Enhanced-Efficiency Fertilizers as Mitigation Options for N_2O and NO Emissions from Agricultural Soils: Meta-Analysis. *Global Change Biology*, 16:9.

Alabama Precision Ag Extension. 2011. Variable-Rate Technology: Alabama Cooperative Extension System: Precision Ag.

Archer, D.W., and A.D. Halvorson. 2010. Greenhouse Gas Mitigation Economics for Irrigated Cropping Systems in Northeatern Colorado. *Soil Science Society of America Journal*, 74(2):6.

Bausch, W.C., and J.A. Delgado. 2005. Impact of Residual Soil Nitrate on In-Season Nitrogen Applications to Irrigated Corn Based on Remotely Sensed Assessments of Crop Nitrogen Status. *Precision Agriculture*, 6:509–519.

Bouwman, A.F., L.J.M. Boumans, and N.H. Batjes. 2002a. Emissions of N_2O and NO from fertilized fields; summary of available measurment data. *Global Biogeochemical Cycles*, 16(4):1058–1070.

Bouwman, A.F., L.J.M. Boumans, and N.H. Batjes. 2002b. Modeling Global Annual N_2O and NO Emissions from Fertilized Fields. *Global Biogeochemical Cycles*, 16(4):1080–1107.

Boyle, K.P. 2006. The Economics of On-site Conservation Tillage. In *West National Technology Support Center Technical Note: Econ 101.01*: U.S. Department of Agriculture, Natural Resources Conservation Service.

Burton, D.L., B.J. Zebarth, K.M. Gillam, and J.A. MacLeod. 2008. Effect of split applicaton of fertilizer nitrogen on N_2O emissions from potatoes. *Canadian Journal of Soil Science*, 88(2):229–239.

CalRice. 2011. Environmental & Conservation Balance Sheet for The California Rice Industry, Chapter 4 - Air Quality. Sacramento, CA: California Rice Commission.

CAST. 2011. *Carbon Sequestration and Greenhouse Gas Fluxes in Agricluture: Challenges and Opportunities*. Ames, IA: Council for Agricultural Science and Technology.

Chester River Association. 2010. Getting REAL with GreenSeeker. In *Chester Riverkeeper Almanac*. Chestertown, MD: Chester River Association.

Chien, S.H., L.I. Prochnow, and H. Cantarella. 2009. Recent Developments of Fertilizer Production and Use to Improve Nutrient Efficiency and Minimize Environmental Impacts. *Advances in Agronomy*, 102:267–323.

Cornell University. 2011. Adapt-N: A tool for adaptive nitrogen management in corn. In *Try Adapt-N*. Ithaca, NY: Cornell University.

CSWCD. 2010. *GreenSeeker™ Study*. Williamsburg, VA: Colonial Soil and Water Conservation District. http://colonialswcd.net/program-areas/agriculture_program/#4.

DACE. 2006. *Costs and Fuel Use for Alternative Tillage Systems*: University of Illinois at Urbana-Champaign. http://www.farmdoc.illinois.edu/manage/newsletters/fefo06_07/fefo06_07.html.

Davenport, J. 2010. Late Spring Nitrate Test. In *AE News Washington State University*.

Decker, J.E., F.M. Epplin, D.L. Morley, and T.F. Peeper. 2009. Economics of Five Wehat Production Systems with No-Till and Conventional Tillage. *Agronomy Journal*, 101(2):364–372.

Delgado, J.A., and R.F. Follett, (eds.). 2010. *Advances in Nitrogen Management for Water Quality*. Ankeny, Iowa: Soil and Water Conservation Society.

Denef, K., S. Archibeque, and K. Paustian. 2011. *Greenhouse Gas Emissions from U.S. Agriculture and Forestry: A Review of Emission Sources, Controlling Factors, and Mitigation Potential*: Interim report to USDA under Contract #GS-23F-8182H. http://www.usda.gov/oce/climate_change/techguide/Denef_et_al_2011_Review_of_reviews_v1.0.pdf.

Diekmann, F., and M.T. Batte. 2010. *2010 Ohio Farming Practicies Survey: Adoption and Use of Precision Farming Technology in Ohio*. Colombus, OH: The Ohio State University.

Duiker, S.W., and J.C. Myers. 2006. *Better Soils with the No-Till System. A Publication to Help Farmers Understand the Effects of No-Till Systems on the Soil*: The Pennsylvania No Till Alliance. http://www.pa.nrcs.usda.gov/No-Till/Documents/BetterSoils.pdf.

Eagle, A.J., L.P. Olander, L.R. Henry, K. Haugen-Kozyra, et al. 2012. *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States A Synthesis of the Literature*. Durham, NC: Nicholas Institute for Environmental Policy Solutions, Duke University.

Edwards, J., F. Epplin, B. Hunger, C. Medlin, et al. 2006. *No-till wheat production in Oklahoma*. Stillwater, OK: Oklahoma Cooperation Extension Service,. http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-3125/PSS-2132web.pdf.

EPA. 2011. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2009*. Washington, DC: U.S. Environmental Protection Agency. http://epa.gov/climatechange/emissions/usinventoryreport.html.

EPA. 2012. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010*. Washington, DC: U.S. Environmental Protection Agency.

Epplin, F.M. 2006. Chapter 6: Economics: No-Till versus Conventional Till: Oklahoma State University.

Fernández, F. 2012. *Fall Nitrogen Application: What, When, Where, and How*: University of Illinois, Department of Crop Sciences. http://bulletin.ipm.illinois.edu/article.php?id=1572.

Fujinuma, R., R.T. Venterea, and C. Rosen. 2011. Broadcast Urea Reduces N_2O but Increases NO Emissions Compared with Conventional and Shallow-Applied Anhydrous Ammonia in a Coarse-Textured Soil. *Journal of Environmental Quality*, 40:9.

Gaunt, J., and K. Driver. 2010. Bringing Biochar Projects Into the Carbon Marketplace: An introduction to carbon policy and markets, project design, and implications for biochar protocols. In *Carbon Consulting LLC*.

Gerhardt, J. 2011. Personal Communication with J. Gerhardt, GreenSeeker™ Product Manager, December 7, 2012.

GreenSeeker. 2011. Manage your Nitrogen and Maximize your Profits! In *Nitrogen/Defoliant/Plant Growth Regulator Greenseeker RT200*.

Halvorson, A.D., S.J. Del Grosso, and C.A. Reule. 2008. Nitrogen, Tillage, and Crop Rotation Effects on Nitrous Oxide Emissions from Irrigated Cropping Systems. *Journal of Environmental Quality*, 37(4):1337–1344.

Halvorson, A.D., S.J. Del Grosso, and F. Alluvione. 2010. Tillage and Inorganic Nitrogen Source Effects on Nitrous Oxide Emissions from Irrigated Cropping Systems. *Soil Science Society of America Journal*, 74(2):9.

Halvorson, A.D., S. Del Grosso, and C.P. Jantalia. 2011. Nitrogen Source Effects on Soil Nitrous Oxide Emissions from Strip-Till Corn. *Journal of Environmental Quality*, 40:11.

Halvorson, A.D., and S.J. Del Grosso. 2012. Nitrogen Source and Placement Effects on Soil Nitrous Oxide Emissions from No-Till Corn. *Journal of Environmental Quality*, 41:11.

Hao, X., C. Change, J.M. Carefoot, H.H. Janzen, et al. 2001. Nitrous oxide emissions from an irrigated soil as affected by fertilizer and straw management. *Nutrient Cycling in Agroecosystems*, 60(1):1–8.

Heimlich, R. 2003. Agricultural Resources and Environmental Indicators-Agriculture Handbook No. (AH722). In *USDA Economic Research Service*.

Hoben, J.P., R.J. Gehl, N. Millar, P.R. Grace, et al. 2011. Nonlinear nitrous oxide (N_2O) response to nitrogen fertilizer in on-farm corn crops of the US Midwest. *Global Change Biology*, 17:1140–1152.

Hoeft, R.G., E.D. Nafziger, R.R. Johnson, and S.R. Aldrich. 2000. *Modern Corn and Soybean Production*. Champaign, Illinois, USA: MCSP Publications.

Horowitz, J., R. Ebel, and K. Ueda. 2010. *"No-Till" Farming is a Growing Practice*. Washington DC.

Jaynes, D.B., D.L. Dinnes, D.W. Meek, D.L. Karlen, et al. 2004. Using the Late Spring Nitrate Test to Reduce Nitrate Loss Within a Watershed. *Journal of Environmental Quality*, 33(2):656–668.

Laboski, C. 2006. Does it pay to use nitrification and urease inhibitors? In *Proceedings of the 2006 Wisconsin Fertilizer, Aglime & Pest Management Conference*.

Lehmann, J. 2007. A Handful of Carbon. *Nature*, 447:143–144.

Li, C., A. Mosier, R. Wassmann, Z. Cai, et al. 2004. Modeling greenhouse gas emissions from rice-based production systems: Sensitivity and upscaling. *Global Biogeochemistry Cycles*, 18(GB1043).

Li, C., S. Frolking, and K. Butterbach-Bahl. 2005. Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. *Climatic Change*, 72(3):321–338.

Liebig, M.A., A.J. Franzluebbers, and R.F. Follett, (eds.). 2012. *Managing Agricultural Greenhouse Gases Coordinated Agricultural Research through GRACEnet to Address Our Changing Climate*. Waltham, MA: Elsevier.

Linhart, R. 2011. GreenSeeker Specialist at Trimble Navigation, edited by R. Steele.

McSwiney, C.P., and G.P. Robertson. 2005. Nonlinear response of N_2O flux to incremental fertilizer addition in a continuous maize (Zea mays L.) cropping system. *Global Change Biology*, 11:1712–1719.

Milkonian, J., H.M. Van Es, A.T. DeGaetano, J.M. Sogbedji, et al. 2007. Application of Dynamic Simulation Modeling for Nitrogen Mangement in Maize. Proceedings of the Proceedings of the Symposium "Integrating Weathe rVariability into Nitrogen Recommendations".

Millar, N., G.P. Robertson, P.R. Grace, R.J. Gehl, et al. 2010. Nitrogen fertilizer management for nitrous oxide (N_2O) mitigation in intensive corn (Maize) production: an emissions reduction protocol for U.S. Midwest agriculture. *Mitigation and Adaption Strategies for Global Change*, 15(2):185–204.

Missouri NRCS. 2012. *Conservation Tillage*: U.S. Department of Agriculture, Natural Resource Conservation Service, Missouri. http://www.mo.nrcs.usda.gov/news/MOphotogallery/conservation_tillage.html.

Mosier, A.R., A.D. Halvorson, C.A. Reule, and X.J. Liu. 2006. Net global wariming potential and greenhouse gas intensity in irrigated cropping systems in Northeastern Colorado. *Journal of Environmental Quality*, 35(4):1584–1598.

N Tech Industries. 2011. GreenSeeker Frequently Asked Questions. In *Greenseeker Variable Rate Application and Mapping Systems*.

Nelson, D.W., and D. Huber. 2001. Nitrification Inhibitors for Corn Production. In *National Corn Handbook-NCH55*: Iowa State University.

Ogle, S., S. Archibeque, R. Gurung, and K. Paustian. 2010. *Report on GHG Mitigation Literature Review for Agricultural Systems*. Fort Collins, CO: U.S. Department of Agriculture, Climate Change Program Office.

Ogle, S. 2011a. Data on Soil C Sequestration Potential of Changing Tillage Intensities, by Crop Type and Region. Stephen Ogle, Colorado State Unviersity, Fort Collins, CO.

Ogle, S. 2011b. Data on N_2O emissions from N Management Options, by Crop and Region. Stephen Ogle, Colorado State Unviersity, Fort Collins, CO.

Ogle, S. 2011c. Data on N application rates, by crop and region, edited by Victoria Thompson ICF International.

Ogle, S. 2011d. Data on changes in yield from management options, by crop and region.

Ogle, S., A. Swan, and K. Paustian. 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. *Agriculture, Ecosystems and Environment*, 149:37–49.

Paustian, K., B., A. Babcock, J. Hatfield, C.L. Kling, et al. 2004. *Climate Change and Greenhouse Gas Mitigation: Challenges and Opportunities for Agriculture*. Ames, IA: Council on Agricultural Science and Technology (CAST).

Penn State. 1996. *Economics of Conservation Tillage*: Pennsylvania State University College of Agricultural Sciences.

Randall, G., and J. Sawyer. 2006. Nitrogen Application Timing, Forms and Additives. In *Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop. US EPA, Washington DC.*

Ribaudo, M., J. Delgado, L. Hansen, M. Livingston, et al. 2011. *Nitrogen in Agricultural Systems; Implications for Convervation Policy*. Washington DC: U.S. Department of Agriculture.

Ro, K.S., K.B. Cantrell, and P.G. Hunt. 2010. High-Temperature Pyrolysis of Blended Animal Manures for Producing Renewable Energy and VAlue-Added Biochar. *Industrrial & Engineering Chemistry Research*, 49:10125–10131.

Rochette, P., D.A. Angers, M.H. Chantigny, N. Bertrand, et al. 2004. Carbon Dioxide and Nitrous Oxide Emissions Following Fall and Spring Applications of Pig Slurry to an Agricultural Soil. *Soil Science Society of America Journal*, 68:1410–1420.

Schwab, G. 2012. *Avoiding Anhyrous Ammonia Seedling Injury*. Cooperative Extension Service: University of Kentucky-College of Agriculture. http://www.uky.edu/Ag/Agronomy/Extension/Soils/agents/seedling%20injury%20with%20anhydrous%20ammonia.pdf.

Sehy, U., R. Ruser, and J.C. Munch. 2003. Nitrous oxide fluxes from maize fields: relationship to yield, site-specific fertilization, and soil conditions. *Agriculture, Ecosystems & Environment*, 99(1–3):97111.

Snyder, C.S., T.W. Bruulsema, T.L. Jensen, and P.E. Fixen. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agriculture, Ecosystems & Environment*, 133(3–4):247–266.

Stein, D. 2010. 2011 Custom Machine and Work Rate Estimates. In *District Farm Business Management, Michigan State University Extension*.

Surjandari, I., and M.T. Batte. 2003. Adoption of Variable Rate Technology. *Makara, Teknologi*, December, 120-124.

University of Hawaii. 2012. *Nitrogen*: University of Hawaii, College of Tropical Agriculture and Human Resources. http://www.ctahr.hawaii.edu/mauisoil/c_nutrients01.aspx.

USDA ERS. 2011a. Commodity Costs and Returns: Data: U.S. Department of Agriculture Economic Research Service.

USDA ERS. 2011b. *Fertilizer Use and Price*: U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/Data/FertilizerUse/.

USDA ERS. 2011c. ARMS Farm Financial and Crop Production Practices. Washington, DC: U.S. Department of Agriculture Economic Research Service.

USDA NASS. 2008. *2007 Census of Agriculture*. Washington, DC: U.S. Department of Agriculture, National Agricultural Statistics Service. http://www.agcensus.usda.gov/Publications/2007/index.php.

USDA NASS. 2011a. Agricultural Prices: U.S. Department of Agriculture, National Agricultural Statistics Service.

USDA NASS. 2011b. Crop Price and Yield Data by State: U.S. Department of Agriculture, National Agriculture Statistics Service.

USDA NASS. 2011c. Farm Labor Statistics: U.S. Department of Agriculture, National Agricultural Statistics Service.

USDA NRCS. 2010a. *Forage and Biomass Planting code 512*. http://www.nrcs.usda.gov/technical/standards/nhcp.html.

USDA NRCS. 2010b. *Tillage Equipment: Pocket Identification Guide*: U.S. Department of Agriculture, Natural Resources Conservation Service. ftp://ftp-fc.sc.egov.usda.gov/IA/technical/TillageGuide.pdf.

USDA NRCS. 2010c. *Air Quality Enhancement Activity–AIR02–Nitrogen Stabilizers or Urease Inhibitors for Nitrous Oxide Control*. Washington DC: U.S. Department of Agriculture, Natural Resource Conservation Service.

USDA NRCS. 2011a. *Natural Conservation Practice Standards: Electronic Field Technical Guide (eFOTG) Database of Practice Costs*: U.S. Department of Agriculture, Natural Resources Conservation Service. http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/fotg.

USDA NRCS. 2011b. *Air Quality Enhancement Activity–AIR02–Nitrogen Stabilizers or Urease Inhibitors for Nitrous Oxide Control*. Washington, DC: U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA NRCS. 2011c. Part 651 Agricultural Waste Management Field Handbook: U.S. Department of Agriculture Natural Resources Conservation Service.

USDA NRCS. 2012. Residue and Tillage Management, edited by USDA. Washington DC: U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA NRCS Iowa. 2012. *Strip Till*: U.S. Department of Agriculture, Natural Resources Conservation Service. http://www.ia.nrcs.usda.gov/technical/StripTill.html.

Van Es, H., J. Melkonian, A. DeGaetano, and L. Joseph. 2010. *Adapt-N A Tool for Adaptive Management of Nitrogen in Corn*. http://www.isafarmnet.com/2010OFNConfPresentations/pdf/Melkonian_Weather_and_Manure_Management.pdf.

Van Kessel, C., and W.R. Horwath. 2012. *Research on Alternative Rice Straw Management Practices in California*. Davis, CA: University of California, Davis. http://www.plantsciences.ucdavis.edu/uccerice/straw_management/research_straw_management.html.

Venterea, R.T., M. Burger, and K.A. Spokas. 2005. Nitrogen Oxide and Methane Emissions under Varying Tillage and Fertilizer Management. *Journal of Environmental Quality*, 34:10.

Venterea, R.T., M.S. Dolan, and T.E. Ochsner. 2010. Urea Decreases Nitrous Oxide Emissions Compared with Anhydrous Ammonia in a Minnesota Corn Cropping System. *Soil Science Society of America Journal*, 74(2):11.

Wassmann, R., R.S. Lantin, H.U. Neue, L.V. Buendia, et al. 2000. Characterization of methane emissions from rice fields in Asia. III. Mitigation options and future research needs. *Nutrient Cycling in Agroecosystems*, 58(1):23–36.

West, T.O., and A.C. McBride. 2005. The contribution of agricultural lime to carbon dioxide emissions in the United States: dissolution, transport, and net emissions. *Agriculture, Ecosystems & Environment*, 108(2):145–154.

Wittry, D. 2011. *USDA Chapter Draft-Nutrient Management 6-29-2011D*: Unpublished.

3. ANIMAL PRODUCTION SYSTEMS

Livestock production occurs on more than 1.1 million farms located throughout the United States (USDA NASS, 2008). Due to the diversity of these operations (with respect to size, geographic location, organizational structure, commodities produced, production technologies and practices employed, climate, and many other environmental factors), they differ significantly with respect to the magnitude of their GHG emissions, opportunities to reduce their GHG footprint, and the level of incentives that would be required to make specific GHG mitigation technologies and practices economically feasible for them to adopt. This chapter discusses GHG mitigation options for animal production systems, focusing primarily on changes to manure management systems for confined beef cattle, dairy cattle, and swine operations.[1] As appropriate, operations are distinguished by size (i.e., small, medium, and large farms)[2] and geographic region (i.e., the 10 USDA production regions). For each technology, information is provided on the current level of adoption, the potential for additional adoption, environmental and production performance, costs for adopting the technology, and break-even prices (\$/mt CO_2-eq mitigation). Options for reducing emissions from enteric fermentation are discussed qualitatively because there is significant uncertainty in the potential mitigation effectiveness of these methods. Options for mitigating emissions related to grazing lands management are, with one exception, also described qualitatively.

3.1 Manure Management

Manure management from dairy cattle, swine, and beef cattle operations in the United States accounts for 26% of all GHG emissions related to livestock sources (see Exhibit 1-10). Approximately 72% of these emissions are methane emitted from manure treated or stored under anaerobic conditions. The remaining 28% are N_2O emitted from manure stored or treated under aerobic conditions.

Conceptually, anaerobic treatment and storage facilities can be viewed as point sources for CH_4 emissions. It is straightforward to (1) pinpoint where emissions occur; (2) identify specific management changes that can be made to the system to reduce these emissions; and (3) quantify the levels of emissions before and after the management changes. Data are available to assess the cost to farmers to implement a number of these changes. In contrast, N_2O emissions from aerobic systems are relatively diffuse, with most of the emissions occurring after the manure is applied to land. Little research has been done to assess how these systems can be changed to reduce N_2O emissions, the magnitude of emissions reductions that these changes could achieve, or how much it would cost farmers to make the changes. For these reasons, GHG mitigation options developed in this section focus primarily on reducing CH_4 emissions from anaerobic facilities (e.g., lagoons, ponds, tanks, pits).

The specific mitigation options considered in this report are the following:

- **Anaerobic Digesters:** Lagoons and tanks that maintain anaerobic conditions and can produce and capture methane-containing biogas. This biogas can be used for electricity and/or heat, or can be flared. Anaerobic digesters are categorized into three types: covered lagoon, complete mix, and plug flow digesters.
- **Covering an Existing Pond, Tank, or Lagoon:** The installation of an airtight cover over an existing pond, tank, or lagoon can reduce emissions by allowing for the capture and destruction of methane gas.
- **Solids Separator:** The process of creating methane under anaerobic manure storage conditions requires the carbon contained in manure solids. By removing a portion of these solids from manure streams, separator systems can reduce methane emissions from existing storage facilities.

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[1] Mitigation options are not addressed for the management of poultry manure because the GHG emissions are significantly lower than those for cattle and swine.

[2] For this study, break-even prices are estimated for several farm sizes to illustrate the range of costs and benefits. Small, medium, and large farm sizes are defined by the number of animals.

- **Nitrification/Denitrification:** The removal of solids and nitrogen from the effluent streams through a multi-step chemical and biological process reduces GHG emissions associated with managing manure from confined swine operations.

The left-hand column of Exhibit 3-1 identifies a set of manure management technologies in common use today; alternative mitigation practices are listed across the top row. The technologies shown in the left-hand column are those defined for the U.S. Inventory of GHG Emissions and Sinks (EPA, 2010a). The mitigation options in the top row address reducing methane and, in one case, reducing N_2O.

A check mark in a cell in Exhibit 3-1 indicates that a change in the current manure management practice to the mitigation option will reduce GHG emissions. For those practices in use today where a mitigation option was not evaluated in this report, the reasons for their omission are briefly described.

Exhibit 3-1: Mitigation Options by Manure Management Practice

Current Manure Management Practice	Mitigation Option						
	Covered Lagoon Digester with EG	Covered Lagoon Digester with Flaring	Complete Mix Digester with EG	Plug Flow Digester with EG[a]	Covering Existing Tank, Pond, or Lagoon[b,c]	Solids Separator[d]	Nitrification / Denitrification System
Dairy Anaerobic Lagoon[e]	✓	✓	✓		✓	✓	
Poultry Anaerobic Lagoon	Poultry manure is rich in nitrogen and protein, and has high economic value as a fertilizer. Most poultry manure is managed by solid scraping with water and is managed for sale as fertilizer. This practice results in limited methane emissions, so the mitigation strategies for poultry manure are not addressed here.						
Swine Anaerobic Lagoon	✓	✓	✓		✓	✓	✓
Dairy Daily Seasonal Spread	Daily spreading of manure is generally not applicable to larger farms where the large volumes of manure cannot be practically spread on a daily basis due to the limitations of land area, labor and other costs, and climatic concerns (e.g., frozen or muddy soils). The mitigation options listed above result in higher emissions than daily spread, so they are not suggested as GHG mitigation options for farms using daily spread.						
Dairy Deep Pit	✓	✓	✓				
Swine Deep Pit	✓	✓	✓				
Beef Drylot	Covered lagoons and other options are not considered for beef drylots because the runoff lagoons associated with beef feedlots generally do not collect significant volatile solids and thus do not produce significant methane emissions.						
Dairy Drylot	Dairy drylots may have treatment trains that include manure runoff storage ponds, but they do not emit significant amounts of methane. For this reason, mitigation options are not considered for dairy drylots.						
Beef Liquid/Slurry[f]			✓	✓			
Dairy Liquid/Slurry	✓	✓	✓	✓	✓		
Swine Liquid/Slurry	✓	✓	✓	✓	✓		

Current Manure Management Practice	Mitigation Option						
	Covered Lagoon Digester with EG	Covered Lagoon Digester with Flaring	Complete Mix Digester with EG	Plug Flow Digester with EG[a]	Covering Existing Tank, Pond, or Lagoon[b,c]	Solids Separator[d]	Nitrification / Denitrification System
Beef Pasture	Not addressed because data on cost and/or N_2O emissions reductions for mitigation options are not readily available.						
Dairy Pasture							
Poultry Pasture							
Swine Pasture							
Poultry with Bedding	Poultry manure is rich in nitrogen and protein, and has high economic value as a fertilizer. Most poultry manure is managed by solid scraping with water and results in limited methane emissions.						
Poultry without Bedding	Most poultry housing without bedding or caged layer operations handle manure as a solid; there is no liquid tank or lagoon, and thus there is limited opportunity for methane generation. There may be a few treatment trains that include some liquid manure lagoon storage, but they do not emit significant methane. For these reasons, mitigation options are not considered for poultry without bedding.						
Dairy Solid Storage	Not addressed because there are limited methane emissions.						
Swine Solid Storage	Not addressed because there are limited methane emissions.						

EG = Electricity generation

[a] A plug flow digester can be used for slurries with a solids content of 11–13%. Dairy manure has a higher viscosity and does not settle out, making dairy manure well suited for plug flow digesters. Plug flow digesters can be used for swine and beef manure, but a mixer may be needed to reduce separation of the manure solids.

[b] Special lagoon covers can be installed that adjust to the changing lagoon levels in response to the filling and emptying of the lagoon.

[c] Swine farms with volatile solids production similar to that of dairy farms would have a similar cost profile and thus were not modeled for this study.

[d] Solids separators were not modeled for liquid/slurry systems because slurry typically has insufficient liquid content for effective separation. If a liquid/slurry system has a lower solids content, solids separators could be a potential mitigation option.

[e] A plug flow system could be used as an alternative for dairy anaerobic lagoons if manure was cleared with a scraping system. Manure is generally flushed with water for dairy anaerobic lagoon systems and, as a result, the viscosity of the manure is too low for use in a plug flow digester. For this reason, the mitigation option of transitioning from dairy anaerobic lagoons to a plug flow system was not modeled for this report.

[f] Beef manure typically has a solids content greater than 3%, and operations are generally found in midwestern and northern States. Given that anaerobic digesters do not generally perform well under these conditions, only complete mix and plug flow digesters are evaluated in this report as a mitigation option for beef liquid/slurry.

3.1.1 Anaerobic Digesters

In the context of confined livestock operations, anaerobic digestion is a process in which certain kinds of bacteria operate in an oxygen-free environment to convert the volatile solids contained in manure (i.e., feces, urine, and wastewater) into biogas and more stable organic compounds. The biogas produced during digestion is primarily CH_4 (55–70%) and CO_2 (30–45%), with trace amounts of other gases (including H_2S, ammonia, and N_2O).

GHG mitigation in this context refers to the reduction of total GHG emissions from transitioning from an anaerobic management system to a digester system. Capturing biogas and combusting it for energy generation or flaring converts CH_4 into CO_2, reducing the potential GHG impact of the operation.

For this report, three types of digesters were evaluated for mitigating GHGs: covered anaerobic lagoon digester, complete mix digester, and plug flow digester. Exhibit 3-2 presents the national annual CH_4 emissions reductions from the current use of these different types of digesters as of September 2012 (EPA, 2012), and illustrates the effectiveness of digesters in reducing GHG emissions from animal operations. The common components of digesters are included in Exhibit 3-3. A more detailed discussion about each type of digester is included in subsequent sections.

Exhibit 3-2: National Annual Methane Emissions Reductions from Use of Anaerobic Digesters as of 2012

Digester Type	Methane Emissions Reductions (mt CO_2-eq per year)
Covered Anaerobic Lagoon	318,158
Complete Mix	239,707
Plug flow	721,025

Source: EPA (2012).

Co-digestion of manure with other wastes (e.g., food waste or processing waste, slaughter byproducts, other agricultural byproducts) from on- or off-farm activities increases the production of biogas in the digester. Heat produced in boilers and electricity generators can be captured and used to heat the digester or adjacent buildings. Most farms with digesters use the biogas to generate electricity for on-farm use or sale to the local electric utility (EPA, 2011a). Generating electricity can lead to significant cost savings or revenue generation for the farm, and can further reduce GHG emissions by decreasing the use of purchased electricity or through the selling of green electricity back to the grid.

The byproducts of anaerobic digestion can also be used on-site or sold off-site, which can provide additional economic value to the project. The effluent and composted sludge can be used as a fertilizer, which can decrease the amount of synthetic fertilizer required for field application. The operator can use or sell the effluent or compostable sludge from the digester; the latter releases its nutrients slowly and is well suited for spreading on crops.[3] The dried solids from the digester can also be used for bedding or sold as a soil amendment.

The cost-effectiveness of transitioning from an existing management practice to a digester depends on the size of the farm, the region, the ability to sell co-benefits, and the price of electricity. The cost-effectiveness will fluctuate with the prices of electricity in a region.

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[3] Repeated applications of manure can lead to excess phosphorus. Variables such as manure type, soil, and weather conditions also make nitrate management a challenge, increasing the risk of loss into the environment (Ribaudo et al., 2011). See Section 2.2.5.3 of the Crop Production Systems chapter for more detail.

Exhibit 3-3: Common Components for Anaerobic Digester Systems

Component	Description
Solids separator	Unheated and unmixed manure is flushed from the animal facility to the digester. Dairy manure contains large fibrous solids that have a tendency to float on the surface and form a crust. This crust inhibits the flow of methane from the liquid to the gas space, so dairy operations generally screen out these solids prior to the manure entering the digester. Additionally, the fibrous solids do not yield as much methane as do the smaller suspended solids that pass through the screen. For swine operations, the separator step is not required because swine manure does not contain fibrous solids. For complete mix and plug flow digesters, a sand separator is used to remove unwanted non-organic dirt and sand from the influent manure. Solids separators may be used after digestion to obtain marketable manure solids.
Digester	A covered lagoon anaerobic digester includes an earthen pit with a non-permeable lining, either clay or geomembrane. In colder climates, one or two layers of liners may be used for heat insulation. Some digesters have equipment to detect leakage from the system. Complete mix and plug flow digesters include a rectangular or circular concrete base with a rigid tank, a gas-tight cover (flexible or rigid), a heating system to maintain 95–100°F in the digester, and an input and output system for manure.
Biogas removal system	The system consists of an airtight cover (either flexible bank-to-bank or floating) and piping under the cover that collects the gas and directs it to a single outlet pipe. Safety relief vent valve(s) are required for when the biogas pressure builds up to levels that can damage the cover.
Biogas handling system	This system takes the biogas from the digester gas outlet pipe and transports it to the end use. This system may include piping, gas pump or blower, gas meter, pressure regulator, and condensate drain(s).
Flare	This flare is specially designed for the complete combustion of biogas. It may be used as an emergency flare when the engine-generator is being serviced, or as a continuous flare for systems that have no other biogas utilization.
Overflow storage lagoon(s) or tank	An anaerobic digester must have some sort of overflow vessel, either an earthen lagoon or tank to contain both the effluent from the digester and any runoff from the feeding area, with enough capacity to satisfy the local water quality regulations regarding the prevention of manure runoff into streams or groundwater.
Biogas scrubbing[a]	A purification system removes H_2S or CO_2 for improved air quality and/or reduced engine corrosion. Moisture removal using a refrigerated drier may also be included to maintain dry gas for effective combustion.
Engine-generator[a]	This should be specially designed for efficient combustion of biogas and reduced emissions of criteria pollutants such as SO_x, NO_x, and unburned hydrocarbons, which may require a catalytic convertor.
Boilers or heaters[a]	Methane-containing biogas can be combusted in gas-heated boilers. These boilers can be used to heat the digester or surrounding buildings.
Compressor[a]	Biogas can be converted to compressed natural gas (CNG) and used or sold as transportation fuel.

[a] This equipment is necessary if biogas will be used on-site or sold.

Barriers to Adoption

For any given farm, a number of regulatory, technical, economic, and other challenges may act as barriers to transitioning to anaerobic digesters. Digester systems require capital investment and adjustment, which will vary depending on the existing collection and treatment systems. The ability to sell electricity to the grid and/or to sell natural gas to a transmission network will decrease the break-even price and, in some cases, may result in a negative break-even price. However, regulations and contracts related to the buyback of farm-generated electricity and/or natural gas could discourage adoption by lowering the farm-gate value of these potential products. Additionally, a lack of infrastructure for feeding farm-generated electricity or natural gas into utility transmission systems will be a barrier for the adoption of digesters in some areas.

Unheated digesters are less effective at producing methane in colder areas because lower temperatures slow the digestion process. During cold months, the methane content of biogas will be lower and the only option for use may be flaring. Complete mix and plug flow digesters can be used in colder climates because the digester is heated; however, the heat requires energy, which reduces the GHG emissions reduction benefits for these systems.

Digester systems can be complex and a variety of factors must be monitored; systems may thus be difficult to operate or require additional personnel to maintain. In particular, constant attention to the quantity and content of the wastes that enter the system is needed to maintain favorable conditions in the digester. The temperature of the digester must be monitored, and supplemental heat may be necessary. A high alkalinity must be maintained to keep the digester operating properly (USDA ERS, 2009). A backup system for handling manure and procuring power is needed when the digester is not operational. The collection of gas can pose a potential combustion risk.

The variable costs of operating a digester and the digester's methane and electrical output will fluctuate from year to year depending on system reliability, weather, and mechanical failures. The combination of these fluctuations and electricity prices makes an investment in a digester a potential income risk, so farmers may be reluctant to invest in the technology.

Capital equipment requirements specific to each system are summarized in the subsequent sections, along with other costs and savings. The assumptions underlying the cost profiles developed for this chapter are presented in Exhibit 3-4.

Exhibit 3-4: Underlying Assumptions for Cost Profiles

Cost Assumption	Value	Unit	Reference
Costs			
Equipment lifetime	15	Years	Estimate.
Annual operations and maintenance cost[a]	4	Percentage of total costs	Estimate.
Biogas Collection and Use			
Biogas system collection efficiency	85	%	Climate Action Reserve Livestock Calculation Tool, Beta v. 2.1.3 (Climate Action Reserve, 2009).
Operational hours of biogas system	8,000	hour	Estimate
Electrical generation efficiency	14,000	BTU/kWh	EPA, AgSTAR Farmware 3.4 (2009).
Price of electricity	See Appendix 3-A	$/kWh	EIA. Average Retail Price of Electricity to Ultimate Consumers by End-Use (EIA, 2012).
Animal Characteristics			
Manure production per lactating cow	17	lb VS/head/day	Table 1.b of ASAE D384.2: Manure Production and Characteristics (2005).
Manure production per dairy heifer	7.1	lb VS/head/day	Table 1.b of ASAE D384.2: Manure Production and Characteristics (2005).
Manure production per sow place[b]	5.2	lb VS/head/day	EPA AgSTAR Farmware 3.4 (2009).

Cost Assumption	Value	Unit	Reference
Manure production per beef	5	lb VS/head/day	Table 1.b of ASAE D384.2: Manure Production and Characteristics (2005).
Methane emitted from volatile solids, cow	3.84	ft^3/lb VS	EPA. Inventory of U.S. GHG Emissions and Sinks: 1990–2009 (2010).
Methane emitted from volatile solids, heifer	2.72	ft^3/lb VS	EPA Inventory of U.S. GHG Emissions and Sinks: 1990–2009 (2010).
Methane emitted from volatile solids, sow place[c]	4.61	ft^3/lb VS	EPA AgSTAR Farmware 3.4 (2009).
Methane emitted from volatile solids, feedlot beef[d]	2.88	ft^3/lb VS	Williams and Hills (1981).
Methane Properties			
Global Warming Potential (GWP) of methane	21	mt CO_2-eq/mt CH_4	IPCC, Second Assessment Report (1996).
Density of methane	0.0417	lb/ft^3	Density at normal temperature and pressure (20°C and 1 atm, respectively)
Energy content of methane	1,000	BTU/ft^3	Estimate.

[a] This operations and maintenance cost does not account for additional personnel that may be required for operating the digester system. The need for additional personnel will vary by operation and will result in an increase in the break-even prices presented in this report.

[b] Sow place refers to the capacity of the swine facility to hold mature female swine (sows) and includes both the lactating sows and gestating sows.

[c] Farmware 3.4 estimates the ultimate methane yield for a farrow-to-finish operation as 0.3525 m^3/kg VS. If this ultimate methane yield is applied to the kinetic equation of Hashimoto used in calculating Farmware methane yields for a complete mixed digester at 20-days HRT and 35°F temperature, the actual methane yield will be 0.29 m^3/kg VS, or 4.61 ft^3/lb VS.

[d] This value is based on D.W. Williams and D. Hills' study (Williams and Hills, 1981) to determine the ultimate methane yield of feedlot manure at varying ages of freshness. The methane yield varied from 0.28 m^3/kg VS for fresh beef feedlot manure to 0.20 m^3/kg VS for manure 3–6 months old. The average for all the samples, including fresh manure and recently scraped manure at 3–6 months, was 0.24 m^3/kg VS (i.e., 3.85 ft^3/lb VS). If this ultimate methane yield is applied to the kinetic equation of Hashimoto used in calculating Farmware methane yields for a complete mixed digester at 20-days HRT and 35°F temperature, the actual methane yield is equivalent to 0.18 m^3/kg VS, or 2.88 ft^3/lb VS.

3.1.2 Covered Lagoon Anaerobic Digester

3.1.2.1 Technology Characterization

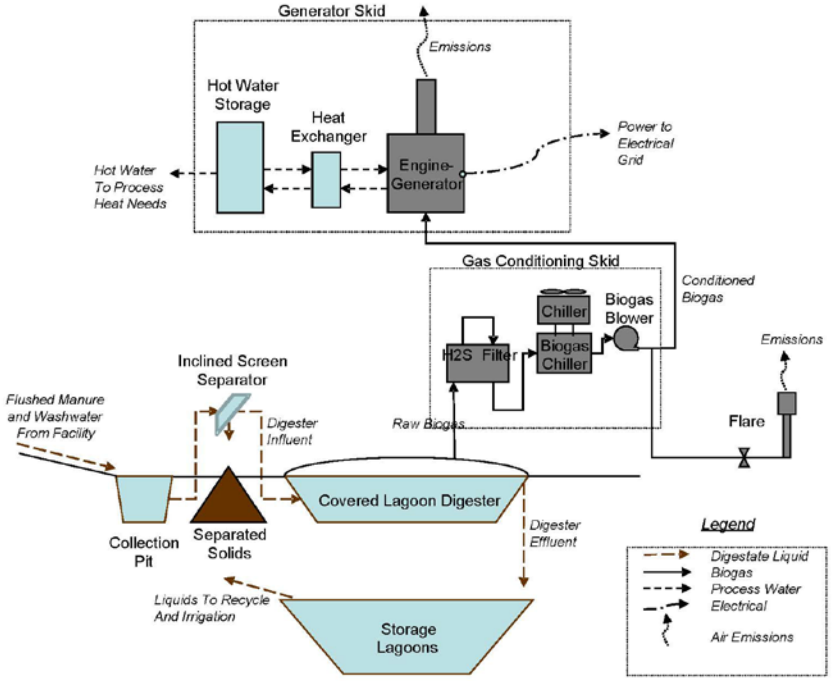
Covered lagoon anaerobic (CLA) digesters are a GHG mitigation option available for confined livestock operations, particularly for dairy and swine operations. CLA digesters promote digestion of manure and production of methane using an earthen lagoon fitted with an airtight, flexible cover to create anaerobic conditions. Inside the digester, the methane-containing biogas bubbles up to the area between the effluent surface and the flexible cover, where it is captured using a system of pipes and transported to a central location.

Key Features of Covered Lagoon Anaerobic Digesters

- Require flush manure collection systems, usually dairy and swine.
- Biogas produced in digesters can be used to generate electricity, heat, or pipeline-quality natural gas.
- Relative to anaerobic lagoons, digesters reduce pathogens and odors, and may reduce surface water and groundwater contamination.
- Byproducts of digestion can be further processed into nutrient-rich soil amendments and bedding for livestock.

Exhibit 3-5 and Exhibit 3-6 show, respectively, a schematic and a photograph of a typical CLA digester system. In the schematic, the biogas is captured for both on-farm and off-farm uses. The photograph clearly illustrates the methane collection system.

Exhibit 3-5: Schematic Diagram of a Typical Covered Lagoon Digester System



Source: Summers and Williams (2012).

Exhibit 3-6: Covered Lagoon Anaerobic Digester with Flexible Cover and Methane Collection System

Source: EPA (2011b).

CLA digesters are the least technically complicated of the digester technologies commercially available for manure management. The required components involve well-established technologies, and the system can be operated by a non-specialist. The range of equipment needs depends on the current manure management system, the end use of the biogas, and a range of site-specific factors. For example, sufficient storage capacity is needed to manage runoff and effluent leaving the digester.[4] For a given size of operation, storage needs will be greater where frozen ground or saturated soil conditions limit the period during which effluent can be applied to fields. Exhibit 3-7 summarizes a number of key characteristics related to the operational efficiency of a covered lagoon digester.[5]

Exhibit 3-7: Key Characteristics of Covered Lagoon Anaerobic Digesters

Key Design Parameters		
Characteristic	**Summary**	**Description/Explanation**
Technology	Well Established	Requires integrated system of a solids separator (for dairy), covered lagoon digester, and storage lagoon. Other technology (e.g., gas conditioning skid, generator skid), which is dependent on biogas use, is well established.
Farm Type	Dairy, Swine	Dairy and swine farms that employ flush manure handling.
Optimum Climate	Temperate/ Warm	Due to the exposure of lagoons to ambient temperatures, GHG mitigation potential is greatest for CLA digesters located in the Southeast, Delta, Southern Plains, and the lower half of the Mountain and Pacific regions.
Supplemental Heat	Varies	Most CLA digesters have an ambient lagoon temperature in the 50–80°F range and psychrophillic methanogens adapt to these temperatures. The digester's temperature changes slowly due to the large volume of liquid in it. Supplemental heat may be required in colder climates during winter months.
Digestion Vessel	Deep Lagoon	The digestion vessel includes an earthen lagoon with a minimum depth of 8 feet over 50% of the area; a freeboard minimum of 2 feet; an inlet pipe at 1 foot below the surface; an outlet pipe such that a constant liquid level is maintained; and an appropriate geomembrane covering that captures methane gas (USDA-NRCS, 2009).
Total Solids	0.5–3%	Fresh manure mixed with water, resulting in total solid between 0.5% and 3%. Fresh manure as excreted contains 15% total solids. When mixed with 5 parts water, the total solids content of the mixture is reduced to 3%. When mixed with 30 parts water, the total solids content falls to 0.5% (EPA, 2009).
Solids Characteristics	Fine	For digesters, flushed manure/water mixture is screened to remove large fibrous manure solids before the liquid goes to the digester. The solids are composted for bedding/soil conditioner.
Hydraulic Retention Time (HRT)[a]	40–60 days	Digester temperatures in the psychrophillic range (e.g., 50–80°F) require long retention times based on climate, typically 40 days in warmer climates, 60 days in colder climates (USDA-NRCS, 2009).
Daily Operations		
▪ Depending on the current manure management system, modifications may be needed to ensure that bedding and other contaminants do not enter the manure management system.		

[a] HRT = Hydraulic retention time, the average number of days that a volume of manure remains in the digester.

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[4] For the situation when covered lagoon digesters overflow into existing storage lagoons, which are needed to contain runoff and prevent nutrients from reaching streams and groundwater, these overflow lagoons will not emit significant methane because most of the volatile solids have been destroyed in the covered lagoon, and the overflow effluent is stabilized in terms of potential methane production.

[5] For more information on covered anaerobic digesters, see www.epa.gov/agstar.

Current and Potential Adoption

As of September 2012, there were 29 operational covered lagoon digesters[6] in the United States. A breakdown of these digesters by region, livestock type, and size is given in Exhibit 3-8. The digesters are located in 13 States and eight USDA production regions. Digesters function optimally in warmer climates, but they are capable of operating in colder climates; additional heat may be required to keep the digester functional during the winter months.

Exhibit 3-8: Current Adoption of Covered Lagoon Anaerobic Digesters by Production Region, Livestock Type, and Farm Size

USDA Production Region	No. of Farms
Northeast	6
Corn Belt	4
Lake States	1
Northern Plains	1
Southeast	0
Appalachia	5
Delta	2
Southern Plains	3
Mountain	0
Pacific	7
Total	**29**

Farm Size[a]	Swine	Dairy	Total Farms
Fewer than 999	0	6	6
1,000 to 9,999	8	10	18
10,000 to 29,999	3	0	3
30,000 to 99,999	0	0	0
More than 100,000	2	0	2
Total	**13**	**16**	**29**

[a] Population of livestock feeding digester.
Source: EPA (2012).

As of 2007, the U.S. livestock sector included about 75,450 swine operations and 70,000 diary operations (USDA, 2007). While swine and dairy farms are distributed throughout the United States, regional and size breakdowns of these operations suggest a significant potential to expand adoption of CLA digesters in response to appropriate incentives to mitigate GHG emissions. For example, larger confined animal operations have an economic advantage in adopting CLA digesters because there are more animal units to spread the costs. Operations in warmer regions also have a technical advantage because supplemental heat is not needed to maintain digester temperatures. Of all swine farms in 2007, about 12,200 had more than 1,000 head and, of these, 1,600 were located in North Carolina. Of the dairy operations, more than 7,600 had more than 200 head, with more than 2,800 located in the Appalachia, Southeast, South Plains, and Pacific USDA production regions. As indicated in Exhibit 3-1, the following types of current manure management systems are best suited to adoption of a CLA digester:

- Dairy anaerobic lagoon
- Swine anaerobic lagoon
- Dairy deep pit
- Swine deep pit
- Dairy liquid/slurry
- Swine liquid/slurry

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[6] Covered lagoon digesters in the AgSTAR database include digesters defined as a partial covered lagoon, a permeable covered lagoon, and a lined and covered basin.

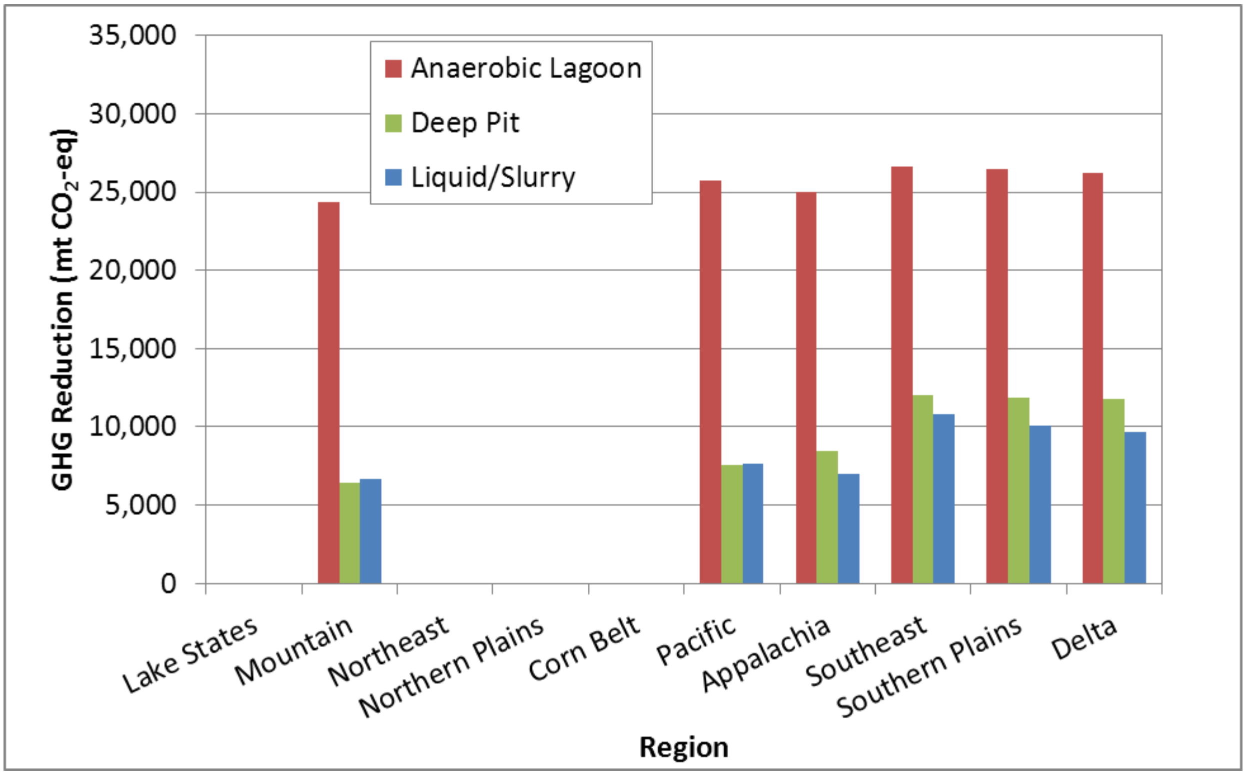
Environmental Impacts

The final effluent leaving a CLA digester can be further processed into products that may have a market value, depending on specific farm and local circumstances. Specifically, if dried and composted, the solids in the final effluent can be turned into livestock bedding for use on the farm or a high-quality, nutrient-rich soil amendment generally sold off of the farm. Relative to an anaerobic lagoon manure management system, a properly maintained CLA digester can reduce odors, the spread of pathogens, and water contamination related to the leakage of nitrogen compounds from the system.[7]

3.1.2.2 GHG Impacts

Both flare and electricity-generating systems mitigate GHGs by combusting the CH_4 to create CO_2, which has a lower global warming potential (GWP) than CH_4. The mitigation potential for transitioning from a current management to an anaerobic digester is provided for each of the applicable current management practices (i.e., dairy anaerobic lagoon, swine anaerobic lagoon, dairy deep pit, swine deep pit, dairy liquid/slurry, and swine liquid/slurry) in Appendix 3-D. The potential GHG reductions for a 5,000-head dairy farm and a 2,500-sow place farm adopting a covered lagoon anaerobic digester are shown in Exhibit 3-9 and Exhibit 3-10, respectively.

Exhibit 3-9: Farm-Level GHG Reduction Potential for Dairy Covered Lagoon Anaerobic Digesters, by Region for a 5,000-Head Dairy



Note: This graph represents the estimated emissions reductions achieved when a dairy operation transitions from an existing manure management practice to a CLA digester in different regions. Details of the calculations can be found in the footnotes for the cost profiles.

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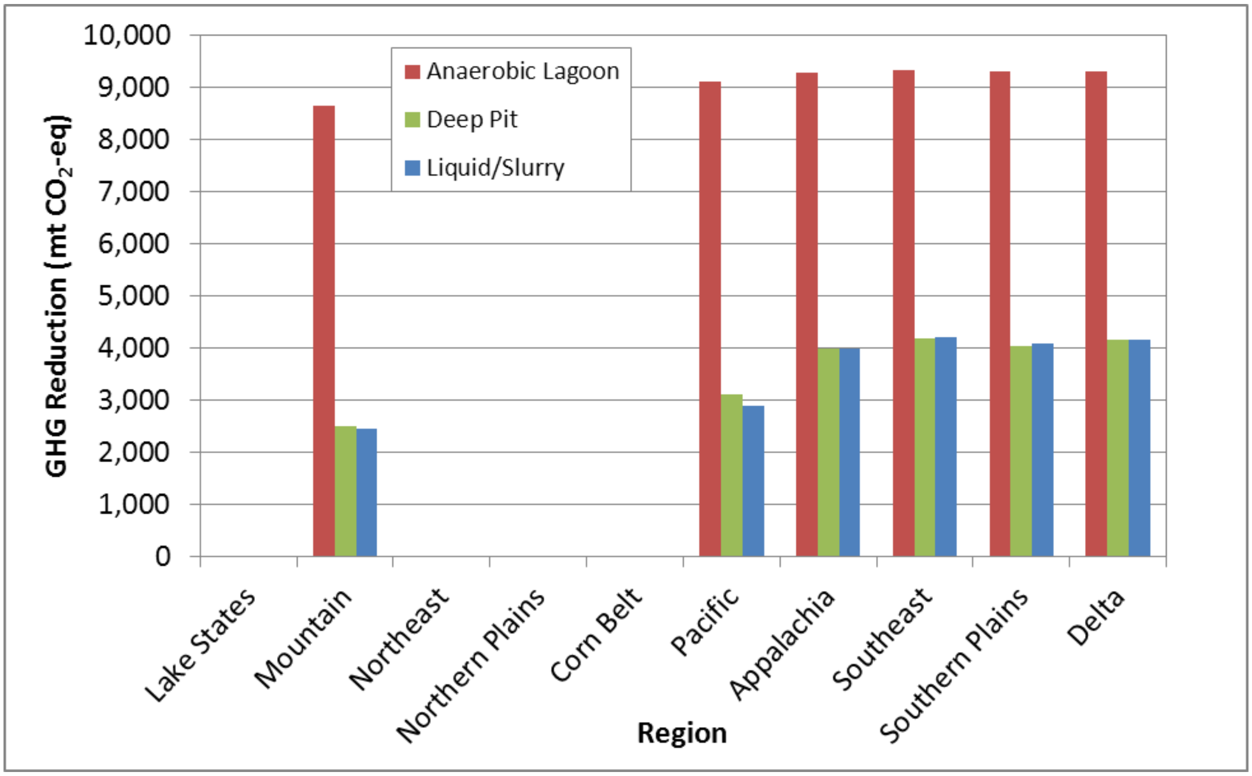
[7] A covered lagoon reduces ammonia emissions, which deposit nitrogen in the surrounding environment (including waterways).

Exhibit 3-10: Farm-Level GHG Reduction Potential for Swine Covered Lagoon Digesters, by Region for a 2,500-Sow Place Farm



Note: This graph represents the estimated emissions reductions achieved when a swine operation transitions from an existing manure management practice to a CLA digester in different regions. Details of the calculations can be found in the footnotes for the cost profiles.

3.1.2.3 Cost Profile

Exhibit 3-11 and Exhibit 3-12 present, respectively, representative farm-level cost profiles for the adoption of a CLA digester for different size dairy and swine operations. One benefit of anaerobic digesters is the opportunity to generate electricity and use it on-site or sell it back to the electrical grid. To model the cost savings of on-site electricity generation, the average electricity price in each region is used. While in some cases a famer could sell excess electricity back to the grid, these additional revenues are not included in the break-even price calculations because of the uncertainty of whether the required infrastructure exists at a given farm. Flare-only digesters do not include the purchase of power-generation equipment because they do not produce electricity; thus, no savings from electricity purchases are accounted for in the break-even price. The total costs of adoption include capital costs and recurring costs.

Exhibit 3-11: Cost Profile for Dairy Covered Lagoon Anaerobic Digesters

Parameter	Value			
Farm Size[a]				
No. of cows	300	600	1,000	5,000
No. of heifers	300	600	1,000	5,000
Manure Collection Efficiency from Cows[b]	75%	75%	75%	75%
Manure Collection Efficiency from Heifers[b]	45%	45%	45%	45%
Capital Costs:[c]	$758,178	$884,617	$1,053,203	$2,739,059

Parameter	Value			
Digester and Engine-Generator Set	$733,957	$856,357	$1,019,557	$2,651,557
Hydrogen Sulfide Treatment ($)	$22,753	$26,547	$31,606	$82,198
Flare ($)	$24,221	$28,260	$33,645	$87,501
Utility Charges ($)	$38,900	$45,387	$54,037	$140,533
Operations and Maintenance Cost ($)	$30,327	$35,385	$42,128	$109,562
Capacity of Conversion Equipment (kW)[d]	50	100	167	837
Lagoon Dimensions:[e]				
Length (ft)	300	350	400	1,000
Width (ft)	100	150	200	250
Depth (ft)	18	20	24	24
Volatile Solids (lb/day)[f]	4,673	9,347	15,578	77,892
Methane Generation (m^3 CH_4)[g]	174,547	349,094	581,823	2,909,114
Methane Captured (m^3 CH_4)[h]	148,365	296,730	494,549	2,472,747
Methane Emitted (m^3 CH_4)[i]	26,182	52,364	87,273	436,367
Methane Emitted (mt CO_2-eq)[j]	367	734	1,224	6,119
Methane Mitigated (mt CO_2-eq)	2,080	4,161	6,934	34,672
Total Electricity Generation (kWh)[k]	401,925	803,849	1,339,749	6,698,743
Electricity Used On-Site (kWh)[l]	237,300 to 330,600	474,600 to 661,200	791,000 to 1,102,000	3,955,000 to 5,510,000
Excess Electricity Generated (kWh)[l]	71,325 to 164,625	142,649 to 329,249	237,749 to 548,749	1,188,743 to 2,743,743

[a] CLA digesters are technically feasible for farms with fewer than 300 cows, but economic considerations (e.g., high adoption costs per unit of output, opportunity costs associated with digester failure) will require significantly higher adoption incentives than for larger operations; consequently, this report does not evaluate CLA digesters for dairy operations with fewer than 300 head of cows. The calculations in this table include the emissions associated with those from cows and heifers.

[b] Assumed value.

[c] Cost Profile for Dairy: AgSTAR analyzed anaerobic digester system capital costs for 40 dairy farms for which itemized cost estimates were available and performed a regression analysis to determine an algorithm for capital costs. For dairy covered lagoon anaerobic digesters, the capital costs ($) = (400 × (no. cows) + $599,566) + flare + H_2S treatment + utility charges. The cost of the flare is 3.3% of the cost of the digester and engine-generator set, the cost of H_2S treatment is 3.1%, the cost of utility charges is 5.3%, and the operations and maintenance cost (O&M) is assumed to be 4%. The values have been converted to 2010 dollars (EPA, 2010b).

[d] kW = [(no. cows) x (lb VS_{cow}/day) × (0.75 collection efficiency) × (3.84 ft^3 methane/lb VS) × (1000 BTU/ft^3 methane)] / [(24 hrs/day) × (14,000 BTU/kWh)] + [(no. heifers) x (lb VS_{heifer}/day) × (0.45 collection efficiency) × (2.72 ft^3 methane/lb VS) × (1000 BTU/ft^3 methane)] / [(24 hrs/day) × (14,000 BTU/kWh)] (EPA, 2006a).

[e] Lagoon dimensions are based on recommendations in EPA (2009); the assumption is that on farms with existing lagoons, a new covered lagoon is required because the existing lagoons are needed for storage capacity for runoff and winter storage of wastewater.

[f] Volatile solids, lb/day = (no. of cows) × (lb VS_{cow}/day) × (cow manure collection efficiency) + (no. of heifers) × (lb VS_{heifer}/day) × (heifer manure collection efficiency).

[g] Methane generation (m^3/yr) = (lb VS_{cow}/day) × (3.84 ft^3 methane/lb VS) × (365 days/yr) × (0.0283 m^3/ft^3) + (lb VS_{heifer}/day) × (2.72 ft^3 methane/lb VS) × (365 days/yr) × (0.0283 m^3/ft^3) (EPA, 2006a).

[h] Methane captured is based on Climate Action Reserve (2009), where the biogas control system collection efficiency is assumed to be 85%.

[i] Methane emitted (m^3) = (methane generation, m^3) – (methane captured, m^3). Methane emitted is the methane that escapes into the atmosphere from the biogas control system.

[j] Methane emitted (mt CO_2-eq) = (Methane emitted, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) × (21 mt CO_2-eq/mt CH_4) / (2,205 lb/mt CH_4). These emissions result from the covered lagoon digester. The ultimate GHGs mitigated depend on the difference between the current practice and the net GHG emissions resulting from a covered lagoon digester.

[k] Total electricity generation (kWh/yr) = (capacity of conversion equipment, kWh) x (8,000 operating hours/yr).

[l] The average electricity use for an operation varies from region to region due to varying heating/cooling demands and technologies. A range has been provided for the energy generated and used on-site. A range has also been provided for the excess energy generated. The assumptions used to estimate energy demand for each operation are from Key and Sneeringer (2011).

Exhibit 3-12: Cost Profile for Swine Covered Lagoon Anaerobic Digesters

Parameter	Value		
Farm Size (No. of sow places)[a, b]	150	500	2,500
Capital Costs:[c]	$768,274	$967,016	$2,102,689
Digester and Engine-Generator Set ($)	$687,801	$865,726	$1,882,443
Hydrogen Sulfide Treatment ($)	$21,321.83	$26,838	$58,356
Flare ($)	$22,697	$28,569	$62,121
Utility Charges ($)	$36,453	$45,883	$99,769
Operations and Maintenance Cost ($)	$30,731	$38,681	$84,108
Capacity of Conversion Equipment (kW)[d]	11	36	178
Lagoon Dimensions:[e]			
Length (ft)	300	400	1,000
Width (ft)	100	200	250
Depth (ft)	18	24	24
Volatile Solids (lb/day)[f]	773	2,576	12,878
Methane Generation (m^3 CH_4)[g]	37,093	123,644	618,218
Methane Captured (m^3 CH_4)[h]	31,529	105,097	525,486
Methane Emitted (m^3 CH_4)[i]	5,564	18,547	92,733
Methane Emitted (mt CO_2-eq)[j]	78	260	1,300
Methane Mitigated (mt CO_2-eq)	442	1,474	7,368
Total Electricity Generation (kWh)[k]	85,413	284,711	1,423,556
Electricity Used On-Site (kWh)[l]	85,413	284,711	1,423,556
Excess Electricity Generated (kWh)[l]	0	0	0

[a] Swine farrow-to-finish farms with fewer than 150 sows are assumed to be too small to support an economically feasible digester. Although digesters are feasible at farms with fewer than 150 sows, economic considerations (e.g., high adoption costs per unit of output, opportunity costs associated with digester failure) will require significantly higher adoption incentives than for larger operations; consequently, this report does not evaluate digesters for swine operations with fewer than 150 sows.

[b] "Sow places" refer to the capacity of the swine facility to hold mature female swine (sows) and includes both the lactating sows and gestating sows. Each of the operations has the following numbers of swine:

- 150-sow places: 50 lactating sows, 100 gestating sows, 470 nursing pigs, 470 weaned pigs, 410 feeder pigs;
- 500-sow places: 167 lactating sows, 333 gestating sows, 1,567 nursing pigs, 1,567 weaned pigs, 1,367 feeder pigs; and
- 2,500-sow places: 833 lactating sows, 1,667 gestating sows, 7,833 nursing pigs, 7,833 weaned pigs, 6,833 feeder pigs.

[c] Cost Profile for Swine: AgSTAR analyzed anaerobic digester system capital costs for eight dairy farms for which itemized cost estimates were available and performed a regression analysis to determine an algorithm for capital costs. The capital costs for swine AD systems was calculated using the formula provided for dairy covered lagoon digesters and scaled based on VS output. The capital costs ($) = (400 × no. of swine × scaling factor + $599,566) + flare + H_2S treatment + utility charges. The scaling factor is equal to (VS_{swine} lb/day) / (VS_{cow} lb/day) = 0.31. The cost of the flare is 3.3% of the cost of the digester and engine-generator set, the cost of H_2S treatment is 3.1%, the cost of utility charges is 5.3%, and the O&M is assumed to be 4%. The values have been converted to 2010 dollars (EPA, 2010b).

[d] kW = [(lb VS/day) × (4.61 ft^3 methane/lb VS) × (1000 BTU/ ft^3 methane)] / [(24 hrs/day) × (14,000 BTU/kWh)] (EPA, 2006a).

[e] Lagoon dimensions are based on recommendations in EPA (2009) Agstar Farmware 3.1; for farms with existing lagoons, a new covered lagoon is assumed to be required because the existing lagoons are needed for storage capacity for runoff and winter storage of wastewater.

[f] Volatile solids per day = (lb VS/day/sow place) × (no. sow places).

[g] Equation for methane generation, m^3/yr = (lb VS/day) × (4.61 ft^3 methane/lb VS) × (365 days/yr) × (0.0283 m^3/ft^3) (EPA, 2006a).

[h] Methane captured is based on Climate Action Reserve (2009), where biogas control system collection efficiency is assumed to be 85%.

[i] Methane emitted (m^3) = (methane generation, m^3) – (methane captured, m^3). Methane emitted is the methane that escapes into the atmosphere from the biogas control system.

[j] Methane emitted (mt CO_2-eq) = (methane emitted, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) x (21 mt CO_2-eq/mt CH_4) / (2,205 lb/mt CH_4). These emissions result from the covered lagoon digester. The ultimate GHGs mitigated depend on the difference between the current practice and these net GHG emissions resulting from a covered lagoon digester.
[k] Total electricity generation (kWh/yr) = (capacity of conversion equipment, kWh) x (8,000 operating hours/yr).
[l] The assumptions used to estimate energy demand for each operation are from Key and Sneeringer (2011).

3.1.2.4 Break-Even Prices

Exhibit 3-13 through Exhibit 3-16 present the break-even prices for the adoption of a CLA digester. These prices include a tax rate of 15%, and discount rate of 5%. For each relevant existing manure management practice, the exhibits present the break-even prices for transitioning to covered lagoon anaerobic digesters for farms of different sizes and in different regions. Negative values are indicated with "<$0" and are due to energy savings at large farms. The energy demand for farms was estimated using energy demand per head estimates from Key and Sneeringer (2011). These estimates are regional averages for all farm sizes and do not take into account the difference in energy demand between larger and smaller farms (i.e., the decrease in energy demand per head as farm sizes increase). Consequently, the estimates here for energy used on-site are likely to be on the high side. The instances of negative break-even prices suggest that, in some regions, it should be technically feasible for some large farms to install a CLA digester without a GHG incentive. In practice, operational risks, uncertainty with respect to electricity prices, and a lack of familiarity with the technology may discourage adoption. As indicated in the exhibit, the break-even prices increase as the farm size decreases, and installing digesters is more difficult financially for small operations than for large ones.

For dairy operations, farms in the Mountain production region and in the South have the lowest break-even prices for transitioning to covered lagoon anaerobic digesters with electricity generation because they incur the highest energy savings due to on-site generation and the use of electricity.

Exhibit 3-13: Break-Even Prices for Dairy Farms that Adopt Electricity-Generating Covered Lagoon Anaerobic Digesters as Alternative to Existing Management Practice

Existing Practice: Anaerobic Lagoon			Existing Practice: Deep Pit			Existing Practice: Liquid/Slurry		
Model Farm Size	**Region**	**Break-Even Price (2010 $/mt CO_2-eq)**	**Model Farm Size**	**Region**	**Break-Even Price (2010 $/mt CO_2-eq)**	**Model Farm Size**	**Region**	**Break-Even Price (2010 $/mt CO_2-eq)**
5,000	Mountain	<$0	5,000	Mountain	<$0	5,000	Mountain	<$0
5,000	Pacific	$2	5,000	Southeast	$8	5,000	Southeast	$9
5,000	Southeast	$4	5,000	Delta	$8	5,000	Pacific	$9
5,000	Southern Plains	$4	5,000	Southern Plains	$9	5,000	Southern Plains	$10
5,000	Delta	$4	5,000	Pacific	$11	5,000	Delta	$11
5,000	Appalachia	$4	5,000	Appalachia	$15	5,000	Appalachia	$20
1,000	Mountain	$15	1,000	Southeast	$40	1,000	Southeast	$45
1,000	Pacific	$17	1,000	Southern Plains	$41	1,000	Southern Plains	$50
1,000	Southeast	$18	1,000	Delta	$42	1,000	Delta	$54
1,000	Southern Plains	$18	600	Southeast	$67	600	Southeast	$75
1,000	Delta	$18	600	Southern Plains	$68	1,000	Pacific	$75
1,000	Appalachia	$20	600	Delta	$69	1,000	Mountain	$81
600	Mountain	$29	1,000	Appalachia	$73	600	Southern Plains	$83
600	Pacific	$30	1,000	Pacific	$84	600	Delta	$90
600	Southeast	$30	1,000	Mountain	$99	1,000	Appalachia	$100
600	Southern Plains	$30	600	Appalachia	$121	600	Pacific	$130
600	Delta	$31	300	Southeast	$134	300	Southeast	$149
600	Appalachia	$33	300	Southern Plains	$136	600	Mountain	$155
300	Southeast	$61	300	Delta	$139	300	Southern Plains	$166
300	Southern Plains	$61	600	Pacific	$146	600	Appalachia	$167
300	Pacific	$61	600	Mountain	$189	300	Delta	$180
300	Delta	$62	300	Appalachia	$243	300	Pacific	$267
300	Mountain	$62	300	Pacific	$299	300	Appalachia	$333
300	Appalachia	$65	300	Mountain	$413	300	Mountain	$339

Note: Negative break-even prices were found for large farms (5,000 head of cows) in the Mountain production region. Estimates from Key and Sneeringer (2011) of average energy demand per head of cow are highest in the Midwest region, thus the potential cost savings for an operation from transitioning to an energy-generating digester can be significant.

Exhibit 3-14: Break-Even Prices for Dairy Farms that Adopt Flare-Only Covered Lagoon Anaerobic Digesters as Alternative to Existing Management Practices

Existing Practice: Anaerobic Lagoon		
Model Farm Size	Region	Break-Even Price (2010 $/ mt CO_2-eq)
5,000	Southeast	$15
5,000	Southern Plains	$15
5,000	Delta	$15
5,000	Pacific	$15
5,000	Appalachia	$16
5,000	Mountain	$16
1,000	Southeast	$28
1,000	Southern Plains	$28
1,000	Delta	$29
1,000	Pacific	$29
1,000	Appalachia	$30
1,000	Mountain	$31
600	Southeast	$39
600	Southern Plains	$39
600	Delta	$40
600	Pacific	$41
600	Appalachia	$42
600	Mountain	$44
300	Southeast	$67
300	Southern Plains	$68
300	Delta	$69
300	Pacific	$70
300	Appalachia	$73
300	Mountain	$75

Existing Practice: Deep Pit		
Model Farm Size	Region	Break-Even Price (2010 $/ mt CO_2-eq)
5,000	Southeast	$32
5,000	Southern Plains	$33
5,000	Delta	$33
5,000	Appalachia	$58
1,000	Southeast	$62
1,000	Southern Plains	$63
1,000	Delta	$64
5,000	Pacific	$74
600	Southeast	$87
600	Southern Plains	$88
600	Delta	$90
5,000	Mountain	$108
1,000	Appalachia	$112
1,000	Pacific	$142
300	Southeast	$149
300	Southern Plains	$151
300	Delta	$154
600	Appalachia	$157
600	Pacific	$199
1,000	Mountain	$207
300	Appalachia	$270
600	Mountain	$290
300	Pacific	$341
300	Mountain	$497

Existing Practice: Liquid/Slurry		
Model Farm Size	Region	Break-Even Price (2010 $/ mt CO_2-eq)
5,000	Southeast	$36
5,000	Southern Plains	$40
5,000	Delta	$43
5,000	Pacific	$66
1,000	Southeast	$69
1,000	Southern Plains	$77
5,000	Appalachia	$80
1,000	Delta	$83
5,000	Mountain	$88
600	Southeast	$96
600	Southern Plains	$108
600	Delta	$116
1,000	Pacific	$127
1,000	Appalachia	$154
300	Southeast	$165
1,000	Mountain	$170
600	Pacific	$177
300	Southern Plains	$184
300	Delta	$199
600	Appalachia	$216
600	Mountain	$238
300	Pacific	$304
300	Appalachia	$370
300	Mountain	$408

Exhibit 3-15: Break-Even Prices for Swine Farms that Adopt Electricity-Generating Covered Lagoon Anaerobic Digesters as Alternative to Existing Management Practices

Existing Practice: Anaerobic Lagoon			Existing Practice: Deep Pit			Existing Practice: Liquid/Slurry		
Model Farm Size (sow places)	**Region**	**Break-Even Price (2010 $/ mt CO_2-eq)**	**Model Farm Size (sow places)**	**Region**	**Break-Even Price (2010 $/ mt CO_2-eq)**	**Model Farm Size (sow places)**	**Region**	**Break-Even Price (2010 $/ mt CO_2-eq)**
2,500	Southeast	$3	2,500	Southeast	$7	2,500	Southeast	$7
2,500	Southern Plains	$3	2,500	Delta	$7	2,500	Delta	$7
2,500	Delta	$3	2,500	Southern Plains	$8	2,500	Southern Plains	$8
2,500	Appalachia	$3	2,500	Appalachia	$8	2,500	Appalachia	$8
2,500	Pacific	$3	2,500	Pacific	$11	2,500	Pacific	$12
2,500	Mountain	$4	2,500	Mountain	$16	2,500	Mountain	$16
500	Southeast	$45	500	Southeast	$100	500	Southeast	$99
500	Southern Plains	$45	500	Delta	$100	500	Delta	$101
500	Delta	$45	500	Southern Plains	$104	500	Southern Plains	$103
500	Appalachia	$45	500	Appalachia	$106	500	Appalachia	$107
500	Pacific	$46	500	Pacific	$150	500	Pacific	$169
500	Mountain	$49	500	Mountain	$211	500	Mountain	$217
150	Southeast	$166	150	Southeast	$369	150	Southeast	$367
150	Southern Plains	$166	150	Delta	$371	150	Delta	$374
150	Delta	$166	150	Southern Plains	$387	150	Southern Plains	$382
150	Appalachia	$166	150	Appalachia	$391	150	Appalachia	$395
150	Pacific	$170	150	Pacific	$554	150	Pacific	$624
150	Mountain	$181	150	Mountain	$779	150	Mountain	$804

Exhibit 3-16: Break-Even Prices for Swine Farms that Adopt Flare-Only Covered Lagoon Anaerobic Digesters as Alternative to Existing Management Practices

Existing Practice: Anaerobic Lagoon			Existing Practice: Deep Pit			Existing Practice: Liquid/Slurry		
Model Farm Size (sow places)	Region	Break-Even Price (2010 $/ mt CO_2-eq)	Model Farm Size (sow places)	Region	Break-Even Price (2010 $/ mt CO_2-eq)	Model Farm Size (sow places)	Region	Break-Even Price (2010 $/ mt CO_2-eq)
2,500	Southeast	$15	2,500	Southeast	$32	2,500	Southeast	$32
2,500	Southern Plains	$15	2,500	Delta	$33	2,500	Delta	$33
2,500	Delta	$15	2,500	Southern Plains	$34	2,500	Southern Plains	$34
2,500	Appalachia	$15	2,500	Appalachia	$34	2,500	Appalachia	$35
2,500	Pacific	$15	2,500	Pacific	$49	2,500	Pacific	$55
2,500	Mountain	$16	2,500	Mountain	$69	2,500	Mountain	$71
500	Southeast	$53	500	Southeast	$118	500	Southeast	$117
500	Southern Plains	$53	500	Delta	$118	500	Delta	$119
500	Delta	$53	500	Southern Plains	$123	500	Southern Plains	$122
500	Appalachia	$53	500	Appalachia	$125	500	Appalachia	$126
500	Pacific	$54	500	Pacific	$177	500	Pacific	$199
500	Mountain	$58	500	Mountain	$249	500	Mountain	$257
150	Southeast	$165	150	Southeast	$367	150	Southeast	$365
150	Southern Plains	$165	150	Delta	$369	150	Delta	$371
150	Delta	$165	150	Southern Plains	$384	150	Southern Plains	$380
150	Appalachia	$166	150	Appalachia	$389	150	Appalachia	$392
150	Pacific	$169	150	Pacific	$551	150	Pacific	$621
150	Mountain	$180	150	Mountain	$775	150	Mountain	$799

3.1.3 Complete Mix Anaerobic Digester

3.1.3.1 Technology Characterization

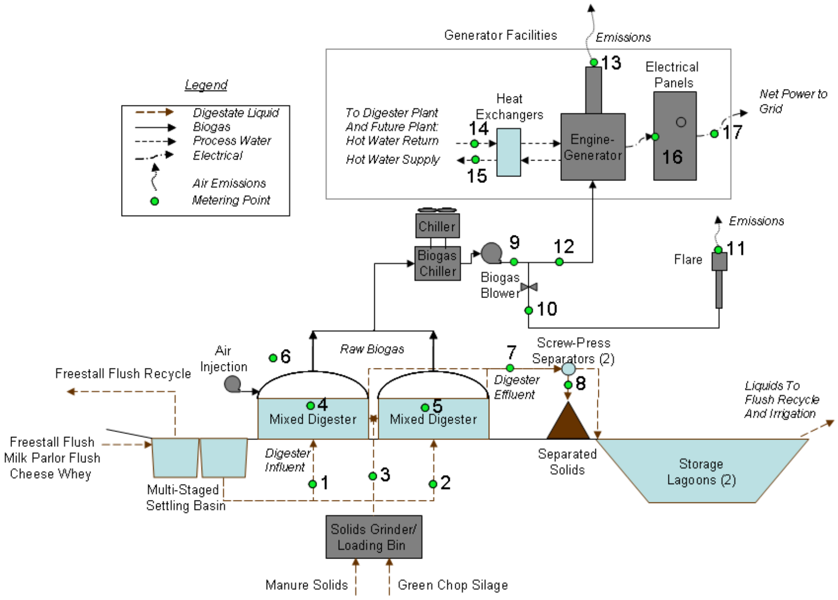
A complete mix anaerobic (CMA) digester is a heated tank, constructed of either reinforced concrete or steel, with a gas-tight cover. The digester contents are mixed periodically, either by a motor-driven impeller or a pump. While CMA digester systems can be designed for a variety of farm types, 60 of the existing digesters are on dairy and swine farms.[8]

Exhibit 3-17 is a schematic of a representative CMA digester system that uses the gas for electrical generation, including a flare for emergency use. When the digester needs maintenance or repair, the manure is bypassed to the storage lagoons. Exhibit 3-18 depicts a diagram of a CMA digester.

Key Features of Complete Mix Anaerobic Digesters

- Require a slurry manure mixture with total solids content of 3–10%, usually from dairy, beef, and swine operations with flush or scrape manure systems.
- Biogas produced in digesters can be used to generate electricity, heat, or pipeline-quality natural gas.
- Adoption of CMA digesters may decrease the release of pathogens and reduce surface water and groundwater contamination.
- Byproducts of CMA digestion can be applied as a fertilizer, sold as a soil amendment, or processed into livestock bedding.

Exhibit 3-17: Schematic Diagram of a Typical Complete Mix Anaerobic Digester System



Source: Williams (2011).

Note: Freestall flush enters the multi-staged settling basin, where solids settle to the bottom of the basin. The material from the bottom of the basin is then pumped into the digester in parallel (steps 1 and 2 in the diagram above). Manure solids and green chop silage are loaded into a loading bin and mixed together. This higher solids material is then transferred into the digesters using screw-type augers and combined with the liquid portion (step 3). Biogas is generated within the digester and then removed for further processing (steps 6 through 17). The effluent can be removed from the digester, solids separated, and then stored in a lagoon (steps 7 and 8).

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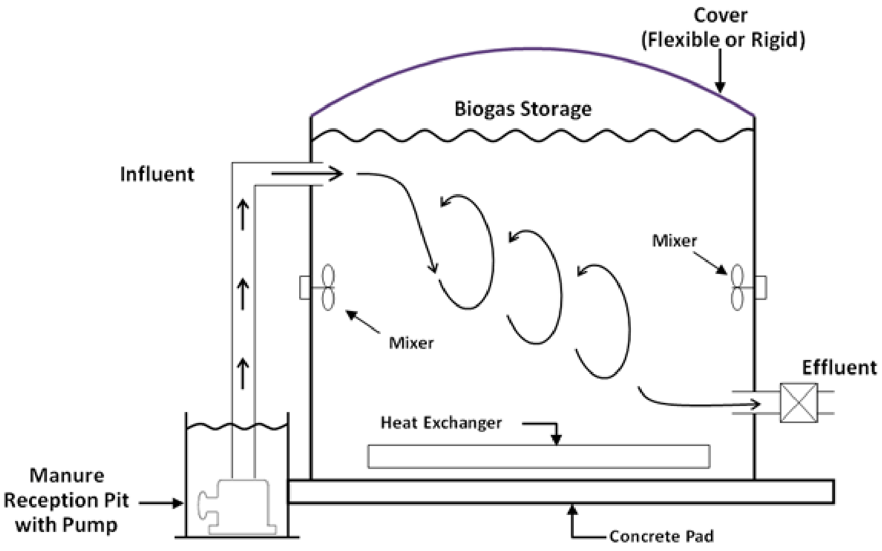
[8] Information on existing digesters was obtained from the AgSTAR database of digesters in the United States. This includes digesters that were operational as of September 2012 (EPA, 2012).

Exhibit 3-18: Diagram of a Complete Mix Anaerobic Digester



Source: EPA (2011a).

Exhibit 3-19: Complete Mix Anaerobic Digester

Source: EPA (2011a).

The key capital equipment systems for all CMA digesters are listed in Exhibit 3-3. Exhibit 3-20 summarizes a number of key characteristics relevant to the efficient operation of a CMA digester.[9]

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[9] For more information on complete mix anaerobic digesters, see www.epa.gov/agstar.

Exhibit 3-20: Key Characteristics of Complete Mix Anaerobic Digesters

Key Design Parameters		
Characteristic	**Summary**	**Description/Explanation**
Technology	Well established	Components that are required in addition to those described earlier for anaerobic digesters include a collection tank and manure transfer system (i.e., a tank that holds at least 2 days of manure production, a mixing/agitation pump, and pump to transfer manure into digester). Typically, a mechanical scraping or flush system is used to collect manure from the barn or drylot. However, CMA digesters are most effective when the manure is mixed with water. Often this water comes from commercial or agricultural wastewater (e.g., milking parlor wash water, slaughterhouse wastewater).
Farm Type	Dairy, swine, beef	Best suited to confined animal facilities that handle manure from concrete or slatted floors. Some water and bedding can be handled in system.
Optimum Climate	All	Heated digester keeps temperature constant in all climates.
Supplemental Heat	Varies	Heat comes from engine water jacket[a] and exhaust; heated water is circulated in pipes in insulated digester to maintain approximately 95°F.
Digestion Vessel	Round/ square in/above-ground tank	Steel or concrete tanks, insulated to prevent heat loss, with built-in mixing and heating equipment; depth is 10–30 feet, with fixed or flexible gas cover.
Total Solids	3–10%	Manure from scrape or pull-plug flushing systems need to be diluted to the appropriate viscosity. Some bedding permissible, must be chopped or ground.
Solids Characteristics	Coarse	All manure loaded into digester. Solids separation occurs after digestion.
Hydraulic Retention Time (HRT)	17+ days	Digester temperature is in the mesophilic range; requires a retention time of at least 17 days (USDA-NRCS, 2009).
Daily Operations		
▪ Regular removal of manure is necessary to maintain the digester. ▪ Attention must be given regularly to the consistency of the contents of the digester (i.e., the load of the digester must have the proper amount of manure at the correct consistency). ▪ Regular maintenance program is needed for the digester and engine-generator operation.		

HRT = Hydraulic Retention Time, the average number of days a volume of manure that remains in the digester.

[a] Engine jacket water refers to the cooling system on engine-generators from which hot water is circulated via heat exchangers to both keep the engine at its normal operating temperature, approximately 200°F, and to provide heating water for digester heating and other hot water processing needs on dairy and swine farms (e.g., washing milking equipment and space heating for young pigs).

Current and Potential Adoption

In 2012, there were 63 complete mix digesters[10] operating in 20 different States. Exhibit 3-21 provides a breakdown of the CMA digesters by USDA production region, livestock type, and size.

Exhibit 3-21: Current Adoption of Complete Mix Anaerobic Digesters by Production Region, Livestock Type, and Farm Size

USDA Production Region	No. of Farms
Northeast	30
Corn Belt	6
Lake States	13
Northern Plains	1
Southeast	0
Appalachia	1
Delta	2
Southern Plains	1
Mountain	5
Pacific	4
Total	**63**

Farm Size (population feeding digester)	No. of Farms by Farm Type			
	Swine[a]	Dairy	Poultry and Duck	Total Farms
Fewer than 999	0	22	0	22
1,000 to 9,999	5	23	0	28
10,000 to 29,999	4	1	0	5
30,000 to 99,999	0	0	1	1
More than 100,000	0	0	2	2
Unknown	1	4	0	5
Total	**10**	**50**	**3**	**63**

[a] Three farms indicated both swine and dairy/cattle populations feeding the digester. These digesters were classified as swine because significantly more head of swine are feeding the digester.

Source: EPA (2012).

As shown in Appendix 3-C, thousands of swine, dairy, and beef operations with 500 or more head are located throughout the United States. With 63 CMA digesters now in operation, there is significant potential to expand adoption rates given the existence of appropriate GHG mitigation incentives. CMA digesters are most likely to be installed on dairy and swine farms because their manure handling systems tend to produce waste streams that are more compatible with the technical requirements of CMA digesters than those produced by the manure handling systems used by most beef feedlots. Confined dairy and swine operations tend to flush manure from animal barns. Beef feedlots usually manage manure in relatively dry forms that are not suitable for treating in a digester.

Certain aerobic manure handling practices have lower emissions than those from CMA digesters, and farms that employ such practices would be less inclined to transition in response to a GHG mitigation incentive. At the same time, swine and dairy farms that are currently placing manure in a storage lagoon, tank, or deep pit could continue to use their infrastructure for storage or overflow, and add a complete mix digester and the other necessary components. CMA digesters are operable in all regions of the country, but some regions require supplemental heat. This heat may be supplied by a boiler that combusts the methane-containing biogas or may operate using purchased electricity or fuel.

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[10] Complete mix digesters include complete mix and earth-supported mixed digesters. For more information on complete mix digesters, see www.epa.gov/agstar.

Due to the capital costs, dairies with fewer than 300 head and swine farms with fewer than 150 sow places are much less likely to install a complete mix digester than are operations with more animals. While digesters are technically feasible for smaller farms, they are generally not economically feasible unless other factors are addressed (such as carefully marketing the fertilizer byproducts and co-digesting other substrates such as sludge and food waste). Consequently, adoption costs and break-even prices for CMA digesters are not developed in this section for dairies with fewer than 300 cows and swine operations with fewer than 150 sows. The current management practices that could install a complete mix digester with electricity generation include the following:

- Dairy anaerobic lagoon
- Swine anaerobic lagoon
- Dairy deep pit
- Swine deep pit
- Beef liquid/slurry
- Dairy liquid/slurry
- Swine liquid/slurry

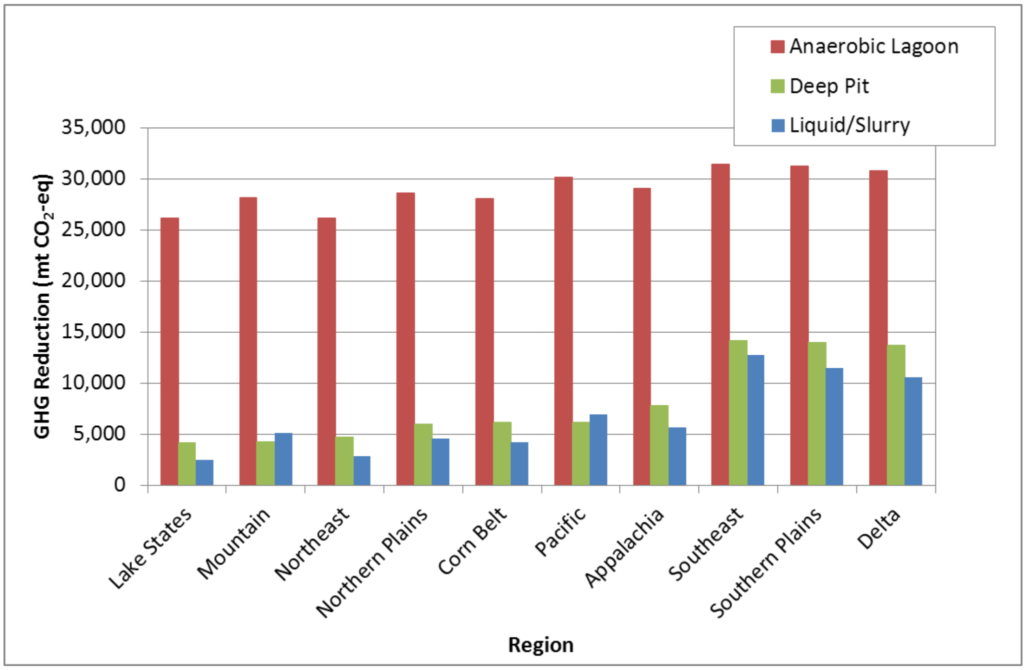
Environmental Impacts

Depending on the how manure is stored before and after installation of a digester, adoption of a covered digester system can decrease the release of pathogens and odors from the manure management system. Installing a CMA digester on a farm can reduce surface water and groundwater contamination and nitrification in the surrounding areas when the effluent of the system is managed properly.

3.1.3.2 GHG Impacts

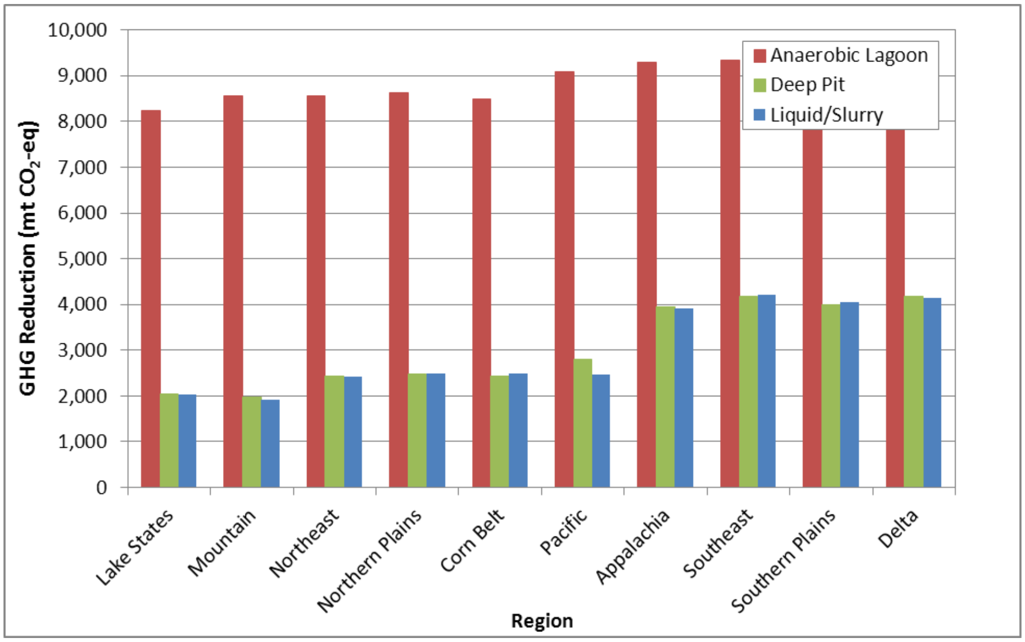
CMA digesters mitigate GHGs by converting CH_4 to CO_2 via combustion. The mitigation potential from transitioning from a current manure management to an anaerobic digester is provided for each of the applicable current management practices (i.e., dairy anaerobic lagoon, swine anaerobic lagoon, dairy deep pit, swine deep pit, dairy liquid/ slurry, swine liquid/slurry, and beef liquid/slurry) in the exhibits below and in Appendix 3-D. The greatest mitigation potential is for large operations, particularly dairy farms. The potential GHG reduction for adopting a CMA digester on a 5,000-head dairy farm, 2,500-sow place farm, and a 2,500-head beef feedlot are shown in Exhibit 3-22, Exhibit 3-23, and Exhibit 3-24, respectively. As indicated in Exhibit 3-22, the GHG mitigation potential from transitioning from an anaerobic lagoon to a CMA digester can be as high as 31,400 mt CO_2-eq for a 5,000 head dairy farm. As indicated in Exhibit 3-23, the GHG mitigation potential from transitioning from an anaerobic lagoon to a CMA digester can be as high as 9,340 MT CO_2-eq for a 2,500 sow place operation. The GHG mitigation potential for beef liquid/slurry systems transitioning to a CMA digester can be as high as 2,870 MT CO_2-eq for a 2,500 head operation, as indicated in Exhibit 3-24. In summary, as indicated in these exhibits, the current management practice has a significant impact on the GHG mitigation potential.

Exhibit 3-22: Farm-Level GHG Reduction Potential for Transitioning to a Complete Mix Anaerobic Digester from Existing Management Practices for a 5,000-Head Dairy Farm



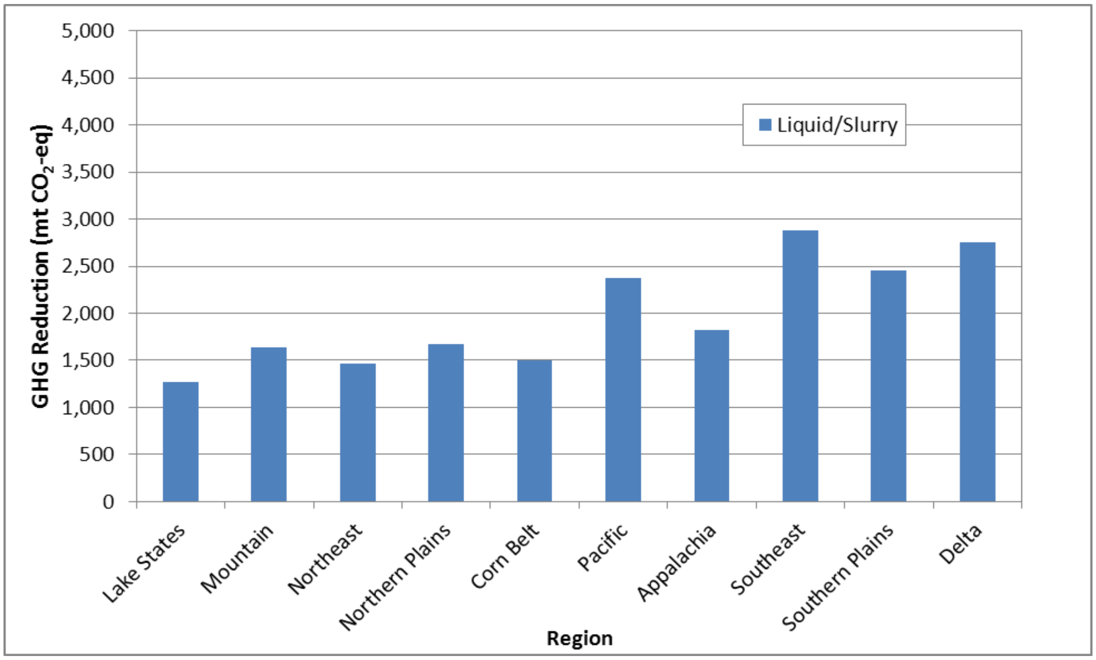
Note: This graph represents the estimated emissions reductions achieved when a dairy operation transitions from an existing manure management practice to a CMA digester in different regions. Details of the calculations can be found in the footnotes for the cost profiles.

Exhibit 3-23: Farm-Level GHG Reduction Potential for Transitioning to a Complete Mix Anaerobic Digester from Existing Management Practices for a 2,500-Sow Place Farm



Note: This graph represents the estimated emissions reductions achieved when a swine operation transitions from an existing manure management practice to a CMA digester in different regions. Details of the calculations can be found in the footnotes for the cost profiles.

Exhibit 3-24: Farm-Level GHG Reduction Potential for Transitioning to a Complete Mix Anaerobic Digester from a Liquid/Slurry Management Practice for a 2,500-Beef Feedlot



Note: This graph represents the estimated emissions reductions achieved when a beef operation transitions from a liquid/slurry manure management practice to a CMA digester in different regions. Details of the calculations can be found in the footnotes for the cost profiles.

3.1.3.3 Cost Profile

This section presents a set of profiles showing the total cost of adopting a CMA digester, including capital costs, recurring costs, and potential electricity savings. Cost profiles are shown for representative confined dairy (Exhibit 3-25), swine (Exhibit 3-26), and beef (Exhibit 3-27) operations. For beef farms, those operations with paved feedlots and completely enclosed housing with regular manure removal as liquid or slurry can transition to a CMA digester if the manure is not contaminated with dirt and rocks, and has the correct solids content of 3–10%. In general, unpaved feedlots cannot transition to a CMA digester because rocks and other debris will adversely affect operation of the digester.

To model the cost savings of on-site electricity generation and use, the average electricity price in each region is used. Although a farmer with CMA digesters often sell excess electricity back to the grid, these revenues are not evaluated here given the uncertainty in the general availability of the necessary infrastructure.

Exhibit 3-25: Cost Profile for Dairy Farms with Complete Mix Anaerobic Digesters

Parameter	Value			
Farm Size[a]				
No. of Lactating Cows	300	600	1,000	5,000
No. of Heifers	300	600	1,000	5,000
Manure Collection Efficiency from Cows	90%	90%	90%	90%
Manure Collection Efficiency from Heifers[b]	50%	50%	50%	50%
Capital Costs:[c]	$558,008	$750,442	$1,007,022	$3,572,815
Digester and Engine-Generator Set ($)	$499,559	$671,837	$901,541	$3,198,581

Parameter	Value			
Hydrogen Sulfide Treatment ($)	$15,486	$20,827	$27,948	$99,156
Flare ($)	$16,485	$22,171	$29,751	$105,553
Utility Charges ($)	$26,477	$35,607	$47,782	$169,525
Operations and Maintenance Cost ($)[d]	$22,320	$30,018	$40,281	$142,913
Capacity of Conversion Equipment (kW)[e]	60	119	199	993
Digester Tank Dimensions:[f]				
Diameter (ft)	39	53	69	80 (3+ digester tanks required)
Depth (ft)	26	26	26	26
Volatile Solids (lb/day)[g]	5,524	11,047	18,412	92,059
Methane Generation (m^3 CH_4)[h]	207,073	414,147	690,245	3,451,225
Methane Captured (m^3 CH_4)[i]	176,012	352,025	586,708	2,933,541
Methane Emitted (m^3 CH_4)[j]	31,061	62,122	103,537	517,684
Methane Emitted (mt CO_2-eq)[k]	436	871	1,452	7,259
Methane Mitigated (mt CO_2-eq)	2,468	4,936	8,227	41,133
Total Electricity Generation (kWh)[l]	**476,823**	**953,646**	**1,589,410**	**7,947,048**
Electricity Used On-Site (kWh)[m]	237,300 to 330,600	474,600 to 661,200	791,000 to 1,102,000	3,955,000 to 5,510,000
Excess Electricity Generated (kWh)[m]	146,223 to 239,523	292,446 to 479,046	487,410 to 798,410	2,437,048 to 3,992,048

[a] Although digesters are feasible at farms with fewer than 300 cows, economic considerations (e.g., high adoption costs per unit of output, opportunity costs associated with digester failure) will require significantly higher adoption incentives than for larger operations. Consequently, this report does not evaluate digesters for dairy operations with fewer than 300 head of cows. The calculations in this table include the emissions of both cows and heifers.

[b] Assumed value. The collection efficiency for complete mix digesters is higher than that for covered anaerobic lagoons or solids separators because the fibrous solids of the manure are not removed prior to entering the digester.

[c] Cost Profile for Dairy: AgSTAR analyzed complete mix anaerobic digester system capital costs for 13 dairy farms for which itemized cost estimates were available and performed a regression analysis to determine an algorithm for capital costs. For dairy complete mix digesters, the capital costs ($) = (563 × (no. of cows) + $320,864) + flare + H_2S treatment + utility charges. The cost of the flare is 3.3% of the cost of the digester and engine-generator set, the cost of H_2S treatment 3.1%, and the cost of utility charges is 5.3%. The values have been converted to 2010 dollars (EPA, 2010b).

[d] O&M is assumed to be 4% of capital costs. This O&M cost includes the cost of water needed for flushing and dilution of manure to appropriate consistency.

[e] kW = [(no. of cows) x (lb VS_{cow}/day) × (0.9 collection efficiency) × (3.84 ft^3 methane/lb VS_{cow}) × (1000 BTU/ft^3 methane) + (no. of heifers) x (lb VS_{heifer}/day) × (0.5 collection efficiency) × (2.72 ft^3 methane/lb VS_{heifer}) × (1000 BTU/ft^3 methane)] / [(24 hrs/day) × (14,000 BTU/kWh)] (EPA, 2006a).

[f] Lagoon dimensions based on industry experience.

[g] Equation for VS, lb/day = (no. of cows) × (lb VS_{cow}/day) × (cow manure collection efficiency) + (no. of heifers) × (lb VS_{heifer}/day) × (heifer manure collection efficiency).

[h] Methane generation, m^3/yr = (lb VS_{cow}/day) × (3.84 ft^3 methane/lb VS_{cow}) × (365 days/yr) × (0.0283 m^3/ft^3) + (lb VS_{heifer}/day) × (2.72 ft^3 methane/lb VS_{heifer}) × (365 days/yr) × (0.0283 m^3/ft^3) (EPA, 2006a).

[i] Methane captured based on Climate Action Reserve (2009), where biogas control system collection efficiency is assumed to be 85%.

[j] Methane emitted (m^3) = (methane generation, m^3) – (methane captured, m^3). Methane emitted is the methane that escapes into the atmosphere from the biogas control system.

[k] Methane emitted (mt CO_2-eq) = (methane emitted, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) × (21 mt CO_2-eq/mt CH_4) / (2,205 lb/mt CH_4). These emissions result from the CMA digester. The ultimate amount of GHGs mitigated depends on the difference between the existing management practice and these net GHG emissions resulting from CMA digesters.

[l] Total electricity generation (kWh/yr) = (capacity of the conversion equipment, kWh) x (8000 operating hours/yr).

[m] The average electricity use for an operation varies from region to region due to varying heating/cooling demands and technologies. A range has been provided for the energy generated and used on-site and for the excess energy generated. The assumptions used to estimate energy demand for each operation are from Key and Sneeringer (2011).

Exhibit 3-26: Cost Profile for Swine Farms with Complete Mix Anaerobic Digesters

Parameter	Value		
Farm Size (no. of sow places)[a,b]	150	500	2,500
Capital Costs:[c]	$395,544	$465,477	$865,092
Digester and Engine-Generator Set ($)	$354,113	$416,721	$774,478
Hydrogen Sulfide Treatment ($)	$10,978	$12,918	$24,009
Flare ($)	$11,686	$13,752	$25,558
Utility Charges ($)	$18,768	$22,086	$41,047
Operations and Maintenance Cost ($)[d]	$15,822	$18,619	$34,604
Capacity of Conversion Equipment (kW)[e]	11	36	178
Digester Tank Dimensions:[f]			
Diameter (ft)	39	69	80 (3+ digester tanks required)
Depth (ft)	26	26	26
Volatile Solids (lb/day)[g]	773	2,576	12,878
Methane Generation (m^3 CH_4)[g,h]	37,093	123,644	618,218
Methane Captured (m^3 CH_4)[i]	31,529	105,097	525,486
Methane Emitted (m^3 CH_4)[j]	5,564	18,547	92,733
Methane Emitted (mt CO_2-eq)[k]	78	260	1,300
Methane Mitigated (mt CO_2-eq)	442	1,474	7,368
Total Electricity Generation (kWh)[l]	**85,413**	**284,711**	**1,423,556**
Electricity Used On-Site (kWh)[m]	63,620 to 85,413	212,077 to 284,711	1,060,333 to 1,423,556
Excess Electricity Generated (kWh)[m]	0 to 21,793	0 to 72,635	0 to 363,223

[a] Swine farrow-to-finish farms with fewer than 150 sows are assumed to be too small to support an economically feasible digester. Although digesters are feasible at farms with fewer than 150 sows, economic considerations (i.e., high adoption costs per unit of output and the opportunity costs associated with digester failure) will require significantly higher adoption incentives than for larger operations. Consequently, this report does not evaluate digesters for swine operations with fewer than 150 sows.

[b] "Sow places" refer to the capacity of the swine facility to hold mature female swine (sows), and includes both the lactating sows and gestating sows. Each of the operations has the following numbers of swine:

- 150-sow places: 50 lactating sows, 100 gestating sows, 470 nursing pigs, 470 weaned pigs, 410 feeder pigs;
- 500-sow places: 167 lactating sows, 333 gestating sows, 1,567 nursing pigs, 1,567 weaned pigs, 1,367 feeder pigs; and
- 2,500-sow places: 833 lactating sows, 1,667 gestating sows, 7,833 nursing pigs, 7,833 weaned pigs, 6,833 feeder pigs.

[c] Cost Profile for Swine: AgSTAR analyzed CMA digester system capital costs for 13 dairy farms for which itemized cost estimates were available and performed a regression analysis to determine an algorithm for capital costs. The capital costs for swine CMA systems were calculated using the formula provided for dairy complete mix digesters and scaled based on VS output. The capital costs ($) = (563 × (no. of sow places) × (scaling factor) + $320,864) + flare + H_2S treatment + utility charges. The scaling factor is equal to (VS_{swine} lb/day) / (VS_{cow} lb/day) = 0.31. The cost of the flare is 3.3% of the cost of the digester and engine-generator set, the cost of H_2S treatment is 3.1%, the cost of utility charges is 5.3%. The values have been converted to 2010 dollars (EPA, 2010b).

[d] O&M is assumed to be 4% of capital costs. This O&M cost includes the cost of water needed for flushing and dilution of manure to the appropriate consistency.

[e] kW = [(lb VS/day) × (4.61 ft^3 methane/lb VS) × (1000 BTU/ ft^3 methane)] / [(24 hrs/day) × (14,000 BTU/kWh)] (EPA, 2006a).

[f] Lagoon dimensions based on industry experience.

[g] lb VS per day = (lb VS/day/sow place) × (no. of sow places).

[h] Equation for methane generation (m^3/yr) = (lb VS/day) × (4.61 ft^3 methane/lb VS) × (365 days/yr) × (0.0283 m^3/ft^3).

[i] Methane captured based on Climate Action Reserve (2009), where biogas control system collection efficiency is assumed to be 85%.

[j] Methane emitted (m^3) = (methane generation, m^3) – (methane captured, m^3). Methane emitted is the methane that escapes into the atmosphere from the biogas control system.

[k] Methane emitted (mt CO_2-eq) = (methane emitted, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) × (21 mt CO_2-eq/mt CH_4) / (2,205 lb/mt CH_4). These emissions result from the CMA digester. The ultimate amount of GHG mitigated depends on the difference between the existing management practice and the net GHG emissions resulting from complete mix digesters.

[l] Total electricity generation (kWh/yr) = (capacity of conversion equipment, kW) x (8,000 operating hours/yr).
[m] The average electricity use for an operation varies from region to region due to varying heating/cooling demands and technologies. A range has been provided for the energy generated and used on-site and for the excess energy generated. A zero value indicates that the energy demand of the operation exceeds the energy generated. The assumptions used to estimate energy demand for each operation are from Key and Sneeringer (2011).

Exhibit 3-27: Cost Profile for Beef Feedlots with Complete Mix Anaerobic Digesters

Parameter	Value		
Farm Size (No. of beef cattle)[a]	500	1,000	2,500
Manure Collection Efficiency (%)	90%	90%	90%
Capital Costs:[b]	$463,929	$562,284	$857,350
Digester and Engine-Generator Set ($)	$415,334	$503,388	$767,547
Hydrogen Sulfide Treatment ($)	$12,875	$15,605	$23,794
Flare ($)	$13,706	$16,612	$25,329
Utility Charges ($)	$22,013	$26,680	$40,680
Operations and Maintenance Cost ($)[c]	$18,557	$22,491	$34,294
Capacity of Conversion Equipment (kW)[d]	20	39	98
Digester Tank Dimensions:			
Diameter (ft)	39	63	80 (3+ digester tanks required)
Depth (ft)	26	26	26
Volatile Solids (lb/day)[e]	2,282	4,564	11,411
Methane Generation (m^3 CH_4)[f]	68,000	135,999	339,998
Methane Captured (m^3 CH_4)[g]	57,800	115,599	288,998
Methane Emitted (m^3 CH_4)[h]	10,200	20,400	51,000
Methane Emitted (mt CO_2-eq)[i]	68,000	135,999	339,998
Methane Mitigated (mt CO_2-eq)	810	1,621	4,052
Total Electricity Generation (kWh) [j]	**156,581**	**313,161**	**782,904**
Electricity Used On-Site (kWh)[k]	156,581	313,161	782,904
Excess Electricity Generated (kWh)[k]	0	0	0

[a] Beef feedlot operations with fewer than 500 head are assumed to be too small to warrant a digester.
[b] Cost Profile for Beef: AgSTAR analyzed anaerobic digester system capital costs for 13 dairy CMA digesters for which itemized cost estimates were available and performed a regression analysis to determine an algorithm for capital costs. The capital costs for beef CMA digester systems was calculated using the formula provided for dairy complete mix digesters and scaled based on VS output. The capital costs ($) = (563 × (no. of cattle) × (scaling factor) + $320,864) + cost of flare + H_2S treatment + utility charges. The scaling factor is (VS_{beef} lb/day) / (VS_{beef} lb/day) = 0.31. The cost of the flare is 3.3% of the cost of the digester and engine-generator set, the cost of H_2S treatment is 3.1%, and the cost of utility charges is 5.3%. The values have been converted to 2010 dollars (EPA, 2010b).
[c] O&M is assumed to be 4%. This O&M cost includes the cost of water needed for flushing and dilution of manure to the appropriate consistency.
[d] kW = [(lb VS/day) × (2.88 ft^3 methane/lb VS) × (0.90 collection efficiency) × (1000 BTU/ ft^3 methane)] / [(24 hrs/day) × 14,000 BTU/kWh)].
[e] VS lb per day= (no. head of cattle) × (lb VS/head/day) × (manure collection efficiency).
[f] Methane generation (m^3/yr) = (lb VS/day) × (2.88 ft^3 methane/lb VS) × (365 days/yr) × (0.0283 m^3/ft^3).
[g] Methane captured based on CAR (2009), where assumption for biogas control system collection efficiency is assumed to be 85%.
[h] Methane emitted (m^3) = (methane generation, m^3) – (methane captured, m^3). Methane emitted is the methane that escapes into the atmosphere from the CMA digester.
[i] Methane emitted (mt CO_2-eq) = (methane emitted, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) × (21 mt CO_2-eq/mt CH_4) / (2,205 lb/mt CH_4). These emissions result from the CMA digester. The ultimate amount of GHG mitigated depends on the difference between the existing practice and the net GHG emissions resulting from complete mix digesters.
[j] Total electricity generation (kWh/yr) = (capacity of conversion equipment, kW) x (8,000 operating hours/yr).

[k] The average electricity use for an operation varies from region to region due to varying heating/cooling demands and technologies. A range has been provided for the energy generated and used on-site and for the excess energy generated. A zero value indicates that the energy demand of the operation exceeds the energy generated. Energy demand data for beef operations were not readily available. Beef operations consume less energy than milking operations associated with dairy farms; consequently, given the lack of national averages, beef energy demand is estimated as 50% of dairy energy demands for the purpose of this report. Dairy energy demand is from Key and Sneeringer (2011).

3.1.3.4 Break-Even Prices

Exhibit 3-28 through Exhibit 3-30 present the break-even prices based on a tax rate of 15% and a discount rate of 5%. The tables indicate the existing manure management practice and the break-even prices for transitioning to a CMA digester for farms of different sizes and in different regions.

For dairy and swine operations, it is most cost-effective to transition from an anaerobic lagoon to a CMA digester than from liquid/slurry or deep pit systems. The majority of swine are on operations of 2,500 head or greater; these operations have economies of scale and require little additional incentive to transition to digester technologies as indicated by break-even prices generally below \$5 per mt CO_2-eq.

Exhibit 3-28: Break-Even Prices for Dairy Farms that Adopt Complete Mix Digesters with Electricity Generation as an Alternative to Existing Management Practices

Existing Practice: Anaerobic Lagoon		
Model Farm Size	**Region**	**Break-Even Price (2010 \$/ mt CO_2-eq)**
5,000	Southeast	\$6
5,000	Southern Plains	\$6
5,000	Delta	\$6
5,000	Appalachia	\$6
5,000	Pacific	\$7
5,000	Northern Plains	\$11
5,000	Mountain	\$11
5,000	Corn Belt	\$11
5,000	Northeast	\$11
5,000	Lake States	\$12
1,000	Southeast	\$12
1,000	Southern Plains	\$13
1,000	Delta	\$13
1,000	Appalachia	\$13
1,000	Pacific	\$14
600	Southeast	\$18
1,000	Northern Plains	\$18

Existing Practice: Deep Pit		
Model Farm Size	**Region**	**Break-Even Price (2010 \$/ mt CO_2-eq)**
5,000	Southeast	\$13
5,000	Southern Plains	\$13
5,000	Delta	\$13
5,000	Appalachia	\$23
1,000	Southeast	\$27
1,000	Southern Plains	\$28
1,000	Delta	\$29
5,000	Pacific	\$36
600	Southeast	\$40
600	Southern Plains	\$40
600	Delta	\$41
5,000	Corn Belt	\$50
1,000	Appalachia	\$50
5,000	Northern Plains	\$51
5,000	Northeast	\$63
1,000	Pacific	\$69
300	Southeast	\$70

Existing Practice: Liquid/Slurry		
Model Farm Size	**Region**	**Break-Even Price (2010 \$/ mt CO_2-eq)**
5,000	Southeast	\$14
5,000	Southern Plains	\$16
5,000	Delta	\$17
1,000	Southeast	\$31
5,000	Pacific	\$32
5,000	Appalachia	\$32
1,000	Southern Plains	\$34
1,000	Delta	\$37
600	Southeast	\$44
600	Southern Plains	\$49
600	Delta	\$53
5,000	Mountain	\$60
1,000	Pacific	\$62
5,000	Northern Plains	\$68
1,000	Appalachia	\$69
5,000	Corn Belt	\$73
300	Southeast	\$78

Existing Practice: Anaerobic Lagoon		
Model Farm Size	Region	Break-Even Price (2010 $/ mt CO_2-eq)
600	Southern Plains	$18
600	Delta	$18
1,000	Mountain	$18
1,000	Corn Belt	$18
1,000	Northeast	$19
600	Appalachia	$19
1,000	Lake States	$20
600	Pacific	$20
600	Northern Plains	$24
600	Mountain	$24
600	Corn Belt	$24
600	Northeast	$26
600	Lake States	$26
300	Southeast	$32
300	Southern Plains	$32
300	Delta	$32
300	Appalachia	$34
300	Pacific	$34
300	Northern Plains	$39
300	Mountain	$40
300	Corn Belt	$40
300	Northeast	$42
300	Lake States	$43

Existing Practice: Deep Pit		
Model Farm Size	Region	Break-Even Price (2010 $/ mt CO_2-eq)
300	Southern Plains	$71
600	Appalachia	$72
300	Delta	$73
5,000	Mountain	$73
5,000	Lake States	$75
1,000	Corn Belt	$83
1,000	Northern Plains	$86
600	Pacific	$97
1,000	Northeast	$106
600	Corn Belt	$111
600	Northern Plains	$114
1,000	Mountain	$122
1,000	Lake States	$125
300	Appalachia	$127
600	Northeast	$143
600	Mountain	$163
600	Lake States	$167
300	Pacific	$167
300	Corn Belt	$180
300	Northern Plains	$186
300	Northeast	$234
300	Mountain	$265
300	Lake States	$271

Existing Practice: Liquid/Slurry		
Model Farm Size	Region	Break-Even Price (2010 $/ mt CO_2-eq)
600	Pacific	$87
300	Southern Plains	$87
300	Delta	$94
600	Appalachia	$99
1,000	Mountain	$100
5,000	Northeast	$104
1,000	Northern Plains	$114
1,000	Corn Belt	$123
5,000	Lake States	$125
600	Mountain	$133
300	Pacific	$149
600	Northern Plains	$152
600	Corn Belt	$164
300	Appalachia	$175
1,000	Northeast	$176
1,000	Lake States	$209
300	Mountain	$217
600	Northeast	$236
300	Northern Plains	$247
300	Corn Belt	$267
600	Lake States	$279
300	Northeast	$386
300	Lake States	$454

Exhibit 3-29: Break-Even Prices for Swine Farms that Adopt Complete Mix Digesters with Electricity Generation as Alternative to Existing Management Practices

Existing Practice: Anaerobic Lagoon			Existing Practice: Deep Pit			Existing Practice: Liquid/Slurry		
Model Farm Size (sow places)	Region	Break-Even Price (2010 $/ mt CO_2-eq)	Model Farm Size (sow places)	Region	Break-Even Price (2010 $/ mt CO_2-eq)	Model Farm Size (sow places)	Region	Break-Even Price (2010 $/ mt CO_2-eq)
2,500	Southeast	$1	2,500	Southeast	$2	2,500	Southeast	$2
2,500	Southern Plains	$1	2,500	Delta	$2	2,500	Delta	$2
2,500	Delta	$1	2,500	Southern Plains	$2	2,500	Southern Plains	$2
2,500	Appalachia	$1	2,500	Appalachia	$2	2,500	Appalachia	$2
2,500	Pacific	$1	2,500	Pacific	$2	2,500	Corn Belt	$3
2,500	Northern Plains	$1	2,500	Northern Plains	$3	2,500	Northern Plains	$3
2,500	Mountain	$1	2,500	Corn Belt	$3	2,500	Pacific	$3
2,500	Corn Belt	$1	2,500	Lake States	$3	2,500	Lake States	$3
2,500	Lake States	$1	2,500	Mountain	$3	2,500	Mountain	$3
2,500	Northeast	$4	2,500	Northeast	$15	2,500	Northeast	$15
500	Southeast	$23	500	Southeast	$51	500	Southeast	$51
500	Southern Plains	$23	500	Delta	$51	500	Delta	$52
500	Delta	$23	500	Southern Plains	$53	500	Southern Plains	$53
500	Appalachia	$23	500	Appalachia	$54	500	Appalachia	$54
500	Pacific	$23	500	Pacific	$77	500	Corn Belt	$86
500	Northern Plains	$25	500	Northern Plains	$86	500	Northern Plains	$86
500	Mountain	$25	500	Corn Belt	$87	500	Pacific	$86
500	Corn Belt	$25	500	Northeast	$100	500	Northeast	$100
500	Lake States	$26	500	Lake States	$105	500	Lake States	$105
500	Northeast	$28	500	Mountain	$108	500	Mountain	$111
150	Southeast	$88	150	Southeast	$195	150	Southeast	$194
150	Southern Plains	$88	150	Delta	$196	150	Delta	$197
150	Delta	$88	150	Southern Plains	$204	150	Southern Plains	$202
150	Appalachia	$88	150	Appalachia	$207	150	Appalachia	$209
150	Pacific	$90	150	Pacific	$293	150	Corn Belt	$328
150	Northern Plains	$95	150	Northern Plains	$330	150	Northern Plains	$329
150	Mountain	$96	150	Corn Belt	$335	150	Pacific	$330
150	Corn Belt	$96	150	Northeast	$348	150	Northeast	$348
150	Northeast	$99	150	Lake States	$400	150	Lake States	$401
150	Lake States	$99	150	Mountain	$412	150	Mountain	$425

Exhibit 3-30: Break-Even Prices for Beef Feedlots that Adopt Complete Mix Digesters as Alternative to Existing Management Practice

Existing Practice: Liquid/Slurry		
Model Farm Size	**Region**	**Break-Even Price (2010 \$/ mt CO_2-eq)**
2,500	Northern Plains	\$5
2,500	Mountain	\$6
2,500	Corn Belt	\$6
2,500	Lake States	\$7
2,500	Northeast	\$8
2,500	Pacific	\$13
2,500	Southeast	\$14
2,500	Delta	\$15
2,500	Southern Plains	\$17
2,500	Appalachia	\$22
1,000	Southeast	\$41
1,000	Delta	\$43
1,000	Pacific	\$46
1,000	Southern Plains	\$48
1,000	Northern Plains	\$52

Existing Practice: Liquid/Slurry		
Model Farm Size	**Region**	**Break-Even Price (2010 \$/ mt CO_2-eq)**
1,000	Mountain	\$53
1,000	Corn Belt	\$58
1,000	Northeast	\$61
1,000	Appalachia	\$65
1,000	Lake States	\$68
500	Southeast	\$86
500	Delta	\$90
500	Pacific	\$100
500	Southern Plains	\$101
500	Northern Plains	\$129
500	Mountain	\$132
500	Appalachia	\$136
500	Corn Belt	\$144
500	Northeast	\$149
500	Lake States	\$170

3.1.4 Plug Flow Anaerobic Digester

3.1.4.1 Technology Characterization

Key Features of Plug Flow Anaerobic Digesters

- Biogas produced in digesters can be used to generate electricity, heat, or pipeline-quality natural gas.
- Adoption of plug flow digesters may decrease the release of pathogens and reduce surface water and groundwater contamination.
- Byproducts of plug flow digesters can be applied as a fertilizer, sold as a soil amendment, or processed into livestock bedding.

A plug flow digester is a long, relatively narrow, heated tank, often built below ground level, with a gas-tight cover. Plug flow digesters are optimal for dairy manure, as evidenced by fact that 82 of the 89 currently operating plug flow digester systems in the United States are on dairy farms.[11]

Plug flow digesters as originally designed are unmixed, heated rectangular tanks. In order for them to work properly, they must be loaded with fresh, scraped undiluted dairy manure at about 11–13% solids. This type of manure slurry, which contains significant fiber, has a viscous consistency in which the slurry remains homogeneous in the plug flow digester and the solids and liquids do not separate. If swine or feedlot manure with little or no fiber, or flushed dairy manure with a lower solids content are used in plug flow digesters, a mixing system must be added to keep the solids from settling and inhibiting efficient operation. Plug flow digesters with mixers are commercially available that can accommodate manure with a solids content that is lower than optimal; however, they are not evaluated in this report.

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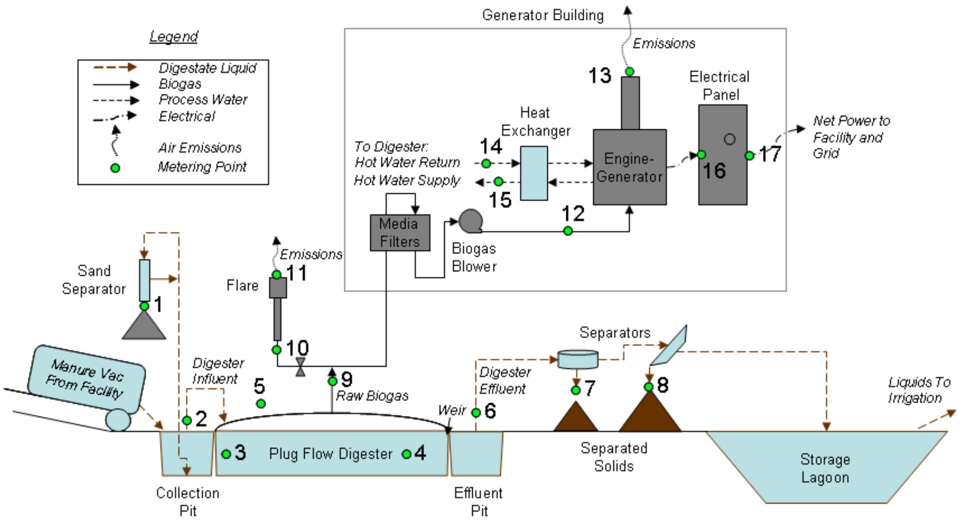
[11] Information on existing digesters was obtained from the AgSTAR database of digesters in the United States. This includes digesters that were operational as of September 2012 (EPA, 2012).

Exhibit 3-31 is a schematic of a typical plug flow anaerobic digester system using biogas for electrical generation, including a flare for emergency use. When the digester needs maintenance or repair, the manure is bypassed to the storage lagoon. Exhibit 3-32 is a diagram of the plug flow digester, showing the cover and the flow of the digester influent through the tank. A plug flow digester is pictured in Exhibit 3-33.

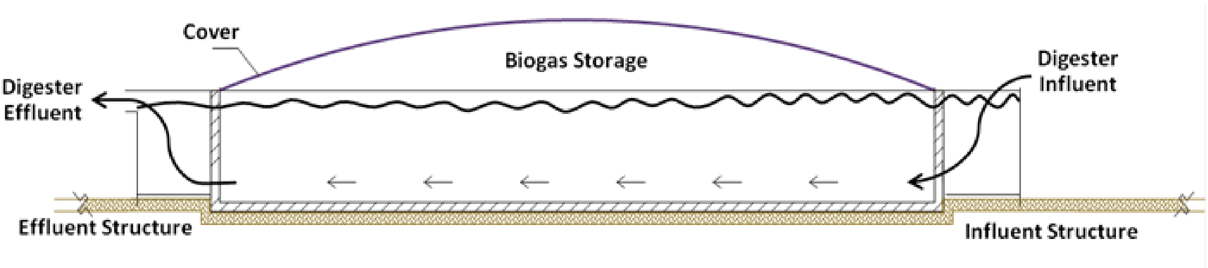
Exhibit 3-31: Schematic Diagram of a Typical Plug Flow Anaerobic Digester System



Source: Williams (2011).

Note: Manure is collected and transferred from the facility into the collection pit. The material is moved from the pit and passed through a sand separator to remove solid materials (steps 1 and 2 in the diagram above). Material from the collection pit is moved into the plug flow digester (steps 3 to 5) where biogas is generated. The biogas is collected and removed for processing and combustion (steps 9 to 17). The effluent moves from the digester to the effluent pit, through solids separators, and eventually to a storage lagoon (steps 6 to 8).

Exhibit 3-32: Diagram of a Plug Flow Anaerobic Digester



Source: EPA (2011a).

The range of equipment needed for a plow flow digester depends on the current management system. For example, a farm with an earthen pit could use it as a storage lagoon. The key types of equipment required to install a plug flow anaerobic digester are listed in Exhibit 3-3. Exhibit 3-34 summarizes additional equipment and key characteristics of a plug flow anaerobic digester.

Exhibit 3-33: Picture of a Plug Flow Anaerobic Digester

Source: EPA (2011a).

Exhibit 3-34: Key Characteristics of Plug Flow Anaerobic Digesters

Key Design Parameters		
Characteristic	**Summary**	**Description/Explanation**
Technology	Well established	Requires integrated system of a plug flow digester, solids separator, and storage lagoon. Typically, a mechanical scraping or flush system is used to collect manure from the barn or drylot. Other technology (gas conditioning skid or generator skid, depending on biogas use) is well established. Requires heating and mixing equipment, which is a more complicated system than covered lagoon anaerobic digesters. Additionally, a manure collection tank is needed that holds at least 2 days' worth of manure production, along with a mixing/agitation pump, and a pump to transfer manure into the digester.
Farm Type	Dairy, beef, swine	Is best suited for undiluted, fresh dairy manure, which has the correct viscosity for solids to remain in suspension. Can be used for beef and swine manure with a solids content of 11–13%.
Optimum Climate	All	Heated digester keeps temperature constant in all climates.
Supplemental Heat	Yes	Heat exchangers recover waste heat from the engine water jacket; exhaust from combustion-heated water is circulated in pipes on the outside of the digester to maintain approximately 95–100°F inside of the digester.
Digestion Vessel	Rectangular in-ground tank	Optimal shape is rectangular, with length approximately four times the width, approximately 10 to 20 feet deep, with a fixed or flexible cover.
Total Solids	11–13%	As-produced dairy manure is optimal for digester operation.
Solids Characteristics	Coarse	Most systems just process animal manure; however, some exist that add other organic wastes, such as food.
Hydraulic Retention Time (HRT)	15+ days	15- to 28-day HRT allows for optimal gas production from manure.
Daily Operations		
▪ Regular maintenance program for the digester and engine-generator operation.		

HRT = Hydraulic Retention Time, the average number of days that a volume of manure remains in the digester.

Current and Potential Adoption

In 2012, there were 89 plug flow digesters[12] operating in the United States. A breakdown of these digesters by region, livestock type, and size is given in Exhibit 3-35. The digesters are located in 19 different States. Plug flow anaerobic digesters can operate in any region and with a variety of farm types, although dairy farms are the most prevalent.

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[12] Plug flow digesters include the following digester types: horizontal plug flow, vertical plug flow, modified mixed plug flow, mixed plug flow, modified plug flow, and modular plug flow. For more information on plug flow anaerobic digesters, see www.epa.gov/agstar.

Exhibit 3-35: Current Adoption of Plug Flow Anaerobic Digesters by Production Region, Livestock Type, and Farm Size

USDA Production Region	No. of Farms
Northeast	33
Corn Belt	15
Lake States	25
Northern Plains	1
Southeast	2
Appalachia	1
Delta	0
Southern Plains	0
Mountain	3
Pacific	9
Total	**89**

Farm Size (no. of head feeding digester)	Swine	Dairy	Beef	Poultry and Duck	Total Farms
Fewer than 999	0	22	0	0	22
1,000 to 9,999	2	57	3	0	62
10,000 to 29,999	0	2	0	0	2
30,000 to 99,999	0	0	0	0	0
More than 100,000	0	0	0	1	1
Unknown	0	1	1	0	2
Total	**2**	**82**[a]	**4**	**1**	**89**

[a] Two farms indicate both swine and dairy/cattle populations feeding the digester. These digesters were classified as dairy/beef because more dairy/beef head are feeding the digester than head of swine.

Source: EPA (2012).

Only farms that have certain manure management practices are likely candidates for transitioning to plug flow anaerobic digesters due to the high barriers to adoption and high capital costs of implementation (e.g., lining, cover, biogas conversion equipment). Certain practices have lower emissions than a plug flow digester, and farms implementing those practices would not transition to plug flow digesters in response to a GHG mitigation incentive. Beef, swine, and poultry farms are less likely to adopt a plug flow digester; however, operations that have manure with the appropriate solids content can implement plug flow digesters. The manure may be collected via scraping or vacuuming. Although dairy farms with more than 300 head are more likely to install a plug flow digester than smaller dairy farms, smaller dairy farms can have economically feasible digesters if other factors are successful, such as careful marketing of the fertilizer byproducts, and co-digesting other substrates such as sludge and food waste. Byproducts are not included in the adoption costs or break-even prices developed in this report.

Environmental Impacts

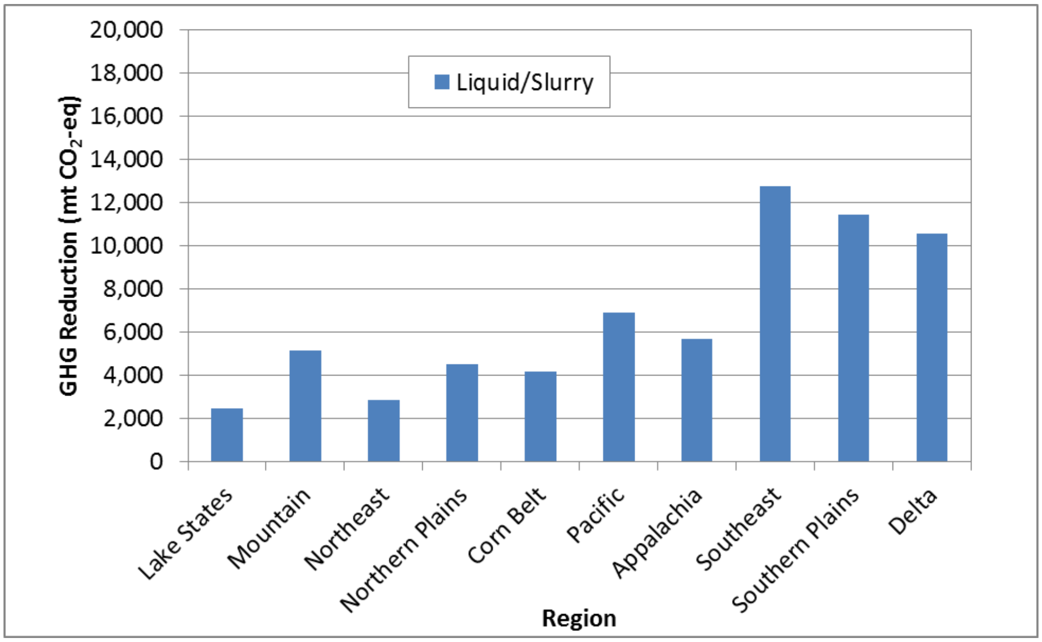
Depending on the storage of the manure before and after digester installation, adoption of a plug flow digester system can decrease the release of pathogens and odors from the manure management system. Installing a plug flow digester can reduce surface water and groundwater contamination and nitrification in the surrounding areas when the effluent of the system is managed properly.

3.1.4.2 GHG Impacts

Plug flow digesters mitigate GHGs by combusting the CH_4 to create CO_2, which has a lower GWP than CH_4. The mitigation potential for transitioning from a current management to an anaerobic digester is provided for each of the applicable current management practices (i.e., dairy liquid/slurry, swine liquid/slurry, and beef liquid/slurry) in the exhibits below and in Appendix 3-D. The mitigation potential for large farms is higher than that of small farms, particularly for large dairy operations. The potential GHG reduction for adopting a dairy, swine, or beef plug flow digester is shown in Exhibit 3-36, Exhibit 3-37, and Exhibit 3-38, respectively.

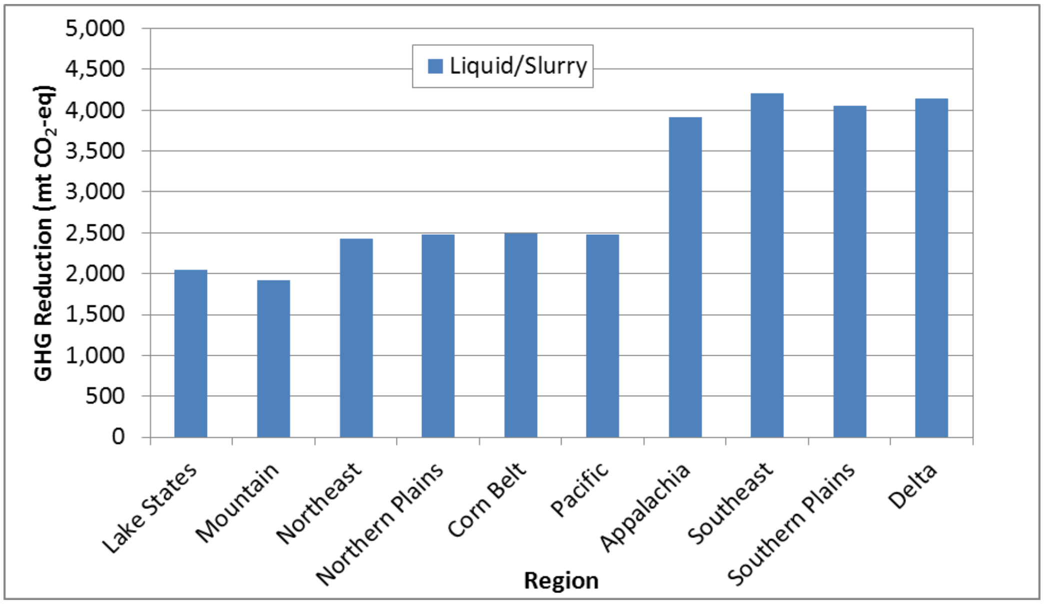
As indicated in Exhibit 3-36, the GHG mitigation potential from transitioning to a plug flow digester can exceed 12,000 mt CO_2-eq for a 5,000 head dairy farm. As indicated in Exhibit 3-37, the GHG mitigation potential from transitioning to a plug flow digester can be as high as 4,200 MT CO_2-eq for a 2,500 sow place operation. The GHG mitigation potential for beef liquid/slurry systems transitioning to a plug flow digester can be as high as 2,870 MT CO_2-eq for a 2,500 head operation, as indicated in Exhibit 3-38.

Exhibit 3-36: Farm-Level GHG Reduction Potential for a Plug Flow Digester, by Region on a 5,000-Head Dairy Farm



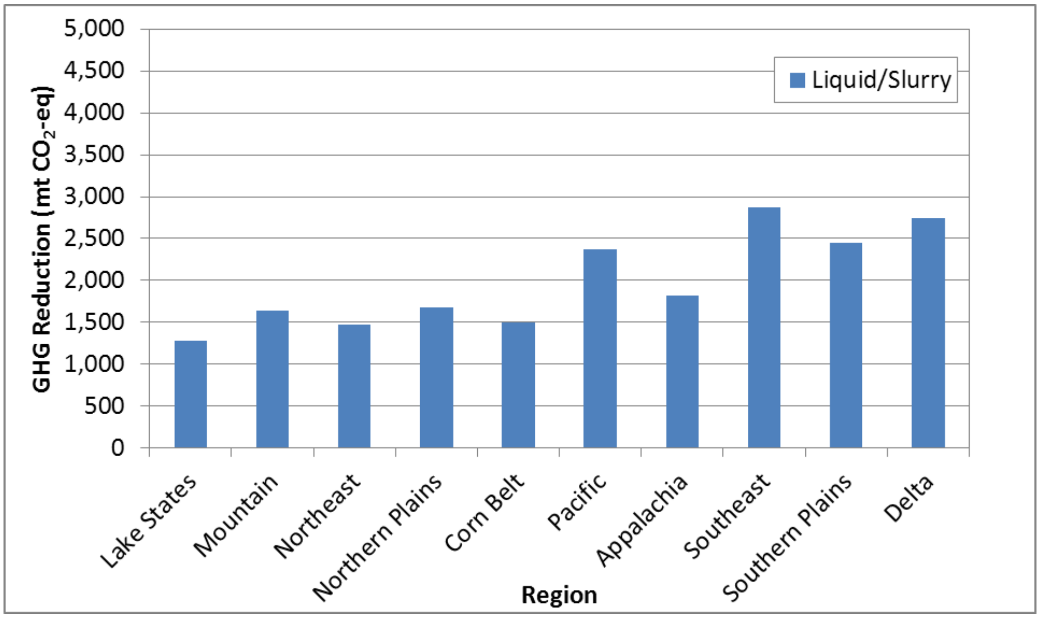
Note: This graph represents the estimated emissions reductions achieved when a dairy operation transitions from an existing manure management practice to a plug flow digester in different regions. Details of the calculations can be found in the footnotes for the cost profiles.

Exhibit 3-37: Farm-Level GHG Reduction Potential for a Plug Flow Digester, by Region for a 2,500-Sow Place Farm



Note: This graph represents the estimated emissions reductions achieved when a swine operation transitions from a liquid/slurry manure management practice to a plug flow digester in different regions. Details of the calculations can be found in the footnotes for the cost profiles.

Exhibit 3-38: Farm-Level GHG Reduction Potential for a Plug Flow Digester, by Region on a 2,500-Head Beef Feedlot



Note: This graph represents the estimated emissions reductions achieved when a beef operation transitions from a liquid/slurry manure management practice to a plug flow digester in different regions. Details of the calculations can be found in the footnotes for the cost profiles.

3.1.4.3 Cost Profile

This section presents a set of representative cost profiles for the total cost of adoption of plug flow digesters, including capital costs, recurring costs, and potential electricity savings, as shown in Exhibit 3-39 through Exhibit 3-41. To model the cost savings of on-site electricity generation and use, the average electricity price in each region is used; however, the potential revenue from selling electricity back to the grid is not included as part of the break-even prices presented in this report due to the uncertainty in the general availability of the needed infrastructure.

Exhibit 3-39: Cost Profile for Dairy Farms with Plug Flow Digesters

Parameter	Value			
Farm Size[a]				
No. of Cows	300	600	1,000	5,000
No. of Heifers	300	600	1,000	5,000
Manure Collection Efficiency from Cows[b]	90%	90%	90%	90%
Manure Collection Efficiency from Heifers[b]	50%	50%	50%	50%
Capital Costs:[c]	$855,765	$1,066,657	$1,347,846	$4,159,737
Digester and Engine-Generator Set ($)	$766,128	$954,930	$1,206,666	$3,724,026
Hydrogen Sulfide Treatment ($)	$23,750	$29,603	$37,407	$115,445
Flare ($)	$25,282	$31,513	$39,820	$122,893
Utility Charges ($)	$40,605	$50,611	$63,953	$197,373

Parameter	Value			
Operations and Maintenance Cost (\$)	\$34,231	\$42,666	\$53,914	\$166,389
Capacity of Conversion Equipment, (kW)[d]	60	119	199	993
Digester Tank Dimensions:[e]				
Length (ft)	80	110	150	150 (3+ digester tanks required)
Width (ft)	20	27	37	37
Depth (ft)	10	10	12	12
Volatile Solids (lb/day)[f]	5,524	11,047	18,412	92,059
Methane Generation (m^3)[g]	207,073	414,147	690,245	3,451,225
Methane Captured (m^3)[h]	176,012	352,025	586,708	2,933,541
Methane Emitted (m^3)[i]	31,061	62,122	103,537	517,684
Methane Emitted (mt CO_2-eq)[j]	436	871	1,452	7,259
Methane Mitigated (mt CO_2-eq)	2,468	4,936	8,227	41,133
Total Electricity Generation (kWh)[k]	476,823	953,646	1,589,410	7,947,048
Electricity Used On-Site (kWh)[l]	237,300 to 330,600	474,600 to 661,200	791,000 to 1,102,000	3,955,000 to 5,510,000
Excess Electricity Generated (kWh)[l]	146,223 to 239,523	292,446 to 479,046	487,410 to 798,410	2,437,048 to 3,992,048

[a] Dairy farms with fewer than 300 cows are assumed to be too small to support an economically feasible digester.

[b] The collection efficiency for plug flow digesters is higher than that for covered anaerobic lagoons or solids separators because the fibrous solids of the manure are not removed prior to entering the digester. The calculations in this table include the emissions of both cows and heifers.

[c] Cost Profile for Dairy: AgSTAR analyzed plug flow digester system capital costs for 19 dairy farms for which itemized cost estimates were available and performed a regression analysis to determine an algorithm for capital costs. For dairy plug flow digesters, the capital costs (\$) = (617 × (no. of cows) + \$566,006) + cost of flare + H_2S treatment + utility charges. The cost of the flare is assumed to be 3.3% of the cost of the digester and engine-generator set, the cost of H_2S treatment is assumed to be 3.1%, the cost of utility charges is assumed to be 5.3%, and the O&M is assumed to be 4%. The values have been converted to 2010 dollars (EPA, 2010b).

[d] kW = [(lb VS_{cow}/day) × (0.9 collection efficiency) × (3.84 ft^3 methane/lb VS) × (1000 BTU/ ft^3 methane)] / [(24 hrs/day × 14,000 BTU/kWh)] + [(lb VS_{heifer}/day) × (0.5 collection efficiency) × (2.72 ft^3 methane/lb VS) × (1000 BTU/ ft^3 methane)] / [(24 hrs/day) × (14,000 BTU/kWh)] (EPA, 2006a).

[e] Dimensions of the digester tanks are based on recommendations in EPA Agstar Farmware 3.1 (2009).

[f] Equation for VS, lb/day = (no. of cows) × (lb VS_{cow}/day) × (cow manure collection efficiency) + (no. of heifers) × (lb VS_{heifer}/day) × (heifer manure collection efficiency).

[g] Equation for methane generation (m^3/yr) = (no. of cows) x (lb VS_{cow}/day) × (3.84 ft^3 methane/lb VS) × (365 days/yr × 0.0283 m^3/ft^3) + (no. of heifers) x (lb VS_{heifer}/day) × (2.72 ft^3 methane/lb VS) × (365 days/yr) × (0.0283 m^3/ft^3) (EPA, 2006a).

[h] Methane captured based on Climate Action Reserve (2009), where biogas control system collection efficiency is assumed to be 85%.

[i] Methane emitted (m^3) = (methane generation, m^3) – (methane captured, m^3). Methane emitted is the methane that escapes into the atmosphere from the biogas control system.

[j] Methane emitted (mt CO_2-eq) = (methane emitted, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) × (21 mt CO_2-eq/mt CH_4) / (2,205 lb/mt CH_4). These emissions result from the plug flow digester. The quantity of GHGs ultimately mitigated depends on the difference between the existing management practice and the net GHG emissions resulting from the plug flow digester.

[k] Total electricity generation (kWh/yr) = (capacity of conversion equipment, kW) x (8000 operating hours/yr).

[l] The average electricity use for an operation varies from region to region due to varying heating/cooling demands and technologies. A range has been provided for the energy generated and used on-site and for the excess energy generated. A zero value indicates that the energy demand of the operation exceeds the energy generated. The assumptions used to estimate energy demand for each operation are from Key and Sneeringer (2011).

Exhibit 3-40 Cost Profile for Swine Farms with Plug Flow Digesters

Parameter	Value		
Farm Size (no. of sow places)[a,b]	150	500	2,500
Manure Collection Efficiency from Sows	100%	100%	100%
Capital Costs:[c]	$776,256	$1,082,817	$2,834,592
Digester and Engine-Generator Set ($)	$694,948	$969,397	$2,537,683
Hydrogen Sulfide Treatment ($)	$21,543.37	$30,051	$78,668
Flare ($)	$22,933.27	$31,990	$83,744
Utility Charges ($)	$36,832.22	$51,378	$134,497
Operations and Maintenance Cost ($)	$31,050	$43,313	$113,384
Capacity of Conversion Equipment, (kW)[d]	11	36	178
Digester Tank Dimensions:[e]			
Length (ft)	110	150	150 (3+ digester tanks required)
Width (ft)	27	37	37
Depth (ft)	10	12	12
Volatile solids (lb/day)[f]	773	2,576	12,878
Methane Generation (m^3)[g]	37,093	123,644	618,218
Methane Captured (m^3)[h]	31,529	105,097	525,486
Methane Emitted (m^3)[i]	5,564	18,547	92,733
Methane Emitted (mt CO_2-eq)[j]	78	260	1,300
Methane Mitigated (mt CO_2-eq)	442	1,474	7,368
Total Electricity Generated (kWh)[k]	85,413	284,711	1,423,556
Electricity Used On-Site (kWh)[l]	63,620 to 85,413	212,077 to 287,711	1,060,333 to 1,423,556
Excess Electricity Generated (kWh)[l]	0 to 21,793	0 to 72,635	0 to 363,223

[a] Swine farrow-to-finish farms with fewer than 150 sows are assumed to be too small to support an economically feasible digester. Although digesters are feasible at farms with fewer than 150 sows, economic considerations (i.e., high adoption costs per unit of output and the opportunity costs associated with digester failure) will require significantly higher adoption incentives than for larger operations. Consequently, this report does not evaluate digesters for swine operations with fewer than 150 sows.

[b] "Sow places" refers to the capacity of the swine facility to hold mature female swine (sows), and includes both the lactating sows and gestating sows. Each of the operations has the following numbers of swine:

- 150-sow places: 50 lactating sows, 100 gestating sows, 470 nursing pigs, 470 weaned pigs, 410 feeder pigs;
- 500-sow places: 167 lactating sows, 333 gestating sows, 1,567 nursing pigs, 1,567 weaned pigs, 1,367 feeder pigs; and
- 2,500-sow places: 833 lactating sows, 1,667 gestating sows, 7,833 nursing pigs, 7,833 weaned pigs, 6,833 feeder pigs.

[c] Cost Profile for Swine: AgSTAR analyzed plug flow digester system capital costs for 19 dairy farms for which itemized cost estimates were available and performed a regression analysis to determine an algorithm for capital costs. The capital costs for swine plug flow systems was calculated using the formula provided for dairy plug flow digesters and scaled based on VS output. The capital costs ($) = (617 × (no. of sow places) × (scaling factor) + $566,006) + flare + H_2S treatment + utility charges. The scaling factor is equal to (VS_{swine} lb/day) / (VS_{cow} lb/day) = 0.31. The cost of the flare is 3.3% of the cost of the digester and engine-generator set, the cost of H_2S treatment is 3.1%, the cost of utility charges 5.3%, and the O&M is assumed to be 4%. Swine plug flow digesters may require a mixing system to keep the manure homogenous; the cost for this additional equipment has not been included into this cost profile. The values have been converted to 2010 dollars (EPA, 2010b).

[d] kW = [(lb VS/day) × (4.61 ft^3 methane/lb VS) × (1000 BTU/ ft^3 methane)] / [(24 hrs/day) × (14,000 BTU/kWh)] (EPA, 2006a).

[e] Dimensions of the digester tanks are based on recommendations in EPA Agstar Farmware 3.1 (2009).

[f] Equation for lb VS per day = (lb VS/day/sow place) × (no. sow places).

[g] Equation for methane generation, m^3/yr = (lb VS/day) × (4.61 ft^3 methane/lb VS) × (365 days/yr) × (0.0283 m^3/ft^3).

[h] Methane captured based on Climate Action Reserve (2009), where biogas control system collection efficiency is assumed to be 85%.

[i] Methane emitted (m^3) = (methane generation, m^3) – (methane captured, m^3). Methane emitted is the methane that escapes into the atmosphere from the biogas control system.

[j] Methane emitted (mt CO_2-eq) = (methane emitted, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) × (21 mt CO_2-eq/mt CH_4) / (2,205 lb/mt CH_4).These emissions result from the plug flow digester. The quantity of GHGs ultimately mitigated depends on the difference between the existing practice and the net GHG emissions resulting from the plug flow digester.

[l] The average electricity use for an operation varies from region to region due to varying heating/cooling demands and technologies. A range has been provided for the energy generated and used on-site and for the excess energy generated. A zero value indicates that the energy demand of the operation exceeds the energy generated. The assumptions used to estimate energy demand for each operation are from Key and Sneeringer (2011).

Exhibit 3-41 Cost Profile for Beef Farms with Plug Flow Digesters

Parameter	Value		
Farm Size (no. of beef cattle)[a]	500	1,000	2,500
Manure Collection Efficiency from Beef Cattle	90%	90%	90%
Capital Costs:[b]	$817,336	$1,076,030	$2,800,656
Digester and Engine-Generator Set ($)	$731,724	$963,321	$2,507,302
Hydrogen Sulfide Treatment ($)	$22,683.45	$29,863	$77,726
Flare ($)	$24,147	$31,790	$82,741
Utility Charges ($)	$38,781	$51,056	$132,887
Operations and Maintenance Cost ($)	$32,693	$43,041	$112,026
Capacity of Conversion Equipment, (kW)[d]	20	39	98
Digester Tank Dimensions:[e]			
Length (ft)	110	150	150 (3+ digester tanks required)
Width (ft)	27	37	37
Depth (ft)	10	12	12
Volatile Solids (lb/day)[f]	2,282	4,564	11,411
Methane Generation (m^3)[g]	68,000	135,999	339,998
Methane Captured (m^3)[h]	57,800	115,599	288,998
Methane Emitted (m^3)[i]	10,200	20,400	51,000
Methane Emitted (mt CO_2-eq)[j]	143	286	715
Methane Mitigated (mt CO_2-eq)	810	1,621	4,052
Total Electricity Generated (kWh)[k]	156,581	313,161	782,904
Electricity Used On-Site (kWh)[l]	156,581	313,161	782,904
Excess Electricity Generated (kWh)[l]	0	0	0

[a] Beef feedlot operations with fewer than 500 head are assumed to be too small to warrant a digester.

[c] Cost Profile for Beef: AgSTAR analyzed anaerobic digester system capital costs for 19 dairy farms for which itemized cost estimates were available and performed a regression analysis to determine an algorithm for capital costs. The capital costs for beef anaerobic digester systems was calculated using the formula provided for dairy plug flow digesters and scaled based on VS output. The capital costs ($) = (617 × (no. of cattle) × (scaling factor) + 566,006) + cost of flare + H_2S treatment + utility charges. The scaling factor is equal to (VS_{beef} lb/day) / (VS_{beef} lb/day) = 0.31. The cost of the flare is 3.3% of the cost of the digester and engine-generator set, the cost of H_2S treatment is 3.1%, and the cost of utility charges is 5.3%. Beef plug flow digesters may require a mixing system to keep the manure homogenous; the cost for this additional equipment has not been included into this cost profile. The values have been converted to 2010 dollars (EPA, 2010b).

[d] kW = [(lb VS/day) × (2.88 ft^3 methane/lb VS) × (0.90 collection efficiency) × (1000 BTU/ ft^3 methane)] / [(24 hrs/day) × 14,000 BTU/kWh)] (EPA, 2006a).

[e] Dimensions of the digester tanks are based on recommendations in EPA Agstar Farmware 3.1 (2009).

[f] Equation for VS lb per day = (no. head of cattle) × (lb VS/head/day) × (manure collection efficiency).

[g] Methane generation (m^3/yr) = (lb VS/day) × (2.88 ft^3 methane/lb VS) × (365 days/yr) × (0.0283 m^3/ft^3).

[h] Methane captured based on Climate Action Reserve (2009), where biogas control system collection efficiency is assumed to be 85%.

[i] Methane emitted (m^3) = (methane generation, m^3) – (methane captured, m^3). Methane emitted is the methane that escapes into the atmosphere from the biogas control system.

[j] Methane emitted (mt CO_2-eq) = (methane emitted, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) × (21 mt CO_2-eq/mt CH_4) / (2,205 lb/mt CH_4). These emissions result from the plug flow digester. The quantity of GHGs ultimate mitigated depends on the difference between the existing practice and the net GHG emissions resulting from the plug flow digester.

[k] Total electricity generation (kWh/yr) = (capacity of conversion equipment, kW) x (8,000 operating hours/yr).

[1] The average electricity use for an operation varies from region to region due to varying heating/cooling demands and technologies. Energy demand data for beef operations was not readily available. Beef operations consume less energy than do milking operations associated with dairy farms; consequently, beef energy demand is estimated as 50% of dairy energy demands for the purpose of this report. Data on dairy energy demand are from Key and Sneeringer (2011).

3.1.4.4 Break-Even Prices

Exhibit 3-42 through Exhibit 3-44: present the break-even prices for adoption of a plug flow digester for a set of representative dairy, swine, and beef operations. These prices reflect a tax rate of 15% and a discount rate of 5%. The tables indicate the break-even prices for transitioning from liquid/slurry systems to plug flow digesters for farms of different sizes and in different regions. Larger farms that transition to plug flow digesters have the lowest break-even prices.

Exhibit 3-42: Break-Even Prices for Dairy Farms that Adopt Plug Flow Digesters as Alternative to Existing Management Practices

Existing Practice: Liquid/Slurry		
Model Farm Size	**Region**	**Break-Even Price (2010 \$/ mt CO_2-eq)**
5,000	Southeast	$21
5,000	Southern Plains	$23
5,000	Delta	$25
5,000	Mountain	$27
5,000	Northern Plains	$31
5,000	Pacific	$32
5,000	Corn Belt	$33
5,000	Appalachia	$47
1,000	Southeast	$50
5,000	Northeast	$52
1,000	Southern Plains	$55
5,000	Lake States	$57
1,000	Delta	$60
600	Southeast	$73
600	Southern Plains	$82
1,000	Pacific	$85
600	Delta	$88
1,000	Mountain	$98
1,000	Appalachia	$111
1,000	Northern Plains	$112
1,000	Corn Belt	$121
600	Pacific	$129
300	Southeast	$133
300	Southern Plains	$148
600	Mountain	$157
300	Delta	$160
600	Appalachia	$165
1,000	Northeast	$179
600	Northern Plains	$179
600	Corn Belt	$193
1,000	Lake States	$205
300	Pacific	$239
600	Northeast	$285
300	Appalachia	$298
300	Mountain	$305
600	Lake States	$329
300	Northern Plains	$347
300	Corn Belt	$375
300	Northeast	$549
300	Lake States	$638

Exhibit 3-43: Break-Even Prices for Swine Farms that Adopt Plug Flow Digesters as Alternative to Existing Management Practices

Existing Practice: Liquid/Slurry		
Model Farm Size[a]	**Region**	**Break-Even Price (2010 $/ mt CO_2-eq)**
2,500	Southeast	$13
2,500	Delta	$13
2,500	Southern Plains	$13
2,500	Appalachia	$13
2,500	Corn Belt	$21
2,500	Northern Plains	$21
2,500	Pacific	$21
2,500	Northeast	$22
2,500	Lake States	$26
2,500	Mountain	$27
500	Southeast	$99
500	Delta	$101
500	Southern Plains	$103
500	Appalachia	$107
500	Corn Belt	$168
500	Northern Plains	$168
500	Pacific	$169
500	Northeast	$172
500	Lake States	$205
500	Mountain	$217
150	Southeast	$352
150	Delta	$358
150	Southern Plains	$366
150	Appalachia	$379
150	Corn Belt	$595
150	Northern Plains	$597
150	Pacific	$599
150	Northeast	$610
150	Lake States	$727
150	Mountain	$771

[a] Sow places.

Exhibit 3-44: Break-Even Prices for Beef Farms that Adopt Plug Flow Digesters as Alternative to Existing Management Practices

Existing Practice: Liquid/Slurry		
Model Farm Size	**Region**	**Break-Even Price (2010 $/ mt CO_2-eq)**
2,500	Southeast	$36
2,500	Delta	$38
2,500	Southern Plains	$42
2,500	Pacific	$44
2,500	Appalachia	$57
2,500	Northern Plains	$62
2,500	Mountain	$63
2,500	Corn Belt	$69
2,500	Northeast	$71
2,500	Lake States	$81
1,000	Southeast	$84
1,000	Delta	$88
1,000	Southern Plains	$98
1,000	Pacific	$102
1,000	Appalachia	$132
1,000	Northern Plains	$144
1,000	Mountain	$147
1,000	Corn Belt	$160
500	Southeast	$163
1,000	Northeast	$164
500	Delta	$171
1,000	Lake States	$189
500	Southern Plains	$191
500	Pacific	$198
500	Appalachia	$258
500	Northern Plains	$281
500	Mountain	$287
500	Corn Belt	$312
500	Northeast	$320
500	Lake States	$368

operation that will have a given mix of animals at various ages, all based on the number of sows in that operation. The use of a consistent scenario facilitates comparing differences across USDA production regions.

[b] The cost of a cover is $2.00/ft^2. The capital cost of a cover and double lining, based on an estimate from Environmental Fabrics Inc. (2011b), is $5.00/ft^2. The additional costs of a flare and associated gas handling equipment are 6.7% and 26.6%, respectively, of the cover and lining cost. The annual O&M is 4% of the capital cost. These costs are based on cost studies of existing digesters in California (Cheremisinoff et al., 2009) and in the United States (EPA, 2010b).

[c] Lagoon dimensions are based on recommendations in EPA Agstar Farmware 3.1(2009). The assumption is that a cover will be installed on existing lagoons.

[d] Volatile solids per sow place per day are based on EPA (2009) AgSTAR Farmware 3.4. "Sow places" refers to the capacity of the swine facility to hold mature female swine (sows), and includes both the lactating sows and gestating sows. Each of the operations has the following numbers of swine:

- 150-sow places: 50 lactating sows, 100 gestating sows, 470 nursing pigs, 470 weaned pigs, 410 feeder pigs;
- 500-sow places: 167 lactating sows, 333 gestating sows, 1,567 nursing pigs, 1,567 weaned pigs, 1,367 feeder pigs; and
- 2,500-sow places: 833 lactating sows, 1,667 gestating sows, 7,833 nursing pigs, 7,833 weaned pigs, 6,833 feeder pigs.

[e] Equation for methane generation (m^3/yr) = (lb VS/day) × (4.61 ft^3 methane/lb VS) × (365 days/yr) × (0.0283 m^3/ft^3) (EPA, 2006a).

[f] Methane captured is based on Climate Action Reserve (2009), where biogas control system collection efficiency is assumed to be 85%.

[g] Methane emitted (m^3) = (methane generation, m^3) – (methane captured, m^3). Methane emitted is the methane that escapes into the atmosphere from the biogas control system.

[h] Methane emitted (mt CO_2-eq) = (methane emitted, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) x (21 mt CO_2-eq/mt CH_4) / (2,205 lb/mt CH_4). These emissions result from the covered pond, tank, or lagoon. The ultimate quantity of GHG mitigated depends on the difference between the existing practice and the net GHG emissions resulting from covering a pit, tank, pond, or lagoon.

3.1.5.4 Break-Even Prices

Exhibit 3-51 and Exhibit 3-52 present break-even prices (estimates of the carbon incentive levels that would be necessary to just cover the farm-level costs) for installing impermeable covers on anaerobic lagoons and liquid/slurry vessels (i.e., ponds and tanks) for representative dairy and swine operations by region and farm size. The break-even prices demonstrate that it is more cost-effective for large farms to cover an existing lagoon, pond, or tank than it is for smaller operations, and the break-even prices for a given size category are quite comparable across different regions.

Exhibit 3-51: Break-Even Prices for Dairy Farms that Cover Existing Pond, Tank, or Lagoon as an Alternative to Existing Management Practices

Existing Practice: Anaerobic Lagoon		
Model Farm Size	**Region**	**Break-Even Price (2010 \$/ mt CO_2-eq)**
5,000	Southeast	$4
5,000	Southern Plains	$4
5,000	Appalachia	$4
5,000	Delta	$4
5,000	Pacific	$5
5,000	Mountain	$5
1,000	Southeast	$7
1,000	Southern Plains	$7
1,000	Appalachia	$7
1,000	Delta	$7
1,000	Pacific	$7
600	Southeast	$8
600	Southern Plains	$8
1,000	Mountain	$8

Existing Practice: Liquid/Slurry		
Model Farm Size	**Region**	**Break-Even Price (2010 \$/ mt CO_2-eq)**
5,000	Southeast	$9
5,000	Southern Plains	$10
5,000	Delta	$11
5,000	Appalachia	$13
5,000	Pacific	$15
1,000	Southeast	$15
1,000	Southern Plains	$16
600	Southeast	$16
1,000	Delta	$17
5,000	Mountain	$17
600	Southern Plains	$18
300	Southeast	$19
600	Delta	$19
300	Southern Plains	$20

Exhibit 3-46: Key Features of Covering an Existing Pond, Tank, or Lagoon

Key Design Parameters		
Characteristic	**Summary**	**Description/Explanation**
Level of Technology	Low	Using lined or unlined pond or lagoon with flexible cover to keep out rainfall, reduce nuisance odors, and capture methane gases. Specialized technology includes the following: ▪ Specialized housing and manure handling for frequently removing manure from animal areas and placing it in specialized storage ponds or lagoons with covers, which will require gas removal and a flaring system to remove dangerous gases. ▪ Equipment for land disposal or off-farm transport is needed when ponds, tanks, or lagoons are cleaned out. ▪ Rainwater diversion equipment is needed to remove rainwater from the top of the cover. ▪ A specialized impermeable cover is required that allows the liquid to be added and removed and whose height follows the level of the liquid (i.e., it has extra materials that allow the cover to move flexibly with the level of the liquid).
Farm Type	Swine, beef or dairy	Used on farms with liquid manure handling, either slurry scrape, pull plug, or flush systems.
Optimum Climate	All	Typically used in warmer climates to control odor.
Total Solids	2 to 15%	Flushed or scraped slurry manure.
Solids Characteristics	Coarse	Typically only manure solids, not bedding, handled as liquid.
HRT (days)	Minimum 90 days	Number of days of manure production that the storage pit can retain (typically at least 90 days to cover the winter months).
Daily Operations		
▪ Requires less labor than daily spread because manure is stored for at least 90 days between cleanouts (and subsequent land applications). ▪ Monitoring and maintenance of ventilation fans are very important, especially in hot weather.		

HRT = Hydraulic Retention Time, the average number of days that a volume of manure remains in the lagoon or pond.

Current and Potential Adoption

There are no data readily available on the total number of ponds, tanks, and lagoons used for manure management that are fitted with impermeable covers. Given the costs of installing an impermeable cover (see Exhibit 3-49 and Exhibit 3-50), the large majority of covered lagoons, tanks, and ponds currently in operation are likely fitted with permeable covers and are in areas where farms face significant problems related to odors. Consequently, a high potential likely exists for farms to increase their adoption of covered ponds, tanks, and lagoons in response to GHG mitigation incentives, particularly in warmer climates. Covering an existing lagoon, pond, or tank has limited mitigation potential in cooler climates such as the Northeast, Northern Plains, Corn Belt, and Lake States production regions due to decreased anaerobic activity in months with low temperatures.

Environmental Impacts

Covering an existing lagoon, tank, or pond can decrease the release of pathogens and odors from the manure management system. Covered lagoons can also provide water quality benefits by preventing water associated with high precipitation events from entering and overflowing the lagoons.

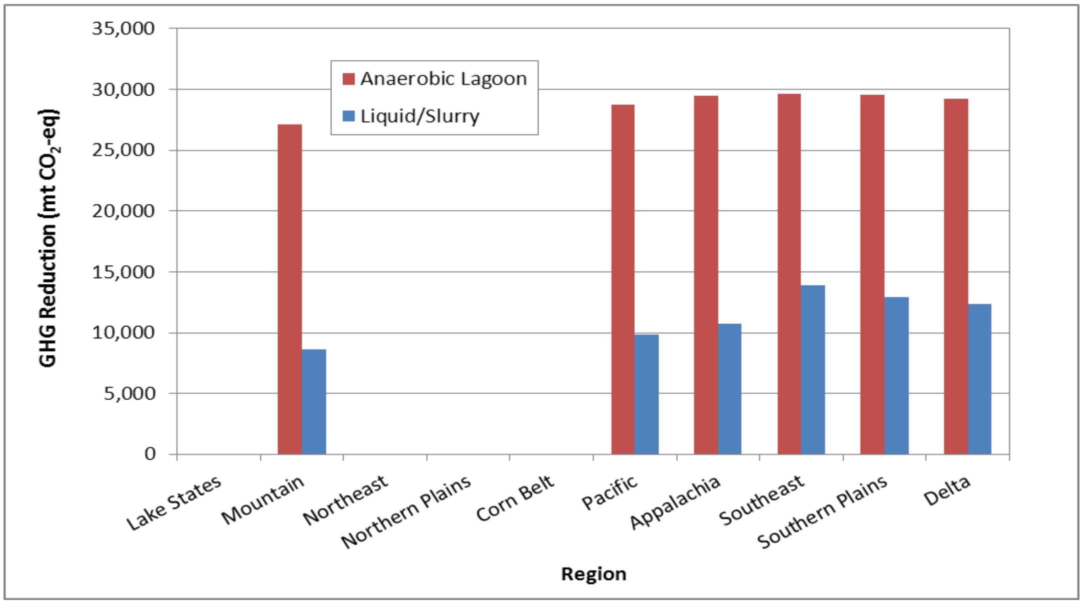
Barriers to Adoption

In some States, legal barriers may significantly lower adoption rates. For example, if a State requires specialized permits for lagoon modification and/or requires existing lagoons that are in the process of being modified to be brought up to current code, the farm-level costs of installing a cover could rise substantially. Such legal requirements are more common where groundwater resources are vulnerable to contamination from lagoon leakage. For example, in parts of California, the Regional Water Quality Control Board may require special linings be installed to prevent leakage into the groundwater.[15]

3.1.5.2 GHG Impacts

Covering an existing lagoon, pond, or tank, and flaring the methane gas reduces GHG emissions because the combusted methane is converted to CO_2 before being emitted to the atmosphere. The mitigation potential from covering an existing lagoon is provided for each of the applicable current management practices (i.e., dairy anaerobic lagoon, swine anaerobic lagoon, dairy liquid/ slurry, and swine liquid/ slurry) in the exhibits below and in Appendix 3-D. The potential GHG reductions from covering an existing lagoon for a 5,000 head dairy and a 2,500 sow place swine farm are shown in Exhibit 3-47 and Exhibit 3-48, respectively.

Exhibit 3-47: Farm-Level GHG Reduction Potential for Transitioning to Covering an Existing Lagoon from Existing Management Practice for a 5,000-Head Dairy Farm



Note: This graph represents the estimated emissions reductions achieved when a dairy operation transitions from an existing manure management practice to covering an existing lagoon in different regions. Details of the calculations can be found in the footnotes for the cost profiles.

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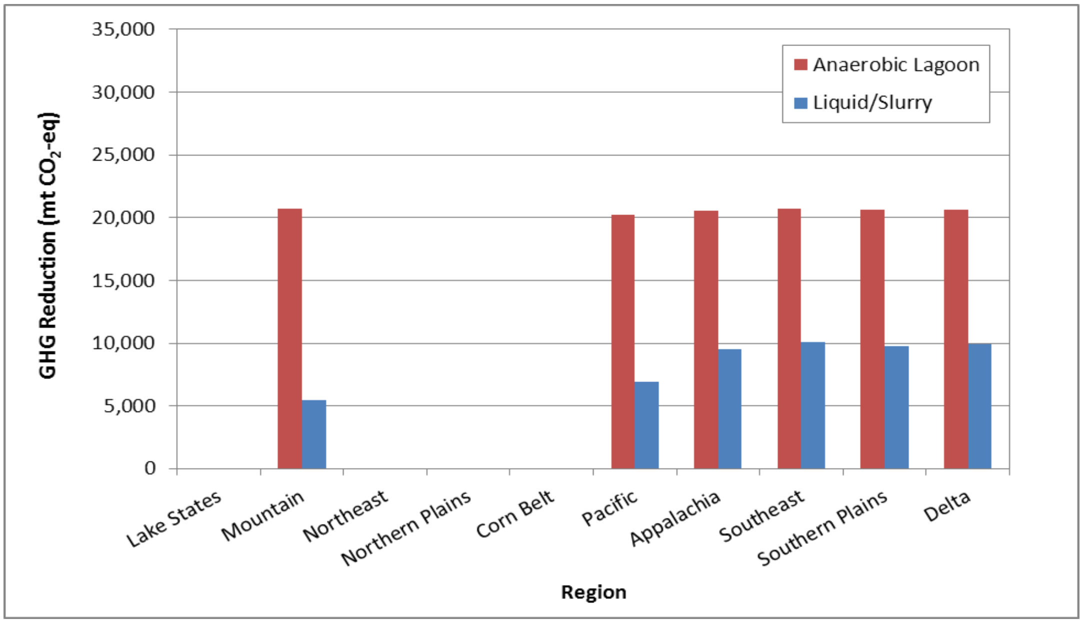
[15] See Title 27, California Code of Regulations (CCR), Division 2, Subdivision 1, Chapter 7, Subchapter 2, Article 1 (California Code of Regulations, 2012).

Exhibit 3-48: Farm-Level GHG Reduction Potential for Transitioning to Covering an Existing Lagoon from Existing Management Practice for a 2,500-Sow Place Farm



Note: This graph represents the estimated emissions reductions achieved when a swine operation transitions from an existing manure management practice to covering an existing lagoon in different regions. Details of the calculations can be found in the footnotes for the cost profiles.

3.1.5.3 Cost Profiles

The cost profiles and associated GHG mitigation are presented in Exhibit 3-49 for dairy operations and Exhibit 3-50 for swine operations. Costs are not separately evaluated for farms with fewer than 300 cows or 150 sow places, as cost-effectiveness per head decreases significantly compared with that of larger farms. The large majority of beef farms use aerobic systems to manage manure. These systems emit limited methane, hence this option is not evaluated for beef farms.

Exhibit 3-49: Cost Profile for Dairy Farm Covering Existing Pond, Tank, or Lagoon

Parameter	Value			
Farm Size[a]				
No. of Cows	300	600	1,000	5,000
No. of Heifers	300	600	1,000	5,000
Manure Collection Efficiency from Cows	75%	75%	75%	75%
Manure Collection Efficiency from Heifers	45%	45%	45%	45%
Capital Costs:[b]	$109,950	$192,413	$ 293,200	$916,250
Cover ($)	$60,000	$105,000	$160,000	$500,000
Flare ($)	$10,050	$17,588	$26,800	$83,750
Balance of Plant ($)	$39,900	$69,825	$106,400	$332,500
Operations and Maintenance Cost ($)	$4,398	$7,697	$11,728	$36,650
Lagoon Dimensions:[c]				
Length (ft)	300	350	400	1000
Width (ft)	100	150	200	250
Depth (ft)	18	20	24	24
Volatile Solids (lb/day)[d]	4,673	9,347	15,578	77,892

Parameter	Value			
Methane Generation (m^3 CH_4)[e]	87,273	174,547	290,911	1,454,557
Methane Captured (m^3 CH_4)[f]	74,182	148,365	247,275	1,236,373
Methane Emitted (m^3 CH_4)[g]	13,091	26,182	43,637	218,184
Methane Emitted (mt CO_2-eq)[h]	184	367	612	3,059
Methane Captured (mt CO_2-eq)	1,040	2,080	3,467	17,336

Note: Recognizing that costs differ by size of lagoons, the basic model is the square footage of the cover, assuming the depth is the same for all anaerobic lagoons, and therefore the costs are directly proportional to the square footage, which is also proportional to the volume, which, in turn, is proportional to the number of animals.

[a] Dairy farms with fewer than 300 cows are assumed to be too small to support an economically feasible digester.

[b] The cost of a cover only is $2.00/ft². The capital cost of a cover and double lining is based on an estimate of $5.00/ft² from Environmental Fabrics Inc. (2011b). The additional costs of a flare and associated gas handling equipment are 6.7% and 26.6%, respectively, of the cover and lining cost. The annual O&M is 4% of the capital cost. These costs are based on cost studies of existing digesters in California (Cheremisinoff et al., 2009) and in the United States (EPA, 2010b).

[c] Lagoon dimensions are based on recommendations in EPA Agstar Farmware 3.1(2009). The cover is assumed to be installed on existing lagoons.

[d] Equation for VS, lb/day = (no. of cows) × (lb VS_{cow}/day) × (cow manure collection efficiency) + (no. of heifers) × (lb VS_{heifer}/day) × (heifer manure collection efficiency).

[e] Equation for methane generation (m^3/yr) = (no. of cows) x (lb VS_{cow}/day) × (3.84 ft^3 methane/lb VS) × (365 days/yr × 0.0283 m^3/ft^3) + (no. of heifers) x (lb VS_{heifer}/day) × (2.72 ft^3 methane/lb VS) × (365 days/yr) × (0.0283 m^3/ft^3) (EPA, 2006a).

[f] Methane captured is based on Climate Action Reserve (2009), where biogas control system collection efficiency is assumed to be 85%.

[g] Methane emitted (m^3) = (methane generation, m^3) – (methane captured, m^3). Methane emitted is the methane that escapes into the atmosphere from the biogas control system.

[h] Methane emitted (mt CO_2-eq) = (methane emitted, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) x (21 mt CO_2-eq/mt CH_4) / (2,205 lb/mt CH_4). These emissions result from the covered pond, tank, or lagoon. The ultimate quantity of GHG mitigated depends on the difference between existing practice and the net GHG emissions resulting from covering a pit, tank, pond, or lagoon.

Exhibit 3-50: Cost Profile for Swine Farm Covering Existing Pond, Tank, or Lagoon

Parameter	Value		
Farm Size (no. of sow places)[a]	150	500	2,500
Capital Costs:[b]	$109,950	$293,331	$916,659
Cover ($)	$60,000	$160,000	$500,000
Flare ($)	$10,050	$26,667	$83,334
Balance of Plant ($)	$39,900	$106,664	$333,325
Operations and Maintenance Cost ($)	$4,398	$11,733	$36,666
Lagoon Dimensions:[c]			
Length (ft)	300	400	1,000
Width (ft)	100	200	250
Depth (ft)	18	24	24
Volatile solids (lb/day)[d]	773	2,576	26,650
Methane Generation (m^3 CH_4)[e]	18,547	61,822	639,660
Methane Captured (m^3 CH_4)[f]	15,765	52,549	543,711
Methane Emitted (m^3 CH_4)[g]	2,782	9,273	95,949
Methane Emitted (mt CO_2-eq)[h]	39	130	1,345
Methane Captured (mt CO_2-eq)	221	737	7,624

Note: Recognizing that costs differ by size of lagoons, the basic model is the square footage of the cover, assuming the depth is the same for all anaerobic lagoons, and therefore the costs are directly proportional to the square footage, which is also proportional to the volume, which, in turn, is proportional to the number of animals.

[a] Even though many swine operations separate some of the life phases of swine production (i.e., farrowing, gestating, weaning, growing, and finishing), the choice to use a complete farrow-to-finish operation as the baseline was made in order to have a consistent swine

operation that will have a given mix of animals at various ages, all based on the number of sows in that operation. The use of a consistent scenario facilitates comparing differences across USDA production regions.

[b] The cost of a cover is \$2.00/ft^2. The capital cost of a cover and double lining, based on an estimate from Environmental Fabrics Inc. (2011b), is \$5.00/ft^2. The additional costs of a flare and associated gas handling equipment are 6.7% and 26.6%, respectively, of the cover and lining cost. The annual O&M is 4% of the capital cost. These costs are based on cost studies of existing digesters in California (Cheremisinoff et al., 2009) and in the United States (EPA, 2010b).

[c] Lagoon dimensions are based on recommendations in EPA Agstar Farmware 3.1(2009). The assumption is that a cover will be installed on existing lagoons.

[d] Volatile solids per sow place per day are based on EPA (2009) AgSTAR Farmware 3.4. "Sow places" refers to the capacity of the swine facility to hold mature female swine (sows), and includes both the lactating sows and gestating sows. Each of the operations has the following numbers of swine:

- 150-sow places: 50 lactating sows, 100 gestating sows, 470 nursing pigs, 470 weaned pigs, 410 feeder pigs;
- 500-sow places: 167 lactating sows, 333 gestating sows, 1,567 nursing pigs, 1,567 weaned pigs, 1,367 feeder pigs; and
- 2,500-sow places: 833 lactating sows, 1,667 gestating sows, 7,833 nursing pigs, 7,833 weaned pigs, 6,833 feeder pigs.

[e] Equation for methane generation (m^3/yr) = (lb VS/day) × (4.61 ft^3 methane/lb VS) × (365 days/yr) × (0.0283 m^3/ft^3) (EPA, 2006a).

[f] Methane captured is based on Climate Action Reserve (2009), where biogas control system collection efficiency is assumed to be 85%.

[g] Methane emitted (m^3) = (methane generation, m^3) – (methane captured, m^3). Methane emitted is the methane that escapes into the atmosphere from the biogas control system.

[h] Methane emitted (mt CO_2-eq) = (methane emitted, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) x (21 mt CO_2-eq/mt CH_4) / (2,205 lb/mt CH_4). These emissions result from the covered pond, tank, or lagoon. The ultimate quantity of GHG mitigated depends on the difference between the existing practice and the net GHG emissions resulting from covering a pit, tank, pond, or lagoon.

3.1.5.4 Break-Even Prices

Exhibit 3-51 and Exhibit 3-52 present break-even prices (estimates of the carbon incentive levels that would be necessary to just cover the farm-level costs) for installing impermeable covers on anaerobic lagoons and liquid/slurry vessels (i.e., ponds and tanks) for representative dairy and swine operations by region and farm size. The break-even prices demonstrate that it is more cost-effective for large farms to cover an existing lagoon, pond, or tank than it is for smaller operations, and the break-even prices for a given size category are quite comparable across different regions.

Exhibit 3-51: Break-Even Prices for Dairy Farms that Cover Existing Pond, Tank, or Lagoon as an Alternative to Existing Management Practices

Existing Practice: Anaerobic Lagoon		
Model Farm Size	**Region**	**Break-Even Price (2010 \$/ mt CO_2-eq)**
5,000	Southeast	\$4
5,000	Southern Plains	\$4
5,000	Appalachia	\$4
5,000	Delta	\$4
5,000	Pacific	\$5
5,000	Mountain	\$5
1,000	Southeast	\$7
1,000	Southern Plains	\$7
1,000	Appalachia	\$7
1,000	Delta	\$7
1,000	Pacific	\$7
600	Southeast	\$8
600	Southern Plains	\$8
1,000	Mountain	\$8

Existing Practice: Liquid/Slurry		
Model Farm Size	**Region**	**Break-Even Price (2010 \$/ mt CO_2-eq)**
5,000	Southeast	\$9
5,000	Southern Plains	\$10
5,000	Delta	\$11
5,000	Appalachia	\$13
5,000	Pacific	\$15
1,000	Southeast	\$15
1,000	Southern Plains	\$16
600	Southeast	\$16
1,000	Delta	\$17
5,000	Mountain	\$17
600	Southern Plains	\$18
300	Southeast	\$19
600	Delta	\$19
300	Southern Plains	\$20

Existing Practice: Anaerobic Lagoon		
Model Farm Size	Region	Break-Even Price (2010 $/ mt CO_2-eq)
600	Appalachia	$8
600	Delta	$8
600	Pacific	$8
600	Mountain	$8
300	Southeast	$9
300	Southern Plains	$9
300	Appalachia	$9
300	Delta	$9
300	Pacific	$9
300	Mountain	$10

Existing Practice: Liquid/Slurry		
Model Farm Size	Region	Break-Even Price (2010 $/ mt CO_2-eq)
1,000	Appalachia	$21
300	Delta	$22
1,000	Pacific	$23
600	Appalachia	$23
600	Pacific	$25
300	Appalachia	$27
1,000	Mountain	$28
300	Pacific	$29
600	Mountain	$31
300	Mountain	$35

Exhibit 3-52: Break-Even Prices for Swine Farms that Cover Existing Pit, Tank, Pond, or Lagoon as Alternative to Existing Management Practices

Existing Practice: Anaerobic Lagoon		
Model Farm Size	Region	Break-Even Price (2010 $/ mt CO_2-eq)
2,500	Pacific	$3
500	Pacific	$6
2,500	Southern Plains	$6
2,500	Delta	$6
2,500	Mountain	$6
2,500	Appalachia	$6
2,500	Southeast	$6
150	Pacific	$7
500	Southern Plains	$21
500	Delta	$21
500	Mountain	$21
500	Appalachia	$21
500	Southeast	$21
150	Southern Plains	$26
150	Delta	$26
150	Mountain	$26
150	Appalachia	$26
150	Southeast	$27

Existing Practice: Liquid/Slurry		
Model Farm Size	Region	Break-Even Price (2010 $/ mt CO_2-eq)
2,500	Pacific	$12
2,500	Southern Plains	$13
2,500	Delta	$13
2,500	Appalachia	$14
500	Pacific	$20
2,500	Southeast	$20
2,500	Mountain	$24
150	Pacific	$25
500	Southern Plains	$43
500	Delta	$43
500	Appalachia	$45
150	Southern Plains	$53
150	Delta	$54
150	Appalachia	$57
500	Southeast	$66
500	Mountain	$81
150	Southeast	$83
150	Mountain	$101

3.1.6 Solids Separator

3.1.6.1 Technology Characterization

Solids separators include a variety of technologies that remove a significant portion of the solids contained in manure streams from confined animal operations. Separators are typically used prior to the effluent stream entering the treatment or storage system. For dairy operations with anaerobic digesters, a separation step is necessary to remove large fibrous solids that can inhibit biogas collection by forming a crust on the effluent surface in the digester.

Separator systems can be either passive or active. Passive systems, like a weeping wall basin or settling pond, use gravity to settle the solids in a pond or basin. Solids must be removed periodically with an excavator or other machine. The photo at the top of Exhibit 3-53 shows an example of a settling pond used for separating solids. Active systems separate the solids from the liquids mechanically; examples include double-screen separators, circular screens, and belt press separators. Solids separation can be enhanced significantly by the addition of a flocculant to the manure stream. A flocculant is a material that causes small manure particles to stick together and form larger particles that can be effectively separated with the mechanical screens. With respect to GHG mitigation, the separated solids require some follow-on treatment (e.g., drying or composting) to ensure that anaerobic activity ceases. Exhibit 3-53 shows two mechanical separator systems developed by Daritech. Exhibit 3-54 presents a schematic diagram of a separator system.

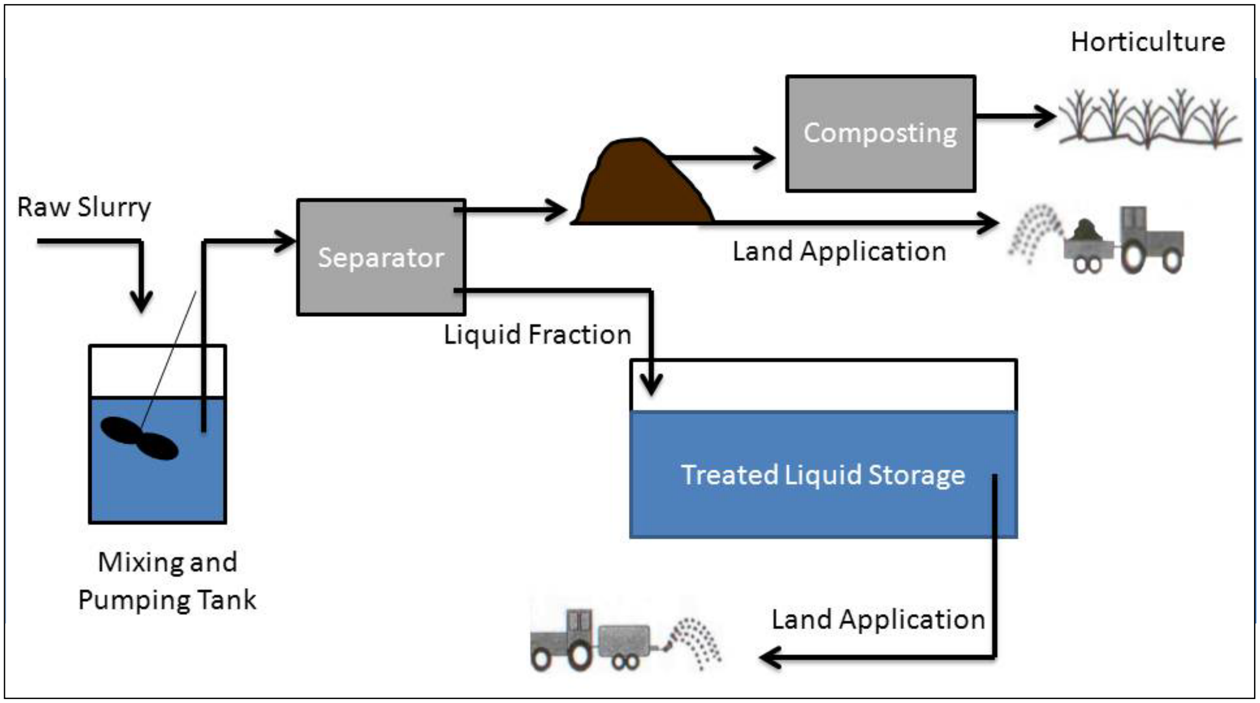
Key Features of Solids Separator

- Separators remove solids from manure streams to reduce the methane generated from the storage lagoon, increase time between storage system cleaning, and prevent crust formation.
- Removal of solids from liquid lagoons reduces odors from the system.
- Byproducts of digestion can be further processed into nutrient-rich soil amendments and bedding for livestock.

Exhibit 3-53: Example of Solids Separators on Dairy Facilities

Settling pond, top (EPA, 2010c); rotary press separator, bottom left (Daritech Inc., 2011); inclined screen separator, bottom right (Daritech Inc, 2012b).

Exhibit 3-54: Schematic of a Separator System



Source: Adapted from NRAES (2001).

For GHG mitigation, solids separation will be most effective on farms that currently use flushed manure systems because these systems will generally not need to modify how they collect manure from their animal barns. In addition, most flush systems already include a pond, tank, or lagoon that can be used for storage of the liquids after separation. Exhibit 3-55 summarizes the key characteristics of solids separators.

Exhibit 3-55: Key Features of Solids Separators

Key Design Parameters		
Characteristic	**Summary**	**Description/Explanation**
Level of Technology	Low	Involves either mechanical or gravity-type solids separation followed by composting and liquid handling system.
Farm Type	Dairy, swine	Pertains to flushed manure situations: Flushed manure optimizes the performance of a solids separator. Scrape systems have insufficient liquids for efficient operation of the separators.
Optimum Climate	Mild	Applies to a climate where freezing is not a problem most of the year. Freezing temperatures can impair the performance of a separator, so mild or warmer temperatures are optimal for solids separators.
Total Solids	1 to 5%	
Daily Operations		
▪ Depending on the system, regular maintenance of pumps, motors, and screens for clogs, periodic clean-out of weeping wall basin, handling of compost.		

Current and Potential Adoption

Less than 20% of the dairy farms in the United States use a manure separator.[16] These separators are used to facilitate the treatment and transport of manure rather than to reduce GHG emissions. This low level of use suggests that a large number of dairies could adopt solids separators if offered an appropriate GHG mitigation incentive.

Swine operations have the potential to adopt solids separators if some modifications to the equipment are made. In particular, in order to separate a significant fraction of the solids from swine manure, technologies such as screw presses, fabric filters, or decanting centrifuges are required, with removal efficiencies from 20–40%. The addition of polymer coagulants–flocculants has been shown to raise the total suspended solids separation efficiency of screens from less than 20% to more than 90% (Hamilton, 2010).

Production Impacts

Once the solids are separated, the remaining effluent is generally placed in a lagoon (or other storage structure). With fewer solids in the system, the time between clean-outs will increase. This may reduce farm labor requirements and/or increase the number of animals that the system can accommodate (effectively increasing herd size without changing the storage structure).

Separation also facilitates additional options for managing both the liquid and solid products of the separation process. For example, the liquid manure can be incorporated into the irrigation equipment and can replace some of the synthetic fertilizer that is put on the fields. The separated liquid will have a reduced odor due to a lower solids content. The solids can be composted and then sold as fertilizer or reused in the animal barns as bedding. A representative price for separated solids is approximately $20 per ton (Central Coast Compost, 2011).

Barriers to Adoption

There are technical and economic barriers to the adoption of improved solids separators on farms in the United States. The most significant barrier is the high operation and maintenance costs for the relatively small amount that the farm will gain back from selling the separated solids. Another technical barrier includes managing the manure properly to achieve the correct total solids content for effective operation of the solids separator. In addition, solids separators work best for separating large, suspended particles. Effectiveness decreases with decreasing particle size without flocculants.

The economic barriers are mainly the high capital cost of the improved solids separators, which can be upwards of $100,000 for medium-sized dairies. The farms must be large enough to afford the investment required for equipment to both separate solids and compost the solids. The composting equipment can also cost upwards of $100,000 for medium to large dairies. The other economic barrier is the operating cost of the systems, which require an increase in daily energy use for mechanical separation. The solids separator will require maintenance, including cleaning of the pumps and screens, which could change or increase the labor needs on the farm. The flocculants required for making the solids separators operate efficiently are an added operational cost for the system.

3.1.6.2 GHG Impacts

Removing solids before the manure stream begins treatment and storage decreases the amount of organic carbon in the system that is available for conversion to methane through anaerobic digestion. For dairy farms, a 1,000-head operation can mitigate approximately 8,160 mt CO_2-eq through the use of a separator, while a 4,000-head operation can mitigate approximately 32,650 mt CO_2-eq.

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[16] MacDonald et al. (2007).

3.1.6.3 Cost Profile

This section presents representative cost profiles that reflect the total cost of adopting one particular improved solids separation system (including capital costs and recurring costs). The separator system analyzed is an inclined screen combined with flocculants to increase the capture of solids, followed by composting. Composting halts anaerobic processes in the solids, destroys weed seeds and pathogens, decreases the bulk of raw inputs by 50–70%, stabilizes nutrients as organic compounds, and slows organic nutrient release (Government of Saskatchewan, 2008). Composting processes solids into a more marketable product that can be used for bedding or as a soil conditioner product. This system is currently applicable only to dairies larger than 1,000 cows where there are sufficient manure solids to justify the equipment expenditure.

Representative costs for a solids separator management system are as follows:[17]

- Rotating screen solids separator: $103,000
- Concrete pad for mounting the separator: $50,000
- Manure pump for feeding the separator: $140,000
- Composting equipment
  - $100,000 for a 2,000-head farm
  - $350,000 for a 4,000-head farm

Operations with 4,000 animals require an additional large screen separator and pump ($35,000).

The annual operations and maintenance cost are estimated as follows:

- Separators: 4% of the total capital costs, plus $6/head/yr for flocculants
- Composting: 4% of the total capital costs, plus $8/head/yr

Exhibit 3-56: Cost Profile for Solids Separators

Parameter	Value	
Farm Size (no. of cows)	1,000	4,000
Manure Collection Efficiency from Cows	75%	75%
Farm Size (no. of heifers)	1,000	4,000
Manure Collection Efficiency from Heifers	45%	45%
Capital Cost for Solids Separation[a]	$167,000	$202,000
Annual Operating Cost for Solids Separation	$12,680	$46,080
Capital Cost for Windrow Composting Equipment	$100,000	$350,000
Annual Operating Cost for Compost Production	$12,000	$46,000
Volatile Solids (lb/day)[b]	15,578	62,313
Volatile Solids Captured by Manure Screen (lb/day)[c]	13,242	52,966
Volatile Solids in Finished Compost (lb/day)[d]	6,621	26,483
Finished Compost Quantity (tons/day)	8	33
Annual Value Finished Compost ($/yr)	$60,415	$241,659
Methane Mitigated (mt CO_2-eq)	8,162	32,648

[a] Price estimates based on Daritech DT360 (Vendor quotation from Daritech (2012a)).
[b] Equation for volatile solids, lb/day = (no. of cows) × (lb VS/cow/day) × (cow manure collection efficiency) + (no. of heifers) × (lb VS/heifer/day) × (heifer manure collection efficiency).
[c] This assumes the screen captures volatile solids with 85% efficiency.
d At 50% bulk of the original.

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[17] Vendor quotation from Daritech Inc. (Daritech Inc, 2012a).

3.1.6.4 Break-Even Prices

Exhibit 3-57 presents the break-even prices for current practices that adopt solids separators when composting equipment and costs are included. However, given the uncertainty in the sale of the resulting compost, the potential revenue for the sale of compost is not accounted for in the break-even price. Consequently, the break-even price is overestimated here for farms where the compost is sold. Exhibit 3-57 also presents the break-even prices for solids separators when composting-related costs are *not* included. The break-even price decreases in this case because less equipment is required when there is no composting.

Exhibit 3-57: Break-Even Prices for Dairy Farms that Adopt Solids Separators Prior to Treatment in an Anaerobic Lagoon, With and Without Composting

Model Farm Size	Region	With Composting	Without Composting
		Break-Even Price (2010 \$/mt CO_2-eq)	Break-Even Price (2010 \$/mt CO_2-eq)
4,000	All Regions	\$4	\$2
1,000	All Regions	\$6	\$4

3.1.7 Nitrification/Denitrification

3.1.7.1 Technology Characterization

Nitrification–denitrification (NDN) is a two-step process used in manure management systems for the biological removal of nitrogen from effluent streams (typically consisting of feces, urine, and flush water) from confined animal operations. This type of system works best with diluted manure from a pull-plug flush system,[18] and with a total solids content of approximately 2%. Untreated effluent contains ammonium (NH_4), which can lead to soil acidification, eutrophication, and human health effects. NDN converts NH_4 to nitrogen gas (N_2), which can then be evaporated into the atmosphere.

The system described here is in operation on a 5,000-plus hog feeder-to-finish operation in North Carolina.[19] The system consists of three distinct process stages: solid–liquid separation, biological nitrogen treatment, and wastewater disinfection and phosphorus removal. Although the use of the NDN system results in increased CO_2 emissions from purchased electricity, net GHGs are reduced due to decreases in N_2O and CH_4 emissions.

Key Features of Nitrification–Denitrification (NDN) Systems

- Suitable for use with pull-plug flush systems with dilute manure.
- Reduce nitrous oxide (N_2O) and methane (CH_4) emissions from manure handling.
- Higher productivity from decreasing animal mortality and increasing feed conversion efficiency in animals. Improve recycled water and air quality by destroying pathogens, minimizing odor, and removing heavy metals associated with raw manure streams.

Stage 1: Solid–Liquid Separation. In the first process stage, subfloor wastewater is emptied weekly by gravity into receiving pits located beneath each animal barn. From the receiving pits, the wastewater is pumped into a homogenization tank where it is kept well mixed using a submersible mixer.[20] The homogenized wastewater stream is then passed through a rotary press liquid–solid separation unit. In the separation process, a flocculent (polyacrylamide) is added to facilitate the separation of fine suspended particles. Separation results in two products: a manure cake (26% solids) and separated wastewater. The manure cake is transported to an off-site facility where it is composted and then processed into a high-quality soil amendment (Vanotti et al., 2009). The separated wastewater is pumped into a storage tank to await further treatment.

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[18] In a pull-plug flush system, manure and wastewater collect in gutters in the swine buildings. When the gutters are full, a drain plug is pulled and manure and wastewater are allowed to flow out. Water can be used to flush the manure out of the gutters.

[19] The system considered in this report was constructed and operated by Terra Blue, Inc. of Clinton, North Carolina.

[20] For a 5,000-plus hog feeder-to-finish operation, the tank has 379 m^3 capacity.

Stage 2: Biological Nitrogen Treatment. In the second stage, nitrogen is removed from the separated wastewater by subjecting it to NDN. The process takes place in two tanks, one for nitrification and one for denitrification. Each tank has a capacity of 227 m^3.

- **Nitrification:** In the nitrification tank, bacteria known as *Nitrosomonas* oxidize ammonium (NH_4^+) and ammonia (NH_3) into nitrite (NO_2^-), while a second bacterium known as *Nitrobacter* converts nitrite to nitrate (NO_3^-). This process occurs in aerobic conditions; a continuous flow of oxygen is supplied by pumps located at the bottom of the tank.
- **Denitrification:** In the denitrification tank, denitrifying bacteria use soluble manure carbon to convert NO_2^- and NO_3^- into N_2 gas. A submersible mixer keeps the effluent well mixed during denitrification. This process requires anaerobic conditions, so there is no pumping of oxygen.

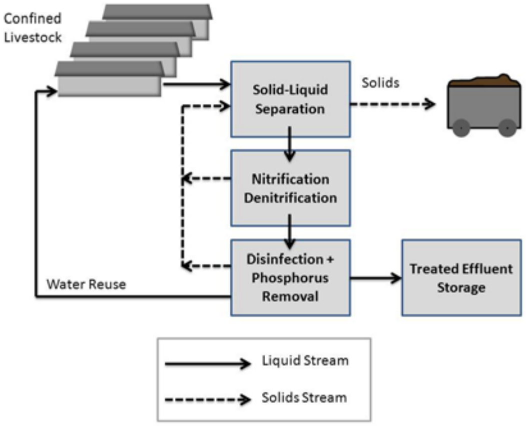
After nitrogen removal, the wastewater is transferred to a clarification tank where suspended solids are collected and either returned to the denitrification tank or sent back to the solids separation unit. After clarification, the effluent is transferred to a treated-water tank where it is recycled, as needed, back into the animal housing facility as flush water. Treated water in excess of flushing needs is subjected to phosphorous separation and pathogen removal, which is the final process stage (see stage 3 below).

Stage 3: Wastewater Disinfection and Phosphorus Removal. In the third process stage, treated water is fed by gravity from the treated-water tank into a phosphorous separation reactor. In the reactor, the effluent is mixed with a hydrated lime slurry and phosphorous is precipitated out of the solution as solid calcium phosphate (Vanotti et al., 2003). The addition of the lime slurry also creates a highly alkaline solution (pH of 9.5–9.7), which significantly reduces pathogen levels in the effluent stream. In the system described here, pathogens (specifically total and fecal coliforms, enterococci, and salmonella) were reduced by 99.9%, and 97.9% of odor-causing compounds were removed (Vanotti et al., 2009). The phosphate solids are removed from the reactor and can be sent back to the separation unit to be incorporated back into the manure cake or removed and dried into a fertilizer grade phosphorous product. Finally, the clarified effluent that is removed from the phosphorous reactor is sent to an aerobic lagoon where it is stored until it is used for crop irrigation.

Exhibit 3-58 illustrates the movement of materials in the NDN system. The solid arrows show the movement of the liquid stream from animal barns to the homogenization tank, nitrification–denitrification tanks, phosphorous separation reactor, and then to a storage tank and/or back to the barns for reuse. Solids are removed at each stage and taken away for off-site treatment.

The NDN system described in this chapter is pictured in Exhibit 3-59. The key components of the capital equipment required are included in Exhibit 3-60. North Carolina has certified the NDN system as an Environmentally Superior Technology (EST).[21] Since July 2007, new or expanded livestock waste management systems in North Carolina have been required to meet the EST standards.

Exhibit 3-58: Schematic Diagram of a Nitrification-Denitrification System



Source: Personal communication with Matias Vanotti (Vanotti, 2011).

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[21] An Environmentally Superior Technology is defined in North Carolina as any technology or combination of technologies that meet five environmental performance standards: (1) eliminate the discharge of animal waste to surface waters and groundwater through direct discharge, seepage, or runoff; (2) substantially eliminate atmospheric emissions of ammonia; (3) substantially eliminate the emission of odor that is detectable beyond the boundaries of the swine farm; (4) substantially eliminate the release of disease-transmitting vectors and airborne pathogens; and (5) substantially eliminate nutrient and heavy metal contamination of soil and groundwater (Vanotti et al., 2009).

Exhibit 3-59: Nitrification Denitrification System

Exhibit 3-60: Key Equipment in a Nitrification–Denitrification Manure Management System

Component	Description
Homogenization tank	Diluted manure is drained from the animal barns to a receiving pit and then pumped into a homogenization tank with a submersible mixer.
Rotary press separator	The liquid and solid are separated by a rotary press liquid–solid separation unit, which is composed of two polymer preparation tanks, a polymer metering pump, a manure feed pump, and an in-line flocculator.
Separated wastewater storage tank	The liquid wastewater stream is moved from the separator to a storage tank for holding between treatments.
Nitrification tank	Wastewater is moved into the nitrification tank where bacteria convert ammonium to nitrates and nitrites. These bacteria require oxygen, which is supplied continually by an aeration unit.
Denitrification tank	Wastewater is treated with a separate batch of bacteria that convert nitrites and nitrates into nitrogen gas. The liquid is mixed with a submersible mixer.
Clarification tank	After NDN, wastewater is transferred to a clarifying tank where suspended particles are removed.
Treated water tank	Effluent that has been denitrified and clarified is then held in a tank until the treated water is needed for flushing out animal barns.
Phosphorus separation unit	Excess effluent can be fed into a phosphorous separation unit. Within this unit, there is a lime slurry mixing chamber, pH probe and controller, lime injection pump, and a settling tank. The addition of lime slurry to the effluent significantly reduces pathogen levels in the effluent stream. The clarified, treated effluent can then be stored in a lagoon until it is needed for irrigation.

Exhibit 3-61: Farm-Level Considerations for Nitrification–Denitrification Systems

Key Design Parameters	
Characteristic	**Description/Explanation**
Level of Technology	The technology has been demonstrated at a commercial scale at a hog operation in Clinton, North Carolina. The NDN system was designed for a farm of 4,000–5,500 animals. The system can be scaled up and/or replicated to accommodate the larger manure quantities of larger operations or multiple operations located in close proximity.
Optimum Climate	Cold temperatures can significantly slow the anaerobic activity that is essential for the denitrification part of the process. This suggests that some modifications to the denitrification tank may be necessary to adapt the system to the northern regions.
Daily Performance statistics	The amount of raw manure entering the homogenization tank is 28.1 m^3; water recycled for barn flushing is 5.5 m^3; and treated water sent to the aerobic lagoon is 23.0 m^3. These performance statistics reflect direct measurement of the effluent stream on a demonstration farm over a 14-month period.
Total Solids	Diluted manure with a total solids content of approximately 2%.
Solids Characteristics	A flocculent is added to facilitate the separation of suspended particles, resulting in a manure cake solid.
HRT (days)	A duration of 4 days is needed to complete the biological transformation of the nutrients.
Daily Operations	
▪ Checking the operation of all pumps, checking the chemical addition, removing the solids that are created, and periodically irrigating the effluent.	

Current and Potential Adoption

To date, one NDN system has been adopted at a demonstration facility in Clinton, NC from which performance has been tracked. As of December 2012, a scaled up facility has been constructed in Wayne County, NC that treats waste from a 12,960 head finishing facility and a supporting 1,200 head sow operation. The break-even prices presented below are based on the evaluation of the costs and GHG benefits for the demonstration project. The validity of extending the benefit and cost estimates obtained from the Clinton facility to hog operations in regions with significantly different temperature and precipitation profiles, or to facilities that handle dairy cows, poultry, or other types of confined livestock has not been established. At present, potential adoption in response to incentives to mitigate GHG emissions should be limited to hog operations with 4,000 head or more in the southern United States, specifically Alabama, Arkansas, Georgia, Mississippi, North Carolina, South Carolina, and Tennessee. Among these States, North Carolina is the largest hog producer and has the greatest potential for NDN adoption. As of 2007, North Carolina had 2,836 farms with hogs, with a total inventory of 10 million animals (USDA, 2011). Within North Carolina, hog operations with more than 4,000 animals accounted for more than half of all farms with hogs and 97% of all hogs sold (National Hog Farmer, 2008).

Environmental and Production Performance

Production Impacts. Over the 15-month observation period, the NDN system demonstrated a number of production-related benefits that have the potential to improve the economics of the system; however, these improvements depend on the value of the benefits being captured in a market. Relative to the traditional anaerobic lagoon system, the NDN system resulted in the following:

- Increased animal production: The treated water (denitrified effluent) recycled back to the animal barns for flushing improved air quality in the barns. Animal health improved in several ways: animal mortality decreased by 57%, feed conversion efficiency increased by 5.1%, and daily weight gain increased by 6.1%. Overall, the operation sold 61,400 pounds more hogs per growing cycle (an increase of 5.8%).
- Potential co-products: The separated solids are retained by the firm that installed and manages the NDN system. The solids are taken off-farm, composted, and processed into a high-quality soil amendment.

Additionally, the phosphorus extracted from the effluent stream is a commercial grade fertilizer; however, the scale of the demonstration system does not produce sufficient volume to be of interest to commercial fertilizer producers at current prices.

Other Environmental Impacts. Other environmental benefits derived from NDN systems include the following:

- Improved air quality: Relative to the baseline anaerobic lagoon system, ammonia emissions were reduced by 90% and five other malodorous compounds common in raw swine manure (phenol, p-cresol, p-ethylphenol, indole, and skatole) were each reduced by more than 99%.
- Improved water quality: Relative to the raw manure stream entering the homogenization tank, the final effluent entering the storage pond had 88% of the total nitrogen and 95% of the phosphorous removed. The phosphorous separation process eliminated more than 99% of all pathogens and heavy metals (copper and zinc) from the final effluent. Because the effluent in the pond is used to irrigate crops, the NDN process significantly reduces potential problems with nutrient runoff and leaching, and eliminates potential problems with the spread of disease and the accumulation of heavy metals in soils relative to traditional anaerobic lagoon systems.
- In the baseline system, the effluent stream was treated and stored in an anaerobic lagoon. After installation of the NDN system, the same lagoon was used to store the final treated effluent. Over a 2-year period, the anaerobic lagoon turned into an aerobic pond.

Barriers to Adoption

At present, hog farmers are not able to capture the value of the environmental benefits associated with the NDN system. Without this ability, the initial capital and installation costs (>$500,000) and the annual operation and maintenance costs (about $60,000) associated with the NDN system put it at a competitive disadvantage compared with the traditional anaerobic lagoon system. Other barriers for the adoption of the technology may include the potentially complex nature of the technology, which is unfamiliar to swine producers; the initial steep learning curve associated with its implementation and management; the necessary mental and time commitment on the part of the producers for the management of the system; and the uncertain markets for the separated solids.

The development of markets for environmental goods and services would significantly improve the farm-level economics of adopting the NDN system—at least for managing swine manure in the southern United States. Relative to anaerobic lagoon systems, the large reductions in methane emissions and nutrient content of the final effluent indicate that the most effective environmental markets would be for GHG emissions reductions and improvements in water quality.

The U.S. hog industry is dominated by contract production. Contract production is an arrangement where hog processors (contractors) engage with producers (growers) to take custody of the pigs and care for them in the producer's facilities. Contractors generally provide inputs for the producer, offer technical assistance, and are responsible for final processing and marketing. In 2004, 28% of all hog operations and 67% of all hog production (sales and removals) were covered by contract arrangements (USDA ERS, 2007). Contracts vary significantly in duration and in the incentives they offer farmers to increase productivity. As such, the structure of contracts could either encourage or discourage adoption of the NDN system for hog operations. Factors that would encourage adoption include incentives to reduce animal mortality, incentives to increase animal weight gain, provisions giving farmers the rights to environment benefits, and making the contract period long enough to allow producers to recover the capital and installation costs associated with adopting the NDN system. If the producer receives no benefits from reducing animal mortality or increasing animal weight gain, such as when farmers are paid a fixed price per animal received, the production benefits described above would not factor into a decision regarding adoption of the NDN system.

3.1.7.2 GHG Impacts

Data related to GHG emissions, air quality, water quality, and hog production from the NDN system were collected from December 2006 through February 2008. The data were similar to those collected at the same facility from December 2005 through February 2006, when a traditional anaerobic lagoon system was in operation. These two data sets were used to assess the relative environmental and production performance of the two systems. Each data collection period was 15 months and included three "all-in, all-out" hog production cycles (i.e., feeder pigs are brought in, fed up to slaughter weight, and shipped out for slaughter). The impacts described in this section were developed from these data sets.

GHG emissions associated with adoption of the NDN system include N_2O and CH_4 associated with on-farm manure-handling activities and indirect CO_2 emissions associated with the generation of purchased electricity. These emissions are summarized in Exhibit 3-62. Relative to the traditional anaerobic lagoon system, the NDN system reduced GHG emissions by more than 96%.

Exhibit 3-62: GHG Emissions from Anaerobic Lagoon and NDN Systems

Project Activity Using Aerobic Treatment (4,360-head swine operation)	Anaerobic Lagoon	NDN System	Net Reduction of Adoption
CH_4 Emissions (mt CO_2-eq/yr)	4,430	18	4,412
N_2O Emissions (mt CO_2-eq/yr)	542	135	407
Leakage Effect from Electricity Consumption (mt CO_2-eq/yr)			42
Total Net Emissions Reductions Due to Project Activity (mt CO_2-eq/yr)			4,777[a]
Net GHG Emissions Reductions per Pig (mt CO_2-eq/yr)[b]			1.1

Source: Vanotti et al. (2008).

[a] Total net emissions reductions due to project activity is calculated as 4,412 mt CO_2-eq/yr CH_4 emissions + 407 mt CO_2-eq/yr N_2O emissions – 42 mt CO_2-eq/yr leakage from electricity consumption.

[b] Net GHG emissions reduction per pig is calculated based as (4,412 mt CO_2-eq/yr CH_4 emissions + 407 mt CO_2-eq/yr N_2O emissions) / 4,360 head of swine.

3.1.7.3 Cost Profile

Exhibit 3-63 presents the costs associated with NDN systems.

Exhibit 3-63: Cost Profile for Swine Farms with NDN Systems

Parameter	Value
Farm Size (no. of finishing head places)[a]	6,000
Total Daily Manure Production per Head (lb VS/head/day)[b]	0.75
Capital Costs:[c]	
Waste Evacuation	$20,000
Solids Removal	$300,000
Soluble Nitrogen Removal	$180,000
Soluble Phosphorus Removal	$56,000
Total Capital Costs ($)	**$556,000**
Operations and Maintenance Cost[d]	
Electricity	$12,000
Maintenance	$10,000
All Other Costs	$36,000
Total Operations and Maintenance Costs ($)	**$58,000**

Parameter	Value
Lifetime (years)[e]	15
Volatile Solids (lb/day)	4,500
Potential Methane Generation Reduction (m^3)[f]	309,575
Potential Methane Generation Reduction (mt CO_2-eq)[g]	4,343

[a] For finishing operations with 6,000 head places, the annual production is 15,000 head.

[b] Volatile solids per head per day based on EPA (2009) Farmware 3.1: 0.9 lb TS and 0.75 lb VS/head per day for an animal of average finishing weight of 135 lbs.

[c] Capital costs and O&M costs (Campbell, 2011).

[d] Operations costs are based on average costs at demonstration farm in Clinton, NC (operational since 2007).

[e] Treatment systems are generally depreciated over 15 years. Life expectancy has not been confirmed.

[f] Annual methane generation, (m^3) = (4,500 lb/day) × (6.66 ft^3 methane/lb VS) × (0.0283 m^3/ft^3) × (365 days/yr).

[g] Methane Reduction (mt CO_2-eq) = (methane reduction, m^3) x (35.31 ft^3/m^3) x (0.0417 lb/ft^3) / (2,205 lb/mt CO_2).

3.1.7.4 Break-Even Prices

Exhibit 3-64 presents the break-even prices for installing a nitrification–denitrification system as a GHG mitigation practice by region. The costs for purchased electricity vary by region. This price reflects the level of carbon incentive, stated in 2010 dollars per metric ton of CO_2-eq mitigated, at which a representative farmer in a given region would view installing a nitrification–denitrification system from the given baseline management practice as economically rational (i.e., the point at which the net present value of the benefits of the practice equals the net present value of the costs). Given that the NDN system has been demonstrated only at swine farms in North Carolina, it is only considered a potential GHG mitigation technology in the Southeast, Delta, and Appalachia USDA production regions.

Exhibit 3-64: Break-Even Prices for Nitrification–Denitrification Systems as a Manure Management Practice

Existing Management Practice	Region	Break-Even Price (2010 $/ mt CO_2-eq)
Lagoon	Delta	$26
Lagoon	Appalachia	$26
Lagoon	Southeast	$27

3.2 Enteric Fermentation

Enteric fermentation, a process that occurs in livestock during digestion, produces methane (CH_4). All animals produce some CH_4 as a byproduct of digestion, but ruminants[22] produce much more than animals with other types of digestive systems.

Methane emissions from enteric fermentation vary across and within ruminant animal types. For example, feedlot (finishing) beef cattle each produce up to 200 liters of CH_4 per day (Beauchemin et al., 2008; Hales et al., 2011; Johnson and Johnson, 1995; McGinn et al., 2004), while lactating dairy cattle emissions can be as great as 590 liters of CH_4 per day (Crutzen et al., 1986; Holter and Young, 1992). Grazing beef cattle produce more CH_4 than finishing (confined) cattle, but less than lactating dairy cows (EPA, 2011c; Harper et al., 1999).

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[22] A ruminant is defined as, "any of various hoofed, even-toed, usually horned mammals of the suborder Ruminantia, such as cows (bovine), sheep (ovine), goats (caprine), deer, giraffes, and camels" (USDA, 2012). Ruminants have a four-chambered stomach: to fully digest food, they regurgitate and chew the partially digested food (cud) multiple times before it finally passes to the lower digestive system. Ruminants are primarily herbivores, and rely on the enteric fermentation process to digest tough plant materials. In contrast, monogastric animals (including humans) are not as well suited to digesting tough, fibrous plant materials.

This section presents the potential options for mitigating CH_4 emissions from enteric fermentation. However, farm-level adoption costs and break-even prices for these options are not presented because more research is needed to evaluate the potential GHG impacts of changes in diets, use of feed additives, and breeding. For example, changes in diets affect GHG emissions from manure management, as well as those from enteric fermentation.

This section provides brief reviews of several options that are often discussed in reference to reducing CH_4 emissions.

Enteric Fermentation Mitigation Options

- Modification of Diet Composition and Level of Intake:
  - Increasing Dietary Fat Content.
  - Providing Higher Quality Forage.
  - Increasing Protein Content of Feed.
  - Decreasing the Forage-to-Concentrate Ratio and Adding Supplemental Concentrates.
  - Processing/Grinding Feed.
- Monensin and Other Feed Additives
- Breeding for Increased Productivity and Decreased CH_4 Production

3.2.1 *Modification of Diet Composition and Level of Intake*

Diet modification is commonly viewed as a promising route to reducing CH_4 emissions from enteric fermentation. Feeds with lesser nutritional content require an animal to ingest more food for an equivalent nutritional benefit. Therefore, emissions are typically greater for animals eating lower quality feeds (including forage). Some of the modeled dietary modifications that have resulted in consistent decreases in emissions from enteric fermentation include increasing dietary fat (although limited to 8% of dry matter), providing higher quality forage,[23] increasing protein content of feed, increasing dry matter intake (DMI), increasing the forage-to-concentrate ratio, and using rapidly degrading starch (such as barley) rather than slowly degrading starch (such as corn) (Beauchemin et al., 2008; Benchaar et al., 2001; Benchaar et al., 1998; Hales et al., 2011; Lovett et al., 2003; Martin et al., 2010). Details about some of these potential dietary changes are provided below.

3.2.1.1 Increasing Dietary Fat Content

A number of studies indicate that supplemental fat can decrease enteric CH_4 emissions in ruminants. One review noted that enteric CH_4 emissions (proportional to DMI) decreased by more than 5% for each 1% increase in dietary fat (Beauchemin et al., 2008), while another study reported a decrease of a little less than 4% with each 1% increase in dietary fat (Martin et al., 2010). In one study, the total measured CH_4 emissions from steers decreased from 260 to 172 liters per day when 350 grams of coconut oil supplemented the baseline diet (which contained no coconut oil) (Lovett et al., 2003). This result was observed consistently, regardless of the dietary forage concentration. Although increasing dietary fat content can reduce enteric CH_4 emissions, ruminants do not respond well to high-fat diets. Hence, total fat content of the diet should be less than 8% of DMI (Hales et al., 2011). Dietary fat *additives* equivalent to less than 3% of DMI may be provided to livestock without negatively affecting ruminal fermentation processes (Knapp et al., 1991) as long as *total* dietary fat content remains less than 8%.

By supplementing daily rations with additional oils, fatty acids, or other lipid sources, producers can meet the energy requirements of their cattle while also reducing methane production by increasing the proportion of propionate produced in the rumen (Giger-Reverdin et al., 2003). For animals already receiving daily rations, adding oils to their diet creates no additional management requirements except those associated with ordering and distributing the oils.

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[23] Planting higher quality pastures would allow foraging animals to utilize a greater proportion of their feed energy, and thus decrease CH_4 emissions. However, this practice is a management-intensive option as it necessitates replanting pasture. Hence, it is less feasible than some of the other options presented here.

For cattle on forage, the applicability of providing additional dietary fat depends on the supplementation practices of the individual farm. For part of the year, ranges often do not provide sufficient nutrients for cattle. During these times, animal diets are supplemented with additional feedstuffs. Adding oils to these supplements would require only moderate effort. Most of the year, however, producers generally do not supplement the diets of range cattle. Providing oils during these times would constitute a major change in grazing management practices. If lipid-containing feeds could be reformulated into blocks, field supplementation of fats might be more feasible.

Although oils containing medium-chain fatty acids (8–16 carbons), such as coconut oil, palm kernel oil, and high-laurate canola oil (Machmuller et al., 2003), have shown great promise, they are relatively expensive and are unlikely to be a cost-effective mitigation strategy from either a farm or policy perspective (Beauchemin et al., 2008; Grainger et al., 2008).

3.2.1.2 Increasing Protein Content of Feed

Increasing crude protein content of feed will result in improved digestibility. Any increase in the quantity of food that can be processed by an animal (as opposed to undigested roughage passing through the animal) results in chemical processes that generate CH_4. Therefore, enhancement of the ratio of crude protein in low-quality forages will increase CH_4 emissions proportionally to the improvement in digestibility. However, overall methane emissions per unit of product would be decreased (Birkelo et al., 1986). Firkins et al. (1991) indicate that the improvement in 24-hour digestibility of cellulose ranges from 3–25% as different protein supplements are added, with the greatest improvement achieved when the supplement is urea (non-protein nitrogen), which is the preferred nitrogen substrate of cellulose-digesting ruminal bacteria (Russell et al., 1992). Most ruminant diets are not protein limited. In fact, many of the diets currently fed in the dairy and beef cattle industries are too high in protein, leading to higher levels of nitrogen in animal manure. The exception to this situation might be beef cattle grazing poor-quality range or stockpiled forage in the late fall and winter. In this case, the addition of protein (or nitrogen in the form of non-protein nitrogen (NPN)) could enhance the efficiency of ruminal fermentation and enhance animal performance. However, this would constitute a major change in grazing management practices.

3.2.1.3 Decreasing the Forage-to-Concentrate Ratio and Adding Supplemental Concentrates

The concentration and form of roughage in the diet will affect both enteric and manure CH_4 production. Generally speaking, increasing the concentration of forage will increase CH_4 emissions due to enteric fermentation, as reported in multiple studies. One study found that daily CH_4 emissions from enteric fermentation were 230 grams per animal in foraging animals, but were only 70 grams from cattle on diets high in concentrates (Harper et al., 1999). Another study indicated that CH_4 emissions from carbohydrate substrates in a concentrate diet with ruminal pH variation and a pH of 6.5 ranged from 2.11 grams of CH_4 per kilogram of food intake (g/kg) for starch to 3.10 g/kg for cellulose (Dijkstra et al., 2007). Another study confirming these results, this time for dairy cows, found that the animals emitted more CH_4 when the forage-to-concentrate ratio was increased from 47:53 to 68:32 (i.e., forage increasing from 47% of feed content to 68% of feed content) (Aguerre et al., 2011). Similarly, Hindrichsen et al., (2006) found that adding supplemental concentrates to diets resulted in an 18% decrease in CH_4 emissions from enteric fermentation.

Hindering the potential for this mitigation options is the fact that cattle in feedlots in the United States already receive a high level of concentrates in their rations, and are thus less likely to experience further improvements. Additionally, foraging cattle would require intensive management and replanting of range areas, which is likely to be cost-prohibitive.

3.2.1.4 Processing/Grinding Feed

Processing feed or forage into pellets or coarsely grinding it can reduce CH_4 emissions (Ferket et al., 2002). The decreased fiber digestibility, decreased availability of organic matter, and increased rate of passage through the digestive system may all help reduce CH_4 emissions associated with enteric fermentation. The application of this option, however, is likely limited. If cattle diets are processed too finely, the decrease in fiber content may increase the incidence of the rumen disorder acidosis. Additionally, dairy and feedlot operations already formulate and process animal diets to optimally meet the nutrition needs of their cattle. There may be some opportunities to apply this option to foraging cattle as pelleting or coarsely grinding forage has not been shown to increase the incidence of acidosis (Boadi et al., 2004).

3.2.2 Monensin and Other Feed Additives

Monensin (trademark name Rumensin®) is an antibiotic that functions in the rumen by inhibiting specific bacteria. Its primary use in livestock agriculture is to aid in prevention of coccidiosis, an intestinal infection caused by protozoa. It works to prevent this infection by increasing production of propionic acid, which is linked with decreased CH_4 emissions from enteric fermentation. It has been shown to both increase productivity and provide an average decrease in CH_4 emissions of 18% (Van Nevel and Demeyer, 1996); the observed range of emissions reduction is 10–30% (Boadi et al., 2004).

Monensin is currently used extensively in conventional dairy and feedlot operations, and has been in use since its introduction in the 1970s (but only in lactating dairy cows since its approval in 2004) (Hamilton and Mitloehner, 2008). Additionally, it is present in some supplements that are provided to grass-fed beef cattle. Currently, only the organic and the newly coined "naturally raised" programs specifically prohibit the use of monensin, although some countries prohibit the use of monensin and therefore the importation of products from cattle that have used monensin.

Although data indicate that monensin results in a decrease in CH_4 emissions from enteric fermentation, there is not a full understanding of the long-term effect of monensin use on CH_4 production. There are data to suggest that despite the sustained increase in propionate, methane production returns to close to non-supplemented levels after as little as 30 days of use (Guan et al., 2006). Several long-term studies have also observed that the decrease in emissions is short-lived (approximately 6 weeks according to these particular studies), and then emissions generally return to baseline levels (Boadi et al., 2004). However, another study reported that monensin decreased emissions by 7–9% for as long as 6 months (Odongo et al., 2007).

At least one study noted that the daily CH_4 production of cattle fed no antibiotics or growth promoters were similar to cattle fed in more traditional systems that use these supplements. However, cattle in the traditional systems (those that use antibiotics and growth promoters) had greater average daily weight gain, and took 42 fewer days to reach the same mature body weight so had a shorter life cycle in which to produce GHG emissions. Therefore, the GHG emissions of cattle fed using modern growth technologies were 31% lower per head (Cooprider et al., 2011).

Regarding other potential supplements:

- At least one study has indicated that adding condensed tannins to cattle diets can decrease enteric CH_4 production by 13–16% (Eckard et al., 2010).
- While bovine somatotropin (bST) is not known to decrease methane emissions, it does increase milk production, thus decreasing emissions per unit of milk product (EPA, 2006b). However, bST has already been used extensively in the dairy industry, and is, in fact, becoming less widely used due to public concern about the use of hormones in dairy cows; it is therefore not likely to be a viable option. It should also be noted that the use of bST has been banned in the European Union, Canada, New Zealand, and Japan, as well as several other countries (ChemEurope, 2012).

3.2.3 Breeding for Increased Productivity and Decreased Methane Production

Cattle have shown genetic predispositions for both increased productivity and decreased methane production. It is hypothesized that these two traits are linked, and by selectively breeding for these traits, cattle producers can further increase productivity while simultaneously decreasing methane production within their herds. However, there are many uncertainties still to be resolved before this option can be considered viable. Even once it has been accepted as an effective strategy, it will likely take several generations to reach peak effect, and the genetic marker and tests for methane production are still under development. This option shows promise for future research, but the ultimate success as a mitigation strategy still depends on methane reduction being heritable (Boadi et al., 2004).

3.3 Grazing Land Management

In this report, grazing land refers to rangeland and pasture as defined by the USDA National Resources Inventory (2009). Grazing land can be divided into two subgroups: rangeland and pasture (see textbox). In the United States, the majority of grazing land is not federally managed (see Exhibit 3-66). The 2007 USDA ERS Major Uses of Land in the United States report estimates that there are 612 million acres of grassland pasture and rangeland in the lower 48 states[24] (Nickerson et al., 2011).

Grazing lands provide ecosystem services, such as the maintenance and improvement of soil and water resources, air quality, wildlife habitat, and aesthetics. Grazing lands filter melting snow, rainfall, and runoff for nearby communities and ecosystems. In addition, rangelands provide society with clean water, a safe food supply, and access to various cultural services (e.g., recreation, open space, vistas) (Havstad et al., 2007). Management of grazing land can influence emissions of CO_2, CH_4, and N_2O. Grazing land management can also influence soil organic carbon (SOC) storage by modifying carbon inputs to the soil, including net primary production, root turnover, and carbon allocation between roots and shoots (Conant et al., 2001). Long-term changes in production and the quality of aboveground/belowground biomass have the potential to alter available nitrogen and the carbon-to-nitrogen ratio of soil organic matter (SOM) (Pineiro et al., 2010).

Definition of Terms

- **Rangeland:** Plant cover is composed principally of native grasses, grasslike plants, forbs, or shrubs suitable for grazing and browsing, and introduced forage species managed in an extensive manner.
- **Pasture:** Used for the production of introduced forage plants for livestock grazing, pasturelands may consist of a single species in a pure stand, a grass mixture, or a grass-legume mixture. Management may include cultural treatments, fertilization, weed control, reseeding or renovation, and control of grazing.

Source: USDA (2009).

Exhibit 3-65: Cattle on Grazing Land

Source: Wilson (2006).

Continuously grazed, unimproved pastures and rangelands are the least management-intensive agricultural systems and the status quo used for most grazing land in the United States. Grazing intensity and input intensity affect soil carbon stocks. Carbon flux in pastures and rangelands also depends on factors such as soil type, rainfall, species composition, rooting patterns, litter quality, and crop rotation history (only applicable to

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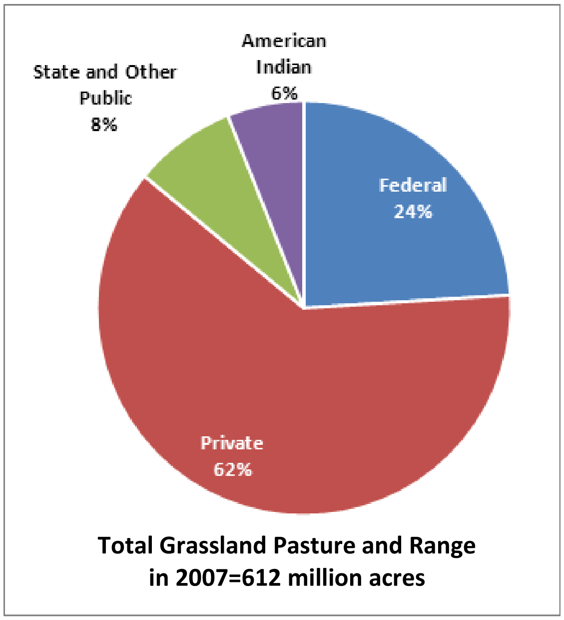
[24] Open permanent pasture and range, both on farms and not on farms, excluding cropland pasture.

pastures) (Ogle et al., 2010). Conant et al. (2001) found that, on average, across climates and regions, management improvements such as irrigation, fertilization, improved grazing, land-use conversion (native to pasture and cultivation to pasture), introduction of legumes, earthworm introduction, and improved grass species led to increases in net soil carbon storage (See Exhibit 3-67).

Grazing impacts on vegetation composition can be as important as the direct impacts of the grazing intensity for SOC levels in rangelands (Derner and Schuman, 2007). Few studies have been conducted to thoroughly quantify GHG emissions and sinks related to grazing intensity and input intensity. In a study by Briske et al. (2008), the majority of studies analyzed (82 out of 93) show that continous grazing has similar or higher animal production per head and plant production compared with rotational grazing. Other studies indicate that stocking rates, effective management, and precipitation are the key factors affecting carbon sequestration rates for grazing lands instead of the specific system of grazing (Briske, 2011; Conant et al., 2001; Derner and Schuman, 2007; Franzluebbers and Stuedemann, 2010; Liebig et al., 2012). Variability in the data are often due to differences in research objectives, approaches, and differences in scale. Despite this variability, it is clear that stocking rate and effective livestock distribution[25] are the most important management variables affecting forage production and soil conservation in grazing land systems (Briske, 2011). Other grazing land management practices fall into the input intensity category (e.g., legume interseeding, irrigation, fertilization, silvopasture).

Exhibit 3-66: U.S. Grassland Pasture and Range[a] Ownership[b] in the Lower 48 States, 2007



[a] Open permanent pasture and range, both on farms and not on farms, excluding cropland pasture.
[b] Federal includes reserved forestland in parks and other special uses.
Source: Nickerson et al. (2011).

In determining which grazing practices have the most GHG mitigation potential, a number of studies were consulted. Conant et al. (2001) conducted a meta-analysis spanning 17 countries, and summarized the carbon sequestration potential as indicated in Exhibit 3-67. Relatively few pastures or rangelands are irrigated. Conant et al., (2001) found that irrigation on pastures resulted in carbon sequestration levels of 0.16 mt CO_2-eq $ac^{-1}yr^{-1}$. This study did not, however consider input requirements for pumping water, and other studies have noted the potential for additional CO_2 emissions resulting from dissolved CO_2 in irrigation water. This dissolved CO_2 can change the soil inorganic carbon (SIC) dynamics, precipitating calcium carbonate that is either released or leached into the soil profile (Eagle et al., 2012). Rangeland fertilization is also relatively uncommon; on the other hand, pasture fertilization is relatively common (e.g., broiler manure application on pastures in the Southeast). Fertilization has been shown to generate soil organic carbon gains averaging 6.1 kg of carbon for every kilogram of nitrogen applied (Conant et al., 2001).

Legume interseeding, or managing the species composition on grazing land, is a promising grazing land GHG mitigation option (CAST, 2011; Conant et al., 2001; Eagle et al., 2012; Liebig et al., 2010b). Additionally, cost data and carbon sequestration estimates are available to allow the estimation of break-even prices for this practice. Consequently, this practice is described in Section 3.3.1. Qualitative descriptions of other grazing land practices are described in Section 3.3.2.

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[25] Livestock distribution refers to practices that are a means of managing the intensity of livestock grazing, such as placement of water developments, supplements, and herding (Briske, 2011).

Exhibit 3-67: Mean Carbon Sequestration Rates and Number of Data Points from Existing Studies, by Grassland Management Practice

Management	Data Points	Carbon Sequestration (mt CO_2-eq $ac^{-1}yr^{-1}$)
Irrigation	2	0.16
Fertilization	42	0.45
Improved Grazing	45	0.52
Conversion: Native to Pasture	42	0.52
Conversion: Cultivation to Pasture	23	1.50
Introduction of Legumes	6	1.11
Earthworm Introduction	2	3.49
Improved Grass Species	5	4.51

Adapted from Conant et al. (2001).

3.3.1 Legume Interseeding

3.3.1.1 Technology Characterization

Legume forages (e.g., red alsike, ladino clover, alfalfa, crown vetch, birdsfoot trefoil) fix nitrogen from air and make it available in soil for plant growth. They also provide a good protein source for grazing animals. With legume interseeding, legume seeds are incorporated or spread into existing cover. Interseeding can increase species diversity in warm- and cool-season plant communities. Legumes are commonly mixed with cool-season grasses, such as orchardgrass, timothy, and redtop, but because legumes tend to be shorter lived than grasses, they are frequently interseeded into established grass stands to maintain the legume presence.

Legumes can be planted with forbs or into established stands of warm-season grasses (e.g., little bluestem, indiangrass, switchgrass, sideoats grama) instead of being incorporated into the initial planting. This practice gives the slower growing warm-season grasses a better opportunity to become established before the faster growing legumes are introduced (Indiana Department of Natural Resources, 2005). Legume interseeding can be used in both pasture and rangeland (Mortenson et al., 2004; Mortenson et al., 2005), although rangelands in drier areas may require special attention to legume species selection to ensure interannual survival and propagation (Hendrickson et al., 2008; Mortenson et al., 2005).

Interseeding of legumes can be categorized under Forage and Biomass Planting (Code 512) in the NRCS conservation practice standard (USDA NRCS, 2010b). Specific criteria considered in the

Key Features of Legume Interseeding

- Legumes typically do better in cool, moist climates.
- Mowing, disking, herbicides, or burning to reduce existing stand height and intensity can increase germination of the seeds (Indiana Department of Natural Resources, 2005).
- Any size operation would benefit from legume interseeding.
- All regions are applicable; however, care must be taken to select plant species that are appropriate based on the climate conditions, soil conditions, and disease resistance.

Exhibit 3-68: Cow Grazing on Birdsfoot Trefoil

Source: NRCS Photo Library (Smith, 2001).

standard for forage and biomass planting include improving and maintaining livestock nutrition and health, providing or increasing forage supply during periods of low forage production, reducing erosion and improving water quality, and producing feedstocks for biofuel or energy production.

In general, increases in soil carbon stocks are more likely if legumes are interseeded in degraded grazing lands, but responses are highly location-specific (Pearson et al., 2010). Legume seed may also be planted by broadcast, drilling, or frost seeding (Mortenson et al., 2004; Mortenson et al., 2005). The latter is a technique where freeze–thaw cycles in late winter/early spring serve to naturally work the seed into the soil. Use of mowing, disking, herbicides, or burning to reduce existing stand height and intensity can increase the rate of seed germination (Iowa State University Extension and Outreach, 2012). The majority of management practices that are employed to increase forage production in pasture systems tend to increase soil carbon stocks by increasing the amount of carbon returned to the soil. However, increased production is also accompanied by increased ecosystem respiration. Whether this results in a net carbon gain or loss will vary by region, climate, and site-specific factors. In general, planting nitrogen-fixing legumes has been shown to promote carbon sequestration in grassland soils and may therefore provide an alternative to nitrogen fertilization with a lower overall GHG footprint (CAST, 2011; Conant et al., 2001; Liebig et al., 2010b; Mortenson et al., 2004).

Exhibit 3-69: Interseeded Legumes and Native-Only Mixed Grass in Southwest North Dakota

Source: USDA ARS (2005).

Current and Potential Adoption

Frost interseeding is the simplest interseeding method. Aggregate data for grassland pasture and range[26] in the United States (excluding Alaska and Hawaii) were gathered from the USDA's Major Uses of Land in the United States, 2007 (Nickerson et al., 2011). No readily available data are currently available on the number of acres where legume interseeding is practiced. Consequently, all Federal and non-Federal grazing land in the lower 48 States is considered applicable for frost interseeding of legumes as summarized in Exhibit 3-70. Grazing land will be affected by climate change and increasing CO_2 levels will likely alter forage quality, making interseeding of legumes more attractive where nitrogen is limited (Izaurralde et al., 2011).

Exhibit 3-70: Grassland Pasture and Range by USDA Production Region[a]

Region	million acres
Appalachia	10.6
Corn Belt	16.4
Delta	7.2
Lake States	7.5
Mountain	303.4
Northeast	4.6
Northern Plains	74.8
Pacific	57.0
Southeast	10.3
Southern Plains	120.4
Total Grassland Pasture and Range[b]	**612.2**

[a] Lower 48 States only.

[b] Open permanent pasture and range, both on farms and not on farms, excluding cropland pasture.

Source: Nickerson et al. (2011).

Production Impacts. Legume interseeding can increase soil nitrogen due to nitrogen fixation; this, in turn, increases soil fertility and decreases need for synthetic inputs (USDA NRCS, 2010b). However, nitrogen use efficiency and nitrogen availability during periods of plant growth could be a problem. Legume interseeding increases forage production (Mortenson et al., 2004), improves livestock

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[26] Open permanent pasture and range, both on farms and not on farms, excluding cropland pasture.

nutrition and health, and produces feedstock for bio-fuels (USDA NRCS, 2010b). However, few studies exist that assess the level of economic benefits for this practice.

Other Environmental Impacts. Legumes can be an important wildlife habitat because they increase the nutritive, vegetative, and structural diversity of the ecosystem (Indiana Department of Natural Resources, 2005). In addition, legume interseeding can reduce erosion by wind and/or water, improve water quality and quantity, and increase soil carbon sequestration (Briske, 2011).

Barriers to Adoption

Potential barriers to interseeding of legumes generally include the costs of machinery, herbicide and fertilizer inputs, seed, labor, and maintenance. Labor constraints and lack of extension information may also limit implementation of legume interseeding (Pearson et al., 2010).

3.3.1.2 GHG Impacts

Considerable variability exists in calculations of the carbon sequestration potential of legume interseeding, with estimates ranging from 0.07 to 1.26 mt CO_2-eq $ac^{-1}yr^{-1}$ (Conant et al., 2001; Follett, 2001; Liebig et al., 2010b; Lynch et al., 2005; Mortenson et al., 2004). The estimated potential carbon sequestration range is largely based on the limited number of studies that have been conducted, each of which was performed under different objectives, environmental conditions, and management conditions. For this study, the values of 0.07 and 1.26 mt CO_2-eq $ac^{-1}yr^{-1}$ are used to assess a low and a high carbon sequestration scenario. While legume interseeding has been observed to increase total plant–soil system carbon sequestration, it has also been shown in some studies to increase N_2O emissions, although results are mixed (Rochette et al., 2004).

3.3.1.3 Cost Profile

Cost profiles were estimated for a set of representative farms for adopting frost seeding of legumes. The profiles include capital costs, recurring costs, and labor costs. This practice entails one or more legumes being broadcast on established grazing land in late February or March. The subsequent freezing, thawing, and rain cycles incorporate the seeds and provide coverage (Iowa State University Extension and Outreach, 2012). The key steps and assumptions for estimating costs are summarized below:

- Labor costs are based on USDA NASS labor statistics (USDA NASS, 2011).
- Total costs are the sum of initial fixed and variable costs per acre for frost seeding of legumes (Iowa State University Extension and Outreach, 2012).
- Soil test costs and annual operation and maintenance costs are based on State-level data (USDA NRCS, 2010a). Costs are constructed to reflect a range of adoption costs rather than to be applicable to any specific location.
- The expected lifetime of legume interseeding is 5 years (i.e., the seeds are planted in year 1 and are expected to last 5 years) (Iowa State University Extension and Outreach, 2012).

The literature indicates that weed control, fertilization, and grazing management facilitate the establishment of seedlings (Indiana Department of Natural Resources, 2005; Iowa State University Extension and Outreach, 2012). To reflect the range of the different soil pH level and nutrient needs across regions, two management intensity scenarios are evaluated. The high-intensity legume interseeding incorporates the costs for lime, potash, and phosphorus amendments. The low-intensity legume interseeding scenario includes only the costs for machinery, seed, and labor.

Exhibit 3-71: Capital Cost Breakdown for Legume Interseeding (Frost Seeding Method)

Parameter	Unit	High-Intensity Initial Cost (2010 $/ acre)	Low-Intensity Initial Cost (2010 $/acre)	Data source
High Carbon Sequestration Potential	mt CO_2-eq $ac^{-1}yr^{-1}$	1.26	1.26	High input (Mortenson et al., 2004)
Low Carbon Sequestration Potential	mt CO_2-eq $ac^{-1}yr^{-1}$	0.07	0.07	Low input (Liebig et al., 2010b)
Capital Costs				
Machinery (e.g., spray herbicide, leased interseeder or broadcast seeder, spreading fertilizer, clipping weeds)	$/acre	$21.85	$21.85	Iowa State University Extension and Outreach (2012)
Soil Test (Cost List Component 689)	each	$13.30	$0.00	USDA NRCS (2010a)
Lime application at 1.81 mt/acre	acre	$45.38	$0.00	Iowa State University Extension and Outreach (2012)
Phosphorus application rate at 50 lb/acre	acre	$30.40	$0.00	Iowa State University Extension and Outreach (2012)
Potash application rate at 30 lb/acre	$/acre	$15.68	$0.00	Iowa State University Extension and Outreach (2012)
Herbicide	$/acre	$9.35	$0.00	Iowa State University Extension and Outreach (2012)
Seed–Birdsfoot trefoil and red clover (8 lb)	$/acre	$40.14	$40.14	Iowa State University Extension and Outreach (2012)
Labor (farm wage)	$/hour	$10.74	$10.74	USDA NASS (2011)
Total Capital Costs		$186.83	$72.73	Calculated
Annual Operations and Maintenance Percentage	per year	2%	2%	USDA NRCS (2010a)
Recurring Costs		$3.74	$1.45	Calculated

3.3.1.4 Break-Even Prices

Estimated break-even prices for frost interseeding of legumes (in $/mt CO_2-eq mitigation) are provided in Exhibit 3-72. Break-even prices are estimated for high- and low-intensity legume interseeding and for high and low carbon sequestration values to illustrate the wide range of break-even prices across the various regions and climates. The break-even prices are based on 5-year time horizons.

Exhibit 3-72: Break-Even Price for Legume Interseeding[a]

Carbon Sequestration Potential	High-Intensity Initial Cost	Low-Intensity Initial Cost
	Break-Even Price (2010 $/mt CO_2-eq)	Break-Even Price (2010 $/mt CO_2-eq)
High	$38	$15
Low	$657	$256

[a] Applicable to all grazing land and all farm sizes in the United States.

3.3.2 Qualitative Assessment of Other Potential GHG Mitigation Options for Grazing Lands

3.3.2.1 Rotational Grazing

Rotational grazing is a system where the land to be grazed is separated into sections—or paddocks—and the livestock are moved among the paddocks at intervals ranging from days up to a year (Briske et al., 2008; Smith et al., 2011). Rotational grazing can be as simple as moving cattle between two pastures, with each pasture grazed for a number of months throughout the year. There is considerable variability among rotational grazing systems, including differences in stocking density, number of herds, length of grazing period, length of rest, and grazing management tactic. Exhibit 3-73 presents an overview of some of the grazing systems that have been implemented on rangelands and their associated characteristics.

Exhibit 3-73: Characteristics of Basic Rotational Grazing Systems Implemented on Rangelands

Grazing System	Stock Density	No. of Herds	Length of Grazing	Length of Rest	Tactic
Deferred Rotation	Moderate	Single	Long	Moderate	HPG[a]
Rest Rotation	Moderate	Multiple	Long	Short	HUG[b]
Rest Rotation	High	Single	Short	Long	HPG
High Intensity-Low Frequency	High	Single	Moderate	Moderate	HUG
Short Duration	High	Single	Short	Moderate	HPG

[a] High-performance grazing (HPG) targets selective grazing of preferred plants.

[b] High-utilization grazing (HUG) targets heavy utilization of both preferred and non-preferred plants

Source: Briske et al (2008).

The GHG mitigation potential of rotational grazing is not well established. Studies have yielded only rudimentary and fragmentary results in few locations. In a majority of studies, plant and animal production in continuous grazing has been shown to be equal to or greater than that in rotational grazing systems (Briske et al., 2008). Considerable planning is required to set up and maintain an effective rotational grazing system. Rotations based simply on timing and not accounting for pasture growth rates and other on-the-ground conditions may result in overgrazing. A successful rotational grazing system is dependent upon the number of paddocks, stocking rate, climate and soil type, and human management (Briske et al., 2008; Briske et al., 2011). Rotational grazing research in Virginia demonstrated a SOC sequestration rate of 0.25 mt C $ac^{-1}yr^{-1}$ over a 14-year period (Liebig et al., 2012). However, very few studies have demonstrated similar or consistent results.

Stockpiling or grass banking is a variation of rotational grazing. Stockpiling occurs when livestock are excluded from an area during a portion of the forage growth season, usually late summer and fall. Later in the season, the accumulated forage is grazed by strip grazing to allow livestock to graze within the strip for a specific amount of time. This can extend the grazing season in highly productive regions and improve manure distribution (USDA NRCS, 2010b). Rotational grazing systems are most often used for cattle, but can also be used for sheep and other livestock.

Rotational grazing is employed to keep forage in a vegetative stage instead of allowing it to enter a reproductive stage, thereby maintaining the forage quality at a higher level longer into the growing season. USDA data (USDA NASS, 2008) indicate that about 388,000 farms in the United States currently employ rotational or intensively managed grazing systems. The USDA census groups rotational grazing and management-intensive grazing into one category, but the two practices are not necessarily the same.[27] Individual data for each practice were not available, so the grouped data are presented as a best estimate for current practice. Due to data uncertainty, potential adoption is not presented for rotational grazing. As is illustrated in Exhibit 3-74, the majority of rotational grazing or management-intensive grazing takes place in the Southern Plains and Appalachia. Pasture is often the preferred type of land for rotational grazing.

Exhibit 3-74: Farms Practicing Rotational or Management Intensive Grazing

Region	No. of Farms
Appalachia	63,821
Corn Belt	58,339
Delta	19,225
Lake States	27,475
Mountain	33,480
Northeast	28,646
Northern Plains	34,021
Pacific	26,382
Southeast	29,638
Southern Plains	66,952
Total	387,979

Source: USDA NASS (2008).

Stocking rate plays a critical role in the response of soil organic carbon in grazing land. In a study by Derner et al. (2006), SOC increased in grazed areas compared with ungrazed areas on the shortgrass prairie, due partially to increasing dominance of shallow-rooted, grazing-resistant plant species (e.g., blue grama, *Bouteloua gracilis*) that concentrate larger amounts of root mass in the upper soil when compared to other mixed-grass species. A similar phenomenon occurrs in the northern mixed-grass prairie, where blue grama is increasingly dominant with moderate to heavy grazing, and soil carbon is more concentrated in the upper soil profile (Schuman et al., 1999). If stocking rates are higher than the optimum for achieving maximum livestock production per unit land area, a corresponding loss of SOC due to reduced plant vigor and root distribution in the soil profile is likely to result (Dunn et al., 2010; Ingram et al., 2008). In addition, suboptimal stocking rates may allow plant residues to develop a thick litter layer at the soil surface, which can reduce forage growth (LeCain et al., 2000). N_2O emissions from grazing land are affected by grazing and can be managed by adjustments to stocking rate and season (Allard et al., 2007). Stocking rate played a minor role in N_2O emissions on North Dakota mixed-grass prairie (Liebig et al., 2010a), but has the potential to counteract potential nitrogen-induced emissions on rangelands by reducing surface biomass, resulting in more extreme soil temperatures, lower soil moisture, and inhibition of microbial activity responsible for N_2O emissions (Wolf et al., 2010).

3.3.2.2 Fertilization

While fertilization increases the net primary productivity of grazing land aboveground and belowground, it also increases ecosystem respiration, thereby offsetting a portion of the soil carbon gains (Kahn et al., 2007). Additionally, a large portion of the soil carbon storage increase from synthetic fertilization (from 0.15 to 2.37 mt CO_2-eq $ac^{-1}yr^{-1}$) can be offset by increases in N_2O and reduced uptake of CH_4. N_2O emissions from fertilizer application (calculated using the IPCC methodology) would increase by 0.28 t CO_2-eq $ac^{-1}yr^{-1}$ if 250 kg of nitrogen fertilizer were applied, and upstream emissions from fertilizer production would amount to 0.36 mt CO_2-eq $ac^{-1}yr^{-1}$ (Eagle et al., 2012). A study by Liebig et al. (2010b) found that 79% of soil carbon accumulated under fertilized crested wheatgrass was offset by N_2O emissions.

Depending on the application method, increased fertilization using organic fertilizers may not be as N_2O-intensive as synthetic fertilizers (Denef et al., 2011). Manures and other organic fertilizers also increase net primary productivity in grazing lands, although quantification is difficult as a result of the variability in carbon contained in the manures. Studies have indicated that carbon sequestration rates are similar with inorganic and organic fertilizer application (Conant et al., 2001). The addition of nitrogen to grazing lands has been shown to suppress CH_4 uptake and increase N_2O emissions (Liebig et al., 2005). Given fertilization's limited net GHG emissions reduction potential, it was not quantitatively analyzed in this report.

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[27] Rotational grazing is a system that employs more than one pasture and livestock are moved from one pasture to another based on feed requirements and forage growth. Management-intensive grazing is a system wherein large fields are divided into smaller paddocks and animals are moved frequently at high stocking rates (Heckman et al., 2007).

3.3.2.3 Irrigation

Water is of particular importance in the American Southwest, where most grazing land is considered rangeland. The lack of rainfall in this region promotes the accumulation of soluble salts and carbonate in the soil profile. Arid and semi-arid soils therefore contain large amounts of soil inorganic carbon (SIC) that could mitigate some of the carbon being released to the atmosphere by biological processes—although SIC accrual is an extremely slow process (Martens et al., 2005). Soils in arid and semi-arid regions are more likely to emit CO_2 following low pH rainfall events via $CaCO_3$ dissolution (Emmerich, 2003). In addition, the capital costs involved in irrigation can range from $43/acre to $145/acre (Hogan et al., 2007).

Irrigation is most effective as a carbon sequestration strategy in water-limited (i.e., semi-arid) climates. However, evidence suggests that irrigation can decrease soil carbon storage by stimulating the decomposition of organic matter through enhanced microbial activity (Denef et al., 2011). Irrigation can also lead to increased N_2O and CH_4 emissions (Pearson et al., 2010), along with increases in fuel use for pumping, which offset soil carbon gains (Eagle et al., 2012).

Irrigation water affects SIC dynamics, and often contains 1% dissolved CO_2. Up to 0.19 mt C $ac^{-1}yr^{-1}$ can be released back into the atmosphere as CO_2 (Martens et al., 2005). In other studies, however, irrigation allows for greater root respiration and leaching of SIC deeper in the soil profile, contributing to the passive carbon pool (Martens et al., 2005). Studies on the carbon sequestration potential of irrigating grazing land have yielded dissimilar results, ranging from zero to 1.19 mt CO_2-eq $ac^{-1}yr^{-1}$, indicating that variability of land management and spatial conditions likely play a significant role (Eagle et al., 2012; Martens et al., 2005).

3.3.2.4 Silvopasture

Silvopasture, a type of agroforestry, involves planting trees on grazing land. Silvopasture systems were shown to have direct near-term carbon storage benefits in trees and soils, and have the potential to offset GHG emissions from deforestation and shifts in agriculture (Dixon, 1995). Sharrow and Ismail (2004) found that silvopastures were more efficient at carbon sequestration than plantations or pasture monocultures, but that nitrogen accumulation was more efficient in pastures than agroforests or plantations. Carbon sequestration potential for silvopasture ranges from 0.19 to 1.12 mt CO_2-eq $ac^{-1}yr^{-1}$ in a literature review conducted by Eagle et al. (2012). Consequently, while silvopasture holds the potential to sequester carbon in the soil and in aboveground biomass, more studies are needed to quantify the full range of GHG impacts.

3.4 Summary of Break-Even Prices for Animal Production Systems Mitigation Options

This chapter on potential GHG mitigation practices for animal production systems is divided into manure management, enteric fermentation, and grazing land management. The break-even prices for implementing the animal production mitigation options are included in Appendix 3-E and are based on data from EPA's AgSTAR program, American Society of Agricultural and Biological Engineers (ASABE), U.S. GHG Inventory data, and industry sources. The break-even price estimates reflect currently available data, are subject to market fluctuation, and will change over time. These break-even prices represent the carbon incentive level at which a given GHG mitigation option becomes economically viable to the farmer (i.e., the point at which the net present value of the benefits equals the net present value of the costs). Certain mitigation practices are more cost-effective due to a number of variables, including the system in place, the size of the farm, the geographic location of the farm, and the animal type. Mitigation options for enteric fermentation are explored qualitatively.

Manure Management

Manure management mitigation options consist of covered lagoon anaerobic digesters, complete mix digesters, plug-flow digesters, covering existing anaerobic storage facilities (i.e., ponds, tanks, or lagoons), improved separators, and nitrification–denitrification systems. The break-even price for a particular mitigation system depends on the current manure management practice being used on the farm. Liquid/slurry systems produce less methane than anaerobic or deep pit systems do; thus, the total mitigation potential is lower.

Livestock operations of sizes greater than 2,500 head have lower break-even prices per metric ton of CO_2, regardless of the type of animal, because the capital cost to install new equipment is spread over more animals. Swine and dairy cow operations have the largest number of mitigation options available due to current manure management methods and the form in which the manure is collected.

For covered anaerobic lagoons, plug flow digesters, covering an existing lagoon and, in some instances, for complete mix digesters, the Southeast, Delta, and Southern Plains regions generally have the largest potential for reducing GHG emissions. Current manure management practices emit more methane in warmer regions than in cooler regions, resulting in a greater potential for GHG reductions and a corresponding lower break-even price. In addition to the difference by production region, transitioning from anaerobic lagoons has a greater GHG reduction potential than transitioning from other current practices.

Transitioning from current manure management practices to digester systems with electricity generating potential on large swine and dairy farms is the most cost-effective of all animal production system mitigation options. The methane production per pound of volatile solids from swine is more than that of dairy cows, so swine systems generally have lower break-even prices compared with dairy systems.

Key Findings

- Digester technologies (and other capital-intensive manure management systems) have been demonstrated at scale. These systems could be cost-effective GHG mitigation options for many confined animal operations, particularly dairy and swine operations:
  - Break-even prices for large operations were generally <\$50/mt CO_2-eq.
  - Break-even prices for medium size operations were generally <\$100/mt CO_2-eq.
- Accounting for co-products (e.g., mulch, bedding, off-farm sale of electricity/natural gas) could significantly lower the break-even prices presented in this report.
- Break-even prices for covering anaerobic lagoons and flaring the biogas, and installing improved solids separators show that relatively small livestock operations have significant GHG mitigation opportunities at CO_2 prices generally <\$50/mt CO_2-eq.

Enteric Fermentation

Emissions from enteric fermentation are highly variable and dependent on livestock type, life stage, activity, and feeding situation (e.g., grazing, feedlot). Several practices demonstrate the potential for efficacy in reducing emissions from enteric fermentation. Although diet modification (e.g., increasing fat content, providing higher quality forage, increasing protein content) and providing supplements (e.g., monensin, bovine somatotropin (bST)) have been evaluated for mitigation potential, each option presents its own barriers and apparent inconsistencies in effectiveness. For example, the efficacy of monensin in mitigating emissions is still not fully understood; the magnitude of reductions varies among peer-reviewed studies (and between animal type and living/feeding conditions), and several studies indicate that initial reductions are temporary and emissions return to baseline levels after several months. Due to the great uncertainty in the efficacy of the various feeding practices to reduce CH_4 emissions, the options for mitigating emissions from enteric fermentation are only qualitatively discussed.

Grazing Lands

Although there is considerable variability in carbon sequestration potential, break-even prices were generated for legume interseeding using the frost seeding method. These range from \$15 to \$657 per mt CO_2-eq $ac^{-1}yr^{-1}$. The potential carbon sequestration range is large due to the limited number of studies that have been conducted, each of which was performed under differing objectives and conditions. Legume interseeding was observed to increase total plant-soil system carbon sequestration (Conant et al., 2001; Mortenson et al., 2004). Conversely, studies have indicated that legumes increase N_2O emissions, although results are mixed and more research is needed (Rochette et al., 2004).

APPENDIX 3-A: AVERAGE ELECTRICITY PRICES FOR EACH STATE AND USDA PRODUCTION REGION AS OF JANUARY 2012

USDA Production Region/State	Electricity Prices (cents per kWh)				
	Residential	Commercial	Industrial	Transportation	All Sectors
Northeast	15.17	12.72	9.88	9.59	13.27
Connecticut	17.33	15.02	13.42	11.16	15.91
Delaware	13.07	9.78	8.13	–	10.84
Maine	15.21	12.72	8.20	–	12.68
Maryland	12.59	10.80	8.27	6.97	11.43
Massachusetts	15.21	13.82	12.90	5.18	14.05
New Hampshire	16.19	13.64	11.75	–	14.48
New Jersey	16.09	12.85	10.64	9.55	13.90
New York	16.83	14.46	6.97	13.04	14.67
Pennsylvania	12.92	9.43	7.33	7.24	10.22
Rhode Island	14.75	13.18	10.94	13.98	13.57
Vermont	16.65	14.17	10.18	–	14.21
Corn Belt	10.10	8.27	5.79	7.07	8.11
Illinois	11.23	8.26	6.18	6.66	8.64
Indiana	9.87	9.00	6.41	9.43	8.19
Iowa	9.81	7.24	4.87	–	7.20
Missouri	8.60	7.20	5.33	5.56	7.48
Ohio	10.99	9.65	6.16	6.61	9.03
Lake States	12.34	9.65	6.87	7.97	9.81
Michigan	13.48	10.36	7.18	7.41	10.68
Minnesota	10.76	8.26	6.3	8.53	8.57
Wisconsin	12.77	10.33	7.14	–	10.17
Northern Plains	8.86	7.80	6.26	–	7.80
Kansas	10.14	8.65	6.62	–	8.63
Nebraska	8.55	7.85	5.97	–	7.51
North Dakota	7.63	6.99	6.2	–	6.99
South Dakota	9.11	7.71	6.24	–	8.05
Southeast	10.90	9.79	6.36	7.68	9.28
Alabama	10.81	10.47	5.68	–	8.75
Florida	11.59	9.94	8.35	8.34	10.65
Georgia	10.1	9.46	5.68	7.02	8.89
South Carolina	11.08	9.28	5.74	–	8.83
Appalachia	9.70	8.58	6.24	8.76	8.39
Kentucky	8.79	8.18	5.25	–	6.96
North Carolina	10.08	8.38	6.11	7.31	8.85
Tennessee	9.63	9.96	6.91	–	8.97
Virginia	10.51	8.17	6.74	9.00	9.05
West Virginia	9.49	8.23	6.21	9.98	8.12
Delta	8.88	8.42	5.41	9.76	7.54
Arkansas	8.45	7.59	5.26	11.32	7.14
Louisiana	8.26	8.16	4.94	8.19	7.02
Mississippi	9.94	9.51	6.04	–	8.47
Southern Plains	9.85	7.84	5.41	10.17	7.98
Oklahoma	8.65	7.14	5.06	–	7.17
Texas	11.04	8.54	5.76	10.17	8.78

USDA Production Region/State	Electricity Prices (cents per kWh)				
	Residential	Commercial	Industrial	Transportation	All Sectors
Mountain	9.84	8.10	5.41	8.37	7.87
Arizona	9.97	8.62	5.66	–	8.68
Colorado	10.54	8.41	6.48	8.77	8.68
Idaho	8.00	6.49	4.70	–	6.66
Montana	9.59	8.92	5.15	–	8.19
Nevada	11.38	8.67	5.18	7.23	8.25
New Mexico	10.82	8.56	5.38	–	8.34
Utah	9.25	7.35	5.11	9.12	7.27
Wyoming	9.13	7.78	5.63	–	6.88
Pacific	11.19	9.31	6.46	8.00	9.47
California	15.5	11.96	9.83	7.79	12.97
Oregon	9.67	8.25	5.42	8.05	8.33
Washington	8.39	7.73	4.13	8.17	7.10
Not Included	27.12	24.45	24.19	–	24.95
Alaska	17.98	14.88	18.71	–	16.8
Hawaii	36.25	34.02	29.67	–	33.10
U.S. Total	11.89	10.12	7.56	8.58	10.12

Source: EIA (2012). Average Retail Price of Electricity to Ultimate Consumers by End-Use, U.S. Energy Information Administration. Available online at http://www.eia.doe.gov/electricity/epm/table5_6_b.html.

Note: USDA production region average electricity prices are the averages of the State averages within the region, not the average price across the entire region.

APPENDIX 3-B: MANURE MANAGEMENT SYSTEMS

Included below are descriptions of manure management systems from the U.S. Inventory of GHG Emissions and Sinks: 1990–2008, Annex 3, Table A-195 (EPA, 2010a).

System	Description
Pasture	The manure from pasture and range grazing animals is allowed to lie as is, and is not managed.
Daily Spread	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion. N_2O emissions during storage and treatment are assumed to be zero.
Solid Storage	Manure is stored, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation.
Drylot	A paved or unpaved open confinement area without any significant vegetative cover where accumulating manure may be removed periodically. Drylots are most typically found in dry climates, but also are used in humid climates.
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 of 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 and move it to the lagoon. Anaerobic lagoons are designed for varying lengths of storage (up to a year or longer), depending on the climate region, the volatile solids loading rate, and other operational factors. Anaerobic lagoons accumulate sludge over time, diminishing treatment capacity. Lagoons must be cleaned out once every 5–15 years, and the sludge is typically applied to agricultural lands. The water from the lagoon may be recycled as flush water or used to irrigate and fertilize fields. Lagoons are sometimes used in combination with a solids separator, typically for dairy waste. Solids separators help control the buildup of non-degradable material such as straw or other bedding materials.
Anaerobic Digester	Animal excreta, with or without straw, are collected and anaerobically digested in a large containment vessel 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	Manure is collected and stored, usually with little or no added water, typically below a slatted floor in an enclosed animal confinement facility. Typical storage periods range from 5–12 months, after which manure is removed from the pit and transferred to a treatment system or applied to land.
Poultry with Litter	Enclosed poultry houses use bedding derived from wood shavings, rice hulls, chopped straw, peanut hulls, or other products, depending on availability. The bedding absorbs moisture and dilutes the manure produced by the birds. Litter is typically cleaned out completely once a year. These manure systems are typically used for all poultry breeder flocks and for the production of meat-type 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. When designed and operated properly, this high-rise system is a form of passive windrow composting.

Note: Descriptions presented here were taken directly from the U.S. Inventory of GHG Emissions and Sinks: 1990–2008, Annex 3, Table A-195 (EPA, 2010a), which were adapted from 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) and the Development Document for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations (EPA, 2002).

APPENDIX 3-C: INVENTORY OF FARMS AND ANIMALS BY USDA PRODUCTION REGION, FARM SIZE, AND ANIMAL TYPE

Swine Farm Size (head)	USDA Production Region									
	Appalachia		Corn Belt		Delta		Lake States		Mountain	
	Farm	No.	Farm	No.	Farm	No.	Farm	No.	Farm	No.
Total	8,095	11,000,358	21,331	32,195,418	2,543	637,201	10,261	9,121,152	4,058	1,969,227
1 to 24	5,302	27,535	6,893	48,355	2,084	11,456	5,083	34,827	3,500	18,663
25 to 49	434	8,159	1,094	37,927	156	5,284	690	23,942	230	5,980
50 to 99	234	9,214	1,140	77,842	78	4,908	553	37,616	125	8,098
100 to 199	133	17,669	1,184	164,262	33	4,299	425	38,967	58	6,587
200 to 499	129	38,492	2,492	825,798	9	2,509	787	204,977	38	11,782
500 to 999	117	83,806	2,051	1,409,951	49	35,750	650	458,103	14	3,860
1,000 or more	1,746	10,798,865	6,477	29,631,283	134	571,430	2,073	8,256,137	93	1,888,302

Swine Farm Size (head)	USDA Production Region											
	Northeast		Northern Plains		Other		Pacific		Southeast		Southern Plains	
	Farm	No.	Farm	No.	Farm	No.	Farm	No.	Farm	No.	Farm	No.
Total	8,020	1,298,104	4,976	6,825,509	268	15,690	4,135	203,653	4,582	755,476	7,173	3,554,162
1 to 24	6,369	35,926	1,587	12,912	181	1,251	3,726	18,435	3,940	20,096	6,382	30,698
25 to 49	486	15,538	356	12,266	38	0	216	5,599	241	6,357	351	11,494
50 to 99	267	16,446	369	25,300	19	1,315	80	5,542	130	8,690	187	12,287
100 to 199	161	21,664	411	56,437	10	1,403	48	6,823	58	7,289	69	9,111
200 to 499	198	55,081	720	229,054	10	2,715	31	9,777	57	18,368	53	15,993
500 to 999	133	87,770	504	351,086	8	4,836	16	11,467	21	12,102	25	18,016
1,000 or more	406	1,064,935	1,029	6,138,454	2	0	18	143,073	135	677,489	106	3,456,563

Farm Size (head)	Appalachia							
	Beef Cows		Milk Cows		Other Cattle[a]		Cattle on Feed[b]	
	Farms	No.	Farms	No.	Farms	No.	Farms	No.
Total	128,097	3,617,283	5,494	309,843	117,796	3,387,774	1,327	52,819
1 to 9	39,996	199,999	2,352	5,638	52,229	228,099	611	957
10 to 19	31,741	432,079	295	3,723	26,313	351,664	250	1,954
20 to 49	37,914	1,137,518	851	28,866	24,240	719,859	206	2,693
50 to 99	12,587	831,126	930	65,753	8,811	584,187	138	5,824
100 to 199	4,398	565,114	784	103,866	3,712	489,298	62	8,046
200 to 499	1,331	356,551	240	65,545	1,961	545,553	54	15,707
500 or more	130	94,896	42	35,838	530	430,297	6	0

Farm Size (head)	Corn Belt							
	Beef Cows		Milk Cows		Other Cattle[a]		Cattle on Feed[b]	
	Farms	No.	Farms	No.	Farms	No.	Farms	No.
Total	116,917	3,951,448	11,901	863,513	126,924	6,838,942	18,564	2,429,430
1 to 9	33,844	162,799	2,890	7,941	48,321	204,790	5,564	24,440
10 to 19	25,642	349,932	949	13,082	24,078	324,669	2,636	35,096
20 to 49	35,307	1,078,448	3,096	103,847	27,639	839,996	3,621	111,399
50 to 99	14,297	953,921	2,919	203,050	13,319	899,771	2,396	161,922
100 to 199	5,768	744,125	1,428	185,113	6,983	932,486	1,602	217,100
200 to 499	1,851	494,731	460	131,764	4,253	1,255,538	1,465	437,442
500 or more	208	167,492	159	218,716	2,331	2,381,692	1,280	1,442,031

Farm Size (head)	Delta							
	Beef Cows		Milk Cows		Other Cattle[a]		Cattle on Feed[b]	
	Farms	No.	Farms	No.	Farms	No.	Farms	No.
Total	53,626	1,980,119	814	67,616	48,656	1,620,924	75	1,965
1 to 9	14,034	71,566	218	510	21,419	91,895	54	166
10 to 19	12,114	164,463	25	0	10,693	141,983	6	0
20 to 49	16,764	507,069	95	3,501	10,179	300,446	4	127
50 to 99	6,679	440,698	217	15,390	3,655	242,698	4	245
100 to 199	2,793	359,702	191	25,280	1,545	204,067	6	802
200 to 499	1,057	295,054	60	16,130	866	256,960	0	0
500 or more	185	141,567	8	5,736	299	382,875	1	0

Farm Size (head)	Lake States							
	Beef Cows		Milk Cows		Other Cattle[a]		Cattle on Feed[b]	
	Farms	No.	Farms	No.	Farms	No.	Farms	No.
Total	37,033	779,088	21,953	2,053,294	65,575	3,984,964	14,009	1,067,669
1 to 9	16,094	72,747	1,432	5,074	19,939	88,558	3,969	17,461
10 to 19	8,584	114,995	1,193	16,826	10,578	142,509	2,373	31,069
20 to 49	8,904	260,517	6,583	232,588	15,260	480,715	3,327	101,417
50 to 99	2,430	158,405	7,986	530,945	10,158	683,212	1,938	128,365
100 to 199	771	97,369	2,939	382,734	5,486	724,005	1,227	162,042
200 to 499	228	55,223	1,344	387,584	3,107	884,733	767	222,067
500 or more	22	14,401	476	497,543	1,047	981,232	408	405,248

Farm Size (head)	Mountain							
	Beef Cows		Milk Cows		Other Cattle[a]		Cattle on Feed[b]	
	Farms	No.	Farms	No.	Farms	No.	Farms	No.
Total	55,342	4,796,273	2,727	1,310,575	55,724	6,587,147	1,810	2,066,244
1 to 9	18,328	75,213	1,254	2,242	25,537	97,881	837	3,120
10 to 19	7,963	106,751	72	831	8,543	112,978	168	2,192
20 to 49	10,616	328,306	142	4,693	8,652	262,333	135	4,038
50 to 99	6,461	444,304	201	14,076	4,838	330,435	146	9,901
100 to 199	5,294	725,123	260	34,467	3,485	474,714	142	18,556
200 to 499	4,876	1,458,941	250	81,044	2,695	816,544	119	36,378
500 or more	1,804	1,657,635	548	1,166,897	1,974	4,492,262	263	1,619,344

Farm Size (head)	Northeast							
	Beef Cows		Milk Cows		Other Cattle[a]		Cattle on Feed[b]	
	Farms	No.	Farms	No.	Farms	No.	Farms	No.
Total	27,937	362,556	17,455	1,477,181	44,604	1,954,447	4,562	192,868
1 to 9	16,723	69,161	2,582	6,421	16,976	71,696	2,131	8,662
10 to 19	5,905	75,069	697	9,227	7,382	93,342	818	10,654
20 to 49	4,189	118,792	4,797	176,207	10,448	326,090	754	21,808
50 to 99	863	54,111	5,769	384,898	5,511	369,016	446	30,569
100 to 199	217	25,402	2,367	306,338	2,556	331,447	191	24,733
200 to 499	35	0	879	251,587	1,298	381,756	156	42,595
500 or more	5	0	364	330,288	433	360,391	64	44,895

Farm Size (head)	Northern Plains							
	Beef Cows		Milk Cows		Other Cattle[a]		Cattle on Feed[b]	
	Farms	No.	Farms	No.	Farms	No.	Farms	No.
Total	67,478	5,985,731	2,327	282,766	66,974	12,476,867	6,069	6,011,715
1 to 9	8,858	43,541	696	1,947	17,614	73,526	760	3,123
10 to 19	8,889	122,482	111	1,523	9,551	129,747	395	5,273
20 to 49	18,084	574,420	505	16,865	13,612	425,884	752	24,698
50 to 99	13,355	920,618	538	36,714	9,227	634,098	932	64,224
100 to 199	10,272	1,377,676	282	36,190	7,121	970,261	945	127,717
200 to 499	6,741	1,919,796	114	33,143	6,025	1,801,187	998	307,013
500 or more	1,279	1,027,198	81	156,384	3,824	8,442,164	1,287	5,479,667

Farm Size (head)	Pacific							
	Beef Cows		Milk Cows		Other Cattle[a]		Cattle on Feed[b]	
	Farms	No.	Farms	No.	Farms	No.	Farms	No.
Total	34,768	1,540,493	3,578	2,200,650	34,872	4,234,917	1,053	851,319
1 to 9	18,375	73,572	1,062	2,516	19,374	75,050	685	2,229
10 to 19	5,506	72,320	62	728	5,183	67,258	80	999
20 to 49	5,355	159,311	90	2,719	4,207	124,407	65	1,836
50 to 99	2,265	152,418	150	10,787	1,803	121,147	66	4,531
100 to 199	1,488	198,905	290	41,584	1,372	183,343	42	5,332
200 to 499	1,227	362,075	636	209,058	1,439	435,989	49	14,480
500 or more	552	521,892	1,288	1,933,258	1,494	3,227,723	66	821,912

Farm Size (head)	Southeast							
	Beef Cows		Milk Cows		Other Cattle[a]		Cattle on Feed[b]	
	Farms	No.	Farms	No.	Farms	No.	Farms	No.
Total	64,007	2,405,886	1,324	227,841	59,055	1,782,538	435	10,351
1 to 9	23,240	111,750	706	1,703	29,179	123,688	300	1,223
10 to 19	14,287	191,466	55	631	12,327	163,681	75	724
20 to 49	16,145	484,590	55	1,513	10,824	317,000	30	382
50 to 99	6,051	398,105	77	5,344	3,597	238,506	18	824
100 to 199	2,536	331,698	175	25,447	1,721	225,302	4	0
200 to 499	1,326	372,981	144	44,609	1,021	297,167	3	850
500 or more	422	515,296	112	148,174	386	417,194	5	4,200

Farm Size (head)	Southern Plains							
	Beef Cows		Milk Cows		Other Cattle[a]		Cattle on Feed[b]	
	Farms	No.	Farms	No.	Farms	No.	Farms	No.
Total	178,828	7,323,456	2,274	470,422	167,507	11,307,002	2,083	3,414,166
1 to 9	57,000	278,427	1,203	2,990	78,471	328,985	894	3,127
10 to 19	39,198	528,373	107	1,315	33,139	438,736	267	3,514
20 to 49	47,384	1,436,143	129	4,136	29,830	884,607	240	7,080
50 to 99	19,172	1,294,476	196	13,690	11,847	797,074	224	15,322
100 to 199	9,980	1,318,416	257	35,467	6,687	890,358	154	20,405
200 to 499	4,928	1,381,917	178	53,452	4,762	1,412,994	133	39,572
500 or more	1,166	1,085,704	204	359,372	2,771	6,554,248	171	3,325,146

[a] Other Cattle: In the 2007 Census, data include heifers that have not calved, steers, calves, and bulls.

[b] Cattle on Feed: Cattle on feed are defined as cattle and calves that were fed a ration of grain or other concentrates that will be shipped directly from the feedlot to the slaughter market and are expected to produce a carcass that will grade select or better. This category excludes cattle that were pastured only, background feeder cattle, and veal calves.

APPENDIX 3-D: FARM-LEVEL GHG REDUCTIONS FOR TRANSITION FROM CURRENT MANURE MANAGEMENT PRACTICES TO DIFFERENT MITIGATION OPTIONS

This appendix presents the annual net emissions reductions at the farm level associated with transitioning from current manure management practice to a mitigation option. The exhibits are organized by mitigation option and are presented in the following order:

- Exhibit 3-D-1: Covered Lagoon Digester
- Exhibit 3-D-2: Complete Mix Digester
- Exhibit 3-D-3: Plug Flow Digester
- Exhibit 3-D-4: Covering Existing Lagoons

Exhibit 3-D-1: Covered Lagoon Digester with Flare Only or Flare and Electricity Generation

Current Practice and USDA Production Region		Farm-Level GHG Reductions for Transition from Current Management Practices to Dairy Covered Lagoon Digester (mt CO_2-eq)				Farm-Level GHG Reductions for Transition from Current Management Practices to Swine Covered Lagoon Digester (mt CO_2-eq)		
		Dairy Farm Size, No. of Lactating Cows				Swine Farm Size, No. of Sows in Farrow-to-Finish Operations		
		300	600	1,000	5,000	150	500	2,500
Liquid/Slurry	Appalachia	420	840	1,399	6,997	239	797	3,987
	Corn Belt	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Delta	578	1,157	1,928	9,640	249	831	4,155
	Lake States	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Mountain	402	805	1,342	6,708	148	493	2,463
	Northeast	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Northern Plains	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Pacific	460	920	1,533	7,665	173	577	2,886
	Southeast	649	1,298	2,163	10,817	253	842	4,209
	Southern Plains	606	1,212	2,020	10,102	245	817	4,086
Anaerobic Lagoon	Appalachia	1,500	3,001	5,001	25,007	558	1,859	9,293
	Corn Belt	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Delta	1,571	3,143	5,238	26,189	558	1,860	9,302
	Lake States	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Mountain	1,460	2,920	4,867	24,336	519	1,729	8,645
	Northeast	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Northern Plains	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Pacific	1,545	3,089	5,149	25,743	547	1,824	9,118
	Southeast	1,596	3,192	5,319	26,596	560	1,868	9,340
	Southern Plains	1,588	3,176	5,294	26,469	558	1,861	9,303
Deep Pit	Appalachia	507	1,015	1,691	8,456	240	801	4,006
	Corn Belt	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Delta	705	1,410	2,350	11,751	250	834	4,171
	Lake States	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Mountain	386	773	1,288	6,441	150	501	2,506
	Northeast	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Northern Plains	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Pacific	452	905	1,508	7,538	187	624	3,121
	Southeast	722	1,445	2,408	12,039	251	837	4,186
	Southern Plains	713	1,427	2,378	11,888	243	809	4,043

N/A = Not applicable

Exhibit 3-D-2: Complete Mix Digester

Current Practice and USDA Production Region		Farm-Level GHG Reductions for Transition from Current Management Practices to Dairy Complete Mix Digester (mt CO_2-eq)				Farm-Level GHG Reductions for Transition from Current Management Practices to Swine Complete Mix Digester (mt CO_2-eq)			Farm-Level GHG Reductions for Transition from Current Management Practices to Beef Complete Mix Digester (mt CO_2-eq)		
		Dairy Farm Size, No. of Lactating Cows				Swine Farm Size, No. of Sows in Farrow-to-Finish Operations			Feedlot Farm Size, No. of Feedlot Cattle		
		300	600	1,000	5,000	150	500	2,500	500	1,000	2,500
Liquid/Slurry	Appalachia	341	683	1,138	5,688	235	784	3,918	363	727	1,817
	Corn Belt	251	502	836	4,182	149	498	2,491	300	600	1,501
	Delta	635	1,270	2,116	10,580	248	828	4,139	550	1,099	2,749
	Lake States	148	295	492	2,461	122	408	2,040	255	510	1,275
	Mountain	309	619	1,031	5,154	115	385	1,924	327	654	1,635
	Northeast	172	345	575	2,875	146	486	2,431	293	586	1,466
	Northern Plains	271	543	905	4,524	149	496	2,482	334	668	1,671
	Pacific	415	831	1,385	6,925	149	495	2,477	474	948	2,370
	Southeast	765	1,531	2,551	12,757	253	842	4,209	575	1,150	2,875
	Southern Plains	686	1,372	2,287	11,435	243	810	4,048	490	980	2,450
Anaerobic Lagoon	Appalachia	1,746	3,492	5,819	29,096	557	1,857	9,286			
	Corn Belt	1,685	3,369	5,616	28,078	510	1,700	8,499			
	Delta	1,849	3,698	6,163	30,814	558	1,859	9,296			
	Lake States	1,570	3,141	5,235	26,174	495	1,649	8,247			
	Mountain	1,687	3,375	5,624	28,121	513	1,710	8,549			
	Northeast	1,568	3,135	5,225	26,126	514	1,712	8,560			
	Northern Plains	1,716	3,432	5,720	28,602	518	1,728	8,638			
	Pacific	1,810	3,620	6,033	30,165	545	1,817	9,087			
	Southeast	1,884	3,769	6,281	31,406	560	1,868	9,340			
	Southern Plains	1,873	3,747	6,244	31,222	558	1,860	9,298			
Deep Pit	Appalachia	469	938	1,563	7,814	237	790	3,951			
	Corn Belt	372	744	1,240	6,201	147	488	2,442			
	Delta	821	1,643	2,738	13,688	250	833	4,166			
	Lake States	247	494	824	4,118	122	408	2,041			
	Mountain	253	507	845	4,223	119	397	1,984			
	Northeast	285	570	949	4,746	146	486	2,430			
	Northern Plains	360	720	1,200	6,002	149	496	2,480			
	Pacific	371	741	1,236	6,178	167	558	2,790			
	Southeast	852	1,704	2,840	14,202	251	837	4,186			
	Southern Plains	836	1,672	2,786	13,932	240	800	3,998			

Exhibit 3-D-3: Plug Flow Digester

Current Practice and USDA Production Region		Farm-Level GHG Reductions for Transition from Current Management Practices to Dairy Plug Flow Digester (mt CO_2-eq)				Farm-Level GHG Reductions for Transition from Current Management Practices to Swine Plug Flow Digester (mt CO_2-eq)			Farm-Level GHG Reductions for Transition from Current Management Practices to Beef Plug Flow Digester (mt CO_2-eq)		
		Dairy Farm Size, No. of Lactating Cows				Swine Farm Size, No. of Sows in Farrow-to-Finish Operations			Feedlot Farm Size, No. of Feedlot Cattle		
		300	600	1,000	5,000	150	500	2,500	500	1,000	2,500
Liquid/Slurry	Appalachia	341	683	1,138	5,688	235	784	3,918	363	727	1,817
	Corn Belt	251	502	836	4,182	149	498	2,491	300	600	1,501
	Delta	635	1,270	2,116	10,580	248	828	4,139	550	1,099	2,749
	Lake States	148	295	492	2,461	122	408	2,040	255	510	1,275
	Mountain	309	619	1,031	5,154	115	385	1,924	327	654	1,635
	Northeast	172	345	575	2,875	146	486	2,431	293	586	1,466
	Northern Plains	271	543	905	4,524	149	496	2,482	334	668	1,671
	Pacific	415	831	1,385	6,925	149	495	2,477	474	948	2,370
	Southeast	765	1,531	2,551	12,757	253	842	4,209	575	1,150	2,875
	Southern Plains	686	1,372	2,287	11,435	243	810	4,048	490	980	2,450

Exhibit 3-D-4: Covering Existing Lagoons

Current and USDA Production Region		Farm-Level GHG Reductions for Transition from Current Management Practices to Covering Dairy Existing Lagoons (mt CO_2-eq)				Farm-Level GHG Reductions for Transition from Current Management Practices to Covering Swine Existing Lagoons (mt CO_2-eq)		
		Dairy Farm Size, No. of Lactating Cows				Swine Farm Size, No. of Sows in Farrow-to-Finish Operations		
		300	600	1,000	5,000	150	500	2,500
Liquid/Slurry	Appalachia	645	1,291	2,151	10,756	276	920	9,524
	Corn Belt	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Delta	742	1,484	2,473	12,367	288	959	9,927
	Lake States	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Mountain	516	1,033	1,721	8,606	157	524	5,426
	Northeast	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Northern Plains	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Pacific	590	1,180	1,967	9,833	200	666	6,894
	Southeast	833	1,665	2,775	13,876	292	972	10,056
	Southern Plains	778	1,555	2,592	12,960	283	943	9,762
Anaerobic Lagoon	Appalachia	1,770	3,540	5,900	29,499	596	1,988	20,568
	Corn Belt	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Delta	1,752	3,504	5,840	29,201	597	1,990	20,588
	Lake States	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Mountain	1,628	3,256	5,427	27,136	600	1,999	20,683
	Northeast	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Northern Plains	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Pacific	1,722	3,444	5,741	28,704	585	1,951	20,182
	Southeast	1,779	3,559	5,931	29,655	599	1,998	20,673
	Southern Plains	1,771	3,542	5,903	29,514	597	1,990	20,591

N/A = Not applicable

APPENDIX 3-E: BREAK-EVEN PRICES FOR TRANSITION FROM CURRENT PRACTICES TO DIFFERENT MITIGATION OPTIONS

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	5,000	Mountain	Dairy	$0
Covered Lagoon Anaerobic Digester with EG	Deep Pit	5,000	Mountain	Dairy	$0
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	5,000	Mountain	Dairy	$0
Complete Mix Digester	Anaerobic Lagoon	2,500	Southeast	Swine	$1
Complete Mix Digester	Anaerobic Lagoon	2,500	Southern Plains	Swine	$1
Complete Mix Digester	Anaerobic Lagoon	2,500	Delta	Swine	$1
Complete Mix Digester	Anaerobic Lagoon	2,500	Appalachia	Swine	$1
Complete Mix Digester	Anaerobic Lagoon	2,500	Pacific	Swine	$1
Complete Mix Digester	Anaerobic Lagoon	2,500	Northern Plains	Swine	$1
Complete Mix Digester	Anaerobic Lagoon	2,500	Mountain	Swine	$1
Complete Mix Digester	Anaerobic Lagoon	2,500	Corn Belt	Swine	$1
Complete Mix Digester	Anaerobic Lagoon	2,500	Lake States	Swine	$1
Complete Mix Digester	Deep Pit	2,500	Southeast	Swine	$2
Complete Mix Digester	Deep Pit	2,500	Delta	Swine	$2
Complete Mix Digester	Deep Pit	2,500	Southern Plains	Swine	$2
Complete Mix Digester	Deep Pit	2,500	Appalachia	Swine	$2
Complete Mix Digester	Deep Pit	2,500	Pacific	Swine	$2
Complete Mix Digester	Liquid/Slurry	2,500	Southeast	Swine	$2
Complete Mix Digester	Liquid/Slurry	2,500	Delta	Swine	$2
Complete Mix Digester	Liquid/Slurry	2,500	Southern Plains	Swine	$2
Complete Mix Digester	Liquid/Slurry	2,500	Appalachia	Swine	$2
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	5,000	Pacific	Dairy	$2
Solids Separator without Composting	Anaerobic Lagoon	4,000	All Regions	Dairy	$2
Complete Mix Digester	Deep Pit	2,500	Northern Plains	Swine	$3
Complete Mix Digester	Deep Pit	2,500	Corn Belt	Swine	$3
Complete Mix Digester	Deep Pit	2,500	Lake States	Swine	$3
Complete Mix Digester	Deep Pit	2,500	Mountain	Swine	$3

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price
					(2010 $/ mt CO_2-eq)
Complete Mix Digester	Liquid/Slurry	2,500	Corn Belt	Swine	$3
Complete Mix Digester	Liquid/Slurry	2,500	Northern Plains	Swine	$3
Complete Mix Digester	Liquid/Slurry	2,500	Pacific	Swine	$3
Complete Mix Digester	Liquid/Slurry	2,500	Lake States	Swine	$3
Complete Mix Digester	Liquid/Slurry	2,500	Mountain	Swine	$3
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	2,500	Southeast	Swine	$3
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	2,500	Southern Plains	Swine	$3
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	2,500	Delta	Swine	$3
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	2,500	Appalachia	Swine	$3
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	2,500	Pacific	Swine	$3
Covering an Existing Lagoon	Anaerobic Lagoon	2,500	Pacific	Swine	$3
Complete Mix Digester	Anaerobic Lagoon	2,500	Northeast	Swine	$4
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	5,000	Southeast	Dairy	$4
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	5,000	Southern Plains	Dairy	$4
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	5,000	Delta	Dairy	$4
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	5,000	Appalachia	Dairy	$4
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	2,500	Mountain	Swine	$4
Covering an Existing Lagoon	Anaerobic Lagoon	5,000	Southeast	Dairy	$4
Covering an Existing Lagoon	Anaerobic Lagoon	5,000	Southern Plains	Dairy	$4
Covering an Existing Lagoon	Anaerobic Lagoon	5,000	Appalachia	Dairy	$4
Covering an Existing Lagoon	Anaerobic Lagoon	5,000	Delta	Dairy	$4
Solids Separator with Composting	Anaerobic Lagoon	4,000	All Regions	Dairy	$4
Solids Separator without Composting	Anaerobic Lagoon	1,000	All Regions	Dairy	$4
Complete Mix Digester	Liquid/Slurry	2,500	Northern Plains	Beef	$5
Covering an Existing Lagoon	Anaerobic Lagoon	5,000	Pacific	Dairy	$5
Covering an Existing Lagoon	Anaerobic Lagoon	5,000	Mountain	Dairy	$5

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	k-Even ice 10 $/ mt CO$_2$-eq)
Complete Mix Digester	Anaerobic Lagoon	5,000	Southeast	Dairy	$6
Complete Mix Digester	Anaerobic Lagoon	5,000	Southern Plains	Dairy	$6
Complete Mix Digester	Anaerobic Lagoon	5,000	Delta	Dairy	$6
Complete Mix Digester	Liquid/Slurry	2,500	Mountain	Beef	$6
Complete Mix Digester	Liquid/Slurry	2,500	Corn Belt	Beef	$6
Covering an Existing Lagoon	Anaerobic Lagoon	500	Pacific	Swine	$6
Covering an Existing Lagoon	Anaerobic Lagoon	2,500	Southern Plains	Swine	$6
Covering an Existing Lagoon	Anaerobic Lagoon	2,500	Delta	Swine	$6
Covering an Existing Lagoon	Anaerobic Lagoon	2,500	Mountain	Swine	$6
Covering an Existing Lagoon	Anaerobic Lagoon	2,500	Appalachia	Swine	$6
Covering an Existing Lagoon	Anaerobic Lagoon	2,500	Southeast	Swine	$6
Solids Separator with Composting	Anaerobic Lagoon	1,000	All Regions	Dairy	$6
Complete Mix Digester	Anaerobic Lagoon	5,000	Appalachia	Dairy	$6
Complete Mix Digester	Liquid/Slurry	2,500	Lake States	Beef	$7
Covered Lagoon Anaerobic Digester with EG	Deep Pit	2,500	Southeast	Swine	$7
Covered Lagoon Anaerobic Digester with EG	Deep Pit	2,500	Delta	Swine	$7
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	2,500	Southeast	Swine	$7
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	2,500	Delta	Swine	$7
Covering an Existing Lagoon	Anaerobic Lagoon	1,000	Southeast	Dairy	$7
Covering an Existing Lagoon	Anaerobic Lagoon	1,000	Southern Plains	Dairy	$7
Covering an Existing Lagoon	Anaerobic Lagoon	1,000	Appalachia	Dairy	$7
Covering an Existing Lagoon	Anaerobic Lagoon	1,000	Delta	Dairy	$7
Covering an Existing Lagoon	Anaerobic Lagoon	1,000	Pacific	Dairy	$7
Covering an Existing Lagoon	Anaerobic Lagoon	150	Pacific	Swine	$7
Complete Mix Digester	Anaerobic Lagoon	5,000	Pacific	Dairy	$7
Complete Mix Digester	Liquid/Slurry	2,500	Northeast	Beef	$8
Covered Lagoon Anaerobic Digester with EG	Deep Pit	5,000	Southeast	Dairy	$8
Covered Lagoon Anaerobic Digester with EG	Deep Pit	5,000	Delta	Dairy	$8

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester with EG	Deep Pit	2,500	Southern Plains	Swine	$8
Covered Lagoon Anaerobic Digester with EG	Deep Pit	2,500	Appalachia	Swine	$8
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	2,500	Southern Plains	Swine	$8
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	2,500	Appalachia	Swine	$8
Covering an Existing Lagoon	Anaerobic Lagoon	600	Southeast	Dairy	$8
Covering an Existing Lagoon	Anaerobic Lagoon	600	Southern Plains	Dairy	$8
Covering an Existing Lagoon	Anaerobic Lagoon	1,000	Mountain	Dairy	$8
Covering an Existing Lagoon	Anaerobic Lagoon	600	Appalachia	Dairy	$8
Covering an Existing Lagoon	Anaerobic Lagoon	600	Delta	Dairy	$8
Covering an Existing Lagoon	Anaerobic Lagoon	600	Pacific	Dairy	$8
Covering an Existing Lagoon	Anaerobic Lagoon	600	Mountain	Dairy	$8
Covered Lagoon Anaerobic Digester with EG	Deep Pit	5,000	Southern Plains	Dairy	$9
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	5,000	Southeast	Dairy	$9
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	5,000	Pacific	Dairy	$9
Covering an Existing Lagoon	Anaerobic Lagoon	300	Southeast	Dairy	$9
Covering an Existing Lagoon	Anaerobic Lagoon	300	Southern Plains	Dairy	$9
Covering an Existing Lagoon	Anaerobic Lagoon	300	Appalachia	Dairy	$9
Covering an Existing Lagoon	Anaerobic Lagoon	300	Delta	Dairy	$9
Covering an Existing Lagoon	Anaerobic Lagoon	300	Pacific	Dairy	$9
Covering an Existing Lagoon	Liquid/Slurry	5,000	Southeast	Dairy	$9
Covering an Existing Lagoon	Anaerobic Lagoon	300	Mountain	Dairy	$10
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	5,000	Southern Plains	Dairy	$10
Covering an Existing Lagoon	Liquid/Slurry	5,000	Southern Plains	Dairy	$10
Complete Mix Digester	Anaerobic Lagoon	5,000	Northern Plains	Dairy	$11
Complete Mix Digester	Anaerobic Lagoon	5,000	Mountain	Dairy	$11
Complete Mix Digester	Anaerobic Lagoon	5,000	Corn Belt	Dairy	$11
Covered Lagoon Anaerobic Digester with EG	Deep Pit	5,000	Pacific	Dairy	$11

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester with EG	Deep Pit	2,500	Pacific	Swine	$11
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	5,000	Delta	Dairy	$11
Covering an Existing Lagoon	Liquid/Slurry	5,000	Delta	Dairy	$11
Complete Mix Digester	Anaerobic Lagoon	5,000	Northeast	Dairy	$11
Complete Mix Digester	Anaerobic Lagoon	5,000	Lake States	Dairy	$12
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	2,500	Pacific	Swine	$12
Covering an Existing Lagoon	Liquid/Slurry	2,500	Pacific	Swine	$12
Complete Mix Digester	Anaerobic Lagoon	1,000	Southeast	Dairy	$12
Complete Mix Digester	Anaerobic Lagoon	1,000	Southern Plains	Dairy	$13
Complete Mix Digester	Anaerobic Lagoon	1,000	Delta	Dairy	$13
Complete Mix Digester	Deep Pit	5,000	Southeast	Dairy	$13
Complete Mix Digester	Liquid/Slurry	2,500	Pacific	Beef	$13
Covering an Existing Lagoon	Liquid/Slurry	5,000	Appalachia	Dairy	$13
Covering an Existing Lagoon	Liquid/Slurry	2,500	Southern Plains	Swine	$13
Covering an Existing Lagoon	Liquid/Slurry	2,500	Delta	Swine	$13
Plug Flow Digesters	Liquid/Slurry	2,500	Southeast	Swine	$13
Plug Flow Digesters	Liquid/Slurry	2,500	Delta	Swine	$13
Plug Flow Digesters	Liquid/Slurry	2,500	Southern Plains	Swine	$13
Plug Flow Digesters	Liquid/Slurry	2,500	Appalachia	Swine	$13
Complete Mix Digester	Deep Pit	5,000	Southern Plains	Dairy	$13
Complete Mix Digester	Deep Pit	5,000	Delta	Dairy	$13
Complete Mix Digester	Anaerobic Lagoon	1,000	Appalachia	Dairy	$13
Complete Mix Digester	Liquid/Slurry	2,500	Southeast	Beef	$14
Covering an Existing Lagoon	Liquid/Slurry	2,500	Appalachia	Swine	$14
Complete Mix Digester	Anaerobic Lagoon	1,000	Pacific	Dairy	$14
Complete Mix Digester	Liquid/Slurry	5,000	Southeast	Dairy	$14
Complete Mix Digester	Deep Pit	2,500	Northeast	Swine	$15
Complete Mix Digester	Liquid/Slurry	2,500	Delta	Beef	$15
Complete Mix Digester	Liquid/Slurry	2,500	Northeast	Swine	$15
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	1,000	Mountain	Dairy	$15

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 \$/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester with EG	Deep Pit	5,000	Appalachia	Dairy	$15
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	5,000	Southeast	Dairy	$15
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	5,000	Southern Plains	Dairy	$15
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	5,000	Delta	Dairy	$15
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	5,000	Pacific	Dairy	$15
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	2,500	Southeast	Swine	$15
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	2,500	Southern Plains	Swine	$15
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	2,500	Delta	Swine	$15
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	2,500	Appalachia	Swine	$15
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	2,500	Pacific	Swine	$15
Covering an Existing Lagoon	Liquid/Slurry	5,000	Pacific	Dairy	$15
Covering an Existing Lagoon	Liquid/Slurry	1,000	Southeast	Dairy	$15
Covered Lagoon Anaerobic Digester with EG	Deep Pit	2,500	Mountain	Swine	$16
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	2,500	Mountain	Swine	$16
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	5,000	Appalachia	Dairy	$16
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	5,000	Mountain	Dairy	$16
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	2,500	Mountain	Swine	$16
Covering an Existing Lagoon	Liquid/Slurry	1,000	Southern Plains	Dairy	$16
Covering an Existing Lagoon	Liquid/Slurry	600	Southeast	Dairy	$16
Complete Mix Digester	Liquid/Slurry	5,000	Southern Plains	Dairy	$16
Complete Mix Digester	Liquid/Slurry	2,500	Southern Plains	Beef	$17
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	1,000	Pacific	Dairy	$17
Covering an Existing Lagoon	Liquid/Slurry	1,000	Delta	Dairy	$17
Covering an Existing Lagoon	Liquid/Slurry	5,000	Mountain	Dairy	$17

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Complete Mix Digester	Liquid/Slurry	5,000	Delta	Dairy	$17
Complete Mix Digester	Anaerobic Lagoon	600	Southeast	Dairy	$18
Complete Mix Digester	Anaerobic Lagoon	1,000	Northern Plains	Dairy	$18
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	1,000	Southeast	Dairy	$18
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	1,000	Southern Plains	Dairy	$18
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	1,000	Delta	Dairy	$18
Covering an Existing Lagoon	Liquid/Slurry	600	Southern Plains	Dairy	$18
Complete Mix Digester	Anaerobic Lagoon	600	Southern Plains	Dairy	$18
Complete Mix Digester	Anaerobic Lagoon	600	Delta	Dairy	$18
Complete Mix Digester	Anaerobic Lagoon	1,000	Mountain	Dairy	$18
Complete Mix Digester	Anaerobic Lagoon	1,000	Corn Belt	Dairy	$18
Covering an Existing Lagoon	Liquid/Slurry	300	Southeast	Dairy	$19
Covering an Existing Lagoon	Liquid/Slurry	600	Delta	Dairy	$19
Complete Mix Digester	Anaerobic Lagoon	1,000	Northeast	Dairy	$19
Complete Mix Digester	Anaerobic Lagoon	600	Appalachia	Dairy	$19
Complete Mix Digester	Anaerobic Lagoon	1,000	Lake States	Dairy	$20
Complete Mix Digester	Anaerobic Lagoon	600	Pacific	Dairy	$20
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	1,000	Appalachia	Dairy	$20
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	5,000	Appalachia	Dairy	$20
Covering an Existing Lagoon	Liquid/Slurry	300	Southern Plains	Dairy	$20
Covering an Existing Lagoon	Liquid/Slurry	500	Pacific	Swine	$20
Covering an Existing Lagoon	Liquid/Slurry	2,500	Southeast	Swine	$20
Plug Flow Digesters	Liquid/Slurry	5,000	Southeast	Dairy	$21
Covering an Existing Lagoon	Anaerobic Lagoon	500	Southern Plains	Swine	$21
Covering an Existing Lagoon	Anaerobic Lagoon	500	Delta	Swine	$21
Covering an Existing Lagoon	Anaerobic Lagoon	500	Mountain	Swine	$21
Covering an Existing Lagoon	Anaerobic Lagoon	500	Appalachia	Swine	$21
Covering an Existing Lagoon	Anaerobic Lagoon	500	Southeast	Swine	$21
Covering an Existing Lagoon	Liquid/Slurry	1,000	Appalachia	Dairy	$21

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 \$/ mt CO_2-eq)
Plug Flow Digesters	Liquid/Slurry	2,500	Corn Belt	Swine	\$21
Plug Flow Digesters	Liquid/Slurry	2,500	Northern Plains	Swine	\$21
Plug Flow Digesters	Liquid/Slurry	2,500	Pacific	Swine	\$21
Complete Mix Digester	Liquid/Slurry	2,500	Appalachia	Beef	\$22
Covering an Existing Lagoon	Liquid/Slurry	300	Delta	Dairy	\$22
Plug Flow Digesters	Liquid/Slurry	2,500	Northeast	Swine	\$22
Complete Mix Digester	Anaerobic Lagoon	500	Southeast	Swine	\$23
Complete Mix Digester	Anaerobic Lagoon	500	Southern Plains	Swine	\$23
Complete Mix Digester	Anaerobic Lagoon	500	Delta	Swine	\$23
Complete Mix Digester	Anaerobic Lagoon	500	Appalachia	Swine	\$23
Complete Mix Digester	Anaerobic Lagoon	500	Pacific	Swine	\$23
Covering an Existing Lagoon	Liquid/Slurry	1,000	Pacific	Dairy	\$23
Covering an Existing Lagoon	Liquid/Slurry	600	Appalachia	Dairy	\$23
Plug Flow Digesters	Liquid/Slurry	5,000	Southern Plains	Dairy	\$23
Complete Mix Digester	Deep Pit	5,000	Appalachia	Dairy	\$23
Covering an Existing Lagoon	Liquid/Slurry	2,500	Mountain	Swine	\$24
Complete Mix Digester	Anaerobic Lagoon	600	Northern Plains	Dairy	\$24
Complete Mix Digester	Anaerobic Lagoon	600	Mountain	Dairy	\$24
Complete Mix Digester	Anaerobic Lagoon	600	Corn Belt	Dairy	\$24
Complete Mix Digester	Anaerobic Lagoon	500	Northern Plains	Swine	\$25
Complete Mix Digester	Anaerobic Lagoon	500	Mountain	Swine	\$25
Complete Mix Digester	Anaerobic Lagoon	500	Corn Belt	Swine	\$25
Covering an Existing Lagoon	Liquid/Slurry	600	Pacific	Dairy	\$25
Covering an Existing Lagoon	Liquid/Slurry	150	Pacific	Swine	\$25
Plug Flow Digesters	Liquid/Slurry	5,000	Delta	Dairy	\$25
Complete Mix Digester	Anaerobic Lagoon	600	Northeast	Dairy	\$26
Complete Mix Digester	Anaerobic Lagoon	500	Lake States	Swine	\$26
Covering an Existing Lagoon	Anaerobic Lagoon	150	Southern Plains	Swine	\$26
Covering an Existing Lagoon	Anaerobic Lagoon	150	Delta	Swine	\$26
Covering an Existing Lagoon	Anaerobic Lagoon	150	Mountain	Swine	\$26
Covering an Existing Lagoon	Anaerobic Lagoon	150	Appalachia	Swine	\$26
Plug Flow Digesters	Liquid/Slurry	2,500	Lake States	Swine	\$26

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price
					(2010 $/ mt CO_2-eq)
Complete Mix Digester	Anaerobic Lagoon	600	Lake States	Dairy	$26
Covering an Existing Lagoon	Anaerobic Lagoon	150	Southeast	Swine	$27
Covering an Existing Lagoon	Liquid/Slurry	300	Appalachia	Dairy	$27
Plug Flow Digesters	Liquid/Slurry	2,500	Mountain	Swine	$27
Plug Flow Digesters	Liquid/Slurry	5,000	Mountain	Dairy	$27
Complete Mix Digester	Deep Pit	1,000	Southeast	Dairy	$27
Complete Mix Digester	Anaerobic Lagoon	500	Northeast	Swine	$28
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	1,000	Southeast	Dairy	$28
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	1,000	Southern Plains	Dairy	$28
Covering an Existing Lagoon	Liquid/Slurry	1,000	Mountain	Dairy	$28
Complete Mix Digester	Deep Pit	1,000	Southern Plains	Dairy	$28
Complete Mix Digester	Deep Pit	1,000	Delta	Dairy	$29
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	600	Mountain	Dairy	$29
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	1,000	Delta	Dairy	$29
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	1,000	Pacific	Dairy	$29
Covering an Existing Lagoon	Liquid/Slurry	300	Pacific	Dairy	$29
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	600	Pacific	Dairy	$30
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	600	Southeast	Dairy	$30
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	600	Southern Plains	Dairy	$30
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	1,000	Appalachia	Dairy	$30
Complete Mix Digester	Liquid/Slurry	1,000	Southeast	Dairy	$31
Plug Flow Digesters	Liquid/Slurry	5,000	Northern Plains	Dairy	$31
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	600	Delta	Dairy	$31
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	1,000	Mountain	Dairy	$31
Covering an Existing Lagoon	Liquid/Slurry	600	Mountain	Dairy	$31
Complete Mix Digester	Anaerobic Lagoon	300	Southeast	Dairy	$32

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price
					(2010 \$/ mt CO_2-eq)
Complete Mix Digester	Anaerobic Lagoon	300	Southern Plains	Dairy	$32
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	5,000	Southeast	Dairy	$32
Covered Lagoon Anaerobic Digester without EG	Deep Pit	2,500	Southeast	Swine	$32
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	2,500	Southeast	Swine	$32
Complete Mix Digester	Liquid/Slurry	5,000	Pacific	Dairy	$32
Complete Mix Digester	Liquid/Slurry	5,000	Appalachia	Dairy	$32
Complete Mix Digester	Anaerobic Lagoon	300	Delta	Dairy	$32
Plug Flow Digesters	Liquid/Slurry	5,000	Pacific	Dairy	$32
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	600	Appalachia	Dairy	$33
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	5,000	Southern Plains	Dairy	$33
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	5,000	Delta	Dairy	$33
Covered Lagoon Anaerobic Digester without EG	Deep Pit	2,500	Delta	Swine	$33
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	2,500	Delta	Swine	$33
Plug Flow Digesters	Liquid/Slurry	5,000	Corn Belt	Dairy	$33
Covered Lagoon Anaerobic Digester without EG	Deep Pit	2,500	Southern Plains	Swine	$34
Covered Lagoon Anaerobic Digester without EG	Deep Pit	2,500	Appalachia	Swine	$34
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	2,500	Southern Plains	Swine	$34
Complete Mix Digester	Liquid/Slurry	1,000	Southern Plains	Dairy	$34
Complete Mix Digester	Anaerobic Lagoon	300	Appalachia	Dairy	$34
Complete Mix Digester	Anaerobic Lagoon	300	Pacific	Dairy	$34
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	2,500	Appalachia	Swine	$35
Covering an Existing Lagoon	Liquid/Slurry	300	Mountain	Dairy	$35
Complete Mix Digester	Deep Pit	5,000	Pacific	Dairy	$36
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	5,000	Southeast	Dairy	$36
Plug Flow Digesters	Liquid/Slurry	2,500	Southeast	Beef	$36

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Complete Mix Digester	Liquid/Slurry	1,000	Delta	Dairy	$37
Plug Flow Digesters	Liquid/Slurry	2,500	Delta	Beef	$38
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	600	Southeast	Dairy	$39
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	600	Southern Plains	Dairy	$39
Complete Mix Digester	Anaerobic Lagoon	300	Northern Plains	Dairy	$39
Complete Mix Digester	Deep Pit	600	Southeast	Dairy	$40
Complete Mix Digester	Anaerobic Lagoon	300	Mountain	Dairy	$40
Complete Mix Digester	Anaerobic Lagoon	300	Corn Belt	Dairy	$40
Covered Lagoon Anaerobic Digester with EG	Deep Pit	1,000	Southeast	Dairy	$40
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	600	Delta	Dairy	$40
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	5,000	Southern Plains	Dairy	$40
Complete Mix Digester	Deep Pit	600	Southern Plains	Dairy	$40
Complete Mix Digester	Liquid/Slurry	1,000	Southeast	Beef	$41
Covered Lagoon Anaerobic Digester with EG	Deep Pit	1,000	Southern Plains	Dairy	$41
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	600	Pacific	Dairy	$41
Complete Mix Digester	Deep Pit	600	Delta	Dairy	$41
Covered Lagoon Anaerobic Digester with EG	Deep Pit	1,000	Delta	Dairy	$42
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	600	Appalachia	Dairy	$42
Plug Flow Digesters	Liquid/Slurry	2,500	Southern Plains	Beef	$42
Complete Mix Digester	Anaerobic Lagoon	300	Northeast	Dairy	$42
Complete Mix Digester	Anaerobic Lagoon	300	Lake States	Dairy	$43
Complete Mix Digester	Liquid/Slurry	1,000	Delta	Beef	$43
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	5,000	Delta	Dairy	$43
Covering an Existing Lagoon	Liquid/Slurry	500	Southern Plains	Swine	$43
Covering an Existing Lagoon	Liquid/Slurry	500	Delta	Swine	$43
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	600	Mountain	Dairy	$44

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price
					(2010 $/ mt CO_2-eq)
Plug Flow Digesters	Liquid/Slurry	2,500	Pacific	Beef	$44
Complete Mix Digester	Liquid/Slurry	600	Southeast	Dairy	$44
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	500	Southeast	Swine	$45
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	500	Southern Plains	Swine	$45
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	500	Delta	Swine	$45
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	500	Appalachia	Swine	$45
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	1,000	Southeast	Dairy	$45
Covering an Existing Lagoon	Liquid/Slurry	500	Appalachia	Swine	$45
Complete Mix Digester	Liquid/Slurry	1,000	Pacific	Beef	$46
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	500	Pacific	Swine	$46
Plug Flow Digesters	Liquid/Slurry	5,000	Appalachia	Dairy	$47
Complete Mix Digester	Liquid/Slurry	1,000	Southern Plains	Beef	$48
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	500	Mountain	Swine	$49
Covered Lagoon Anaerobic Digester without EG	Deep Pit	2,500	Pacific	Swine	$49
Complete Mix Digester	Liquid/Slurry	600	Southern Plains	Dairy	$49
Plug Flow Digesters	Liquid/Slurry	1,000	Southeast	Dairy	$50
Complete Mix Digester	Deep Pit	5,000	Corn Belt	Dairy	$50
Complete Mix Digester	Deep Pit	1,000	Appalachia	Dairy	$50
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	1,000	Southern Plains	Dairy	$50
Complete Mix Digester	Deep Pit	500	Southeast	Swine	$51
Complete Mix Digester	Deep Pit	500	Delta	Swine	$51
Complete Mix Digester	Liquid/Slurry	500	Southeast	Swine	$51
Complete Mix Digester	Deep Pit	5,000	Northern Plains	Dairy	$51
Plug Flow Digesters	Liquid/Slurry	5,000	Northeast	Dairy	$52
Complete Mix Digester	Liquid/Slurry	1,000	Northern Plains	Beef	$52
Complete Mix Digester	Liquid/Slurry	500	Delta	Swine	$52
Complete Mix Digester	Deep Pit	500	Southern Plains	Swine	$53

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Complete Mix Digester	Liquid/Slurry	1,000	Mountain	Beef	$53
Complete Mix Digester	Liquid/Slurry	500	Southern Plains	Swine	$53
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	500	Southeast	Swine	$53
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	500	Southern Plains	Swine	$53
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	500	Delta	Swine	$53
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	500	Appalachia	Swine	$53
Covering an Existing Lagoon	Liquid/Slurry	150	Southern Plains	Swine	$53
Complete Mix Digester	Liquid/Slurry	600	Delta	Dairy	$53
Complete Mix Digester	Deep Pit	500	Appalachia	Swine	$54
Complete Mix Digester	Liquid/Slurry	500	Appalachia	Swine	$54
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	1,000	Delta	Dairy	$54
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	500	Pacific	Swine	$54
Covering an Existing Lagoon	Liquid/Slurry	150	Delta	Swine	$54
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	2,500	Pacific	Swine	$55
Plug Flow Digesters	Liquid/Slurry	1,000	Southern Plains	Dairy	$55
Plug Flow Digesters	Liquid/Slurry	5,000	Lake States	Dairy	$57
Covering an Existing Lagoon	Liquid/Slurry	150	Appalachia	Swine	$57
Plug Flow Digesters	Liquid/Slurry	2,500	Appalachia	Beef	$57
Complete Mix Digester	Liquid/Slurry	1,000	Corn Belt	Beef	$58
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	5,000	Appalachia	Dairy	$58
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	500	Mountain	Swine	$58
Complete Mix Digester	Liquid/Slurry	5,000	Mountain	Dairy	$60
Plug Flow Digesters	Liquid/Slurry	1,000	Delta	Dairy	$60
Complete Mix Digester	Liquid/Slurry	1,000	Northeast	Beef	$61
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	300	Southeast	Dairy	$61
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	300	Southern Plains	Dairy	$61

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	300	Pacific	Dairy	$61
Complete Mix Digester	Liquid/Slurry	1,000	Pacific	Dairy	$62
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	300	Delta	Dairy	$62
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	300	Mountain	Dairy	$62
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	1,000	Southeast	Dairy	$62
Plug Flow Digesters	Liquid/Slurry	2,500	Northern Plains	Beef	$62
Complete Mix Digester	Deep Pit	5,000	Northeast	Dairy	$63
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	1,000	Southern Plains	Dairy	$63
Plug Flow Digesters	Liquid/Slurry	2,500	Mountain	Beef	$63
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	1,000	Delta	Dairy	$64
Complete Mix Digester	Liquid/Slurry	1,000	Appalachia	Beef	$65
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	300	Appalachia	Dairy	$65
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	5,000	Pacific	Dairy	$66
Covering an Existing Lagoon	Liquid/Slurry	500	Southeast	Swine	$66
Covered Lagoon Anaerobic Digester with EG	Deep Pit	600	Southeast	Dairy	$67
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	300	Southeast	Dairy	$67
Complete Mix Digester	Liquid/Slurry	5,000	Northern Plains	Dairy	$68
Complete Mix Digester	Liquid/Slurry	1,000	Lake States	Beef	$68
Covered Lagoon Anaerobic Digester with EG	Deep Pit	600	Southern Plains	Dairy	$68
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	300	Southern Plains	Dairy	$68
Complete Mix Digester	Liquid/Slurry	1,000	Appalachia	Dairy	$69
Covered Lagoon Anaerobic Digester with EG	Deep Pit	600	Delta	Dairy	$69
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	300	Delta	Dairy	$69
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	1,000	Southeast	Dairy	$69

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 \$/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester without EG	Deep Pit	2,500	Mountain	Swine	\$69
Plug Flow Digesters	Liquid/Slurry	2,500	Corn Belt	Beef	\$69
Complete Mix Digester	Deep Pit	1,000	Pacific	Dairy	\$69
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	300	Pacific	Dairy	\$70
Complete Mix Digester	Deep Pit	300	Southeast	Dairy	\$70
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	2,500	Mountain	Swine	\$71
Plug Flow Digesters	Liquid/Slurry	2,500	Northeast	Beef	\$71
Complete Mix Digester	Deep Pit	300	Southern Plains	Dairy	\$71
Complete Mix Digester	Deep Pit	600	Appalachia	Dairy	\$72
Complete Mix Digester	Deep Pit	300	Delta	Dairy	\$73
Complete Mix Digester	Deep Pit	5,000	Mountain	Dairy	\$73
Covered Lagoon Anaerobic Digester with EG	Deep Pit	1,000	Appalachia	Dairy	\$73
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	300	Appalachia	Dairy	\$73
Plug Flow Digesters	Liquid/Slurry	600	Southeast	Dairy	\$73
Complete Mix Digester	Liquid/Slurry	5,000	Corn Belt	Dairy	\$73
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	5,000	Pacific	Dairy	\$74
Complete Mix Digester	Deep Pit	5,000	Lake States	Dairy	\$75
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	600	Southeast	Dairy	\$75
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	1,000	Pacific	Dairy	\$75
Covered Lagoon Anaerobic Digester with Flaring	Anaerobic Lagoon	300	Mountain	Dairy	\$75
Complete Mix Digester	Deep Pit	500	Pacific	Swine	\$77
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	1,000	Southern Plains	Dairy	\$77
Complete Mix Digester	Liquid/Slurry	300	Southeast	Dairy	\$78
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	5,000	Appalachia	Dairy	\$80
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	1,000	Mountain	Dairy	\$81
Covering an Existing Lagoon	Liquid/Slurry	500	Mountain	Swine	\$81

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price
					(2010 $/ mt CO_2-eq)
Plug Flow Digesters	Liquid/Slurry	2,500	Lake States	Beef	$81
Plug Flow Digesters	Liquid/Slurry	600	Southern Plains	Dairy	$82
Complete Mix Digester	Deep Pit	1,000	Corn Belt	Dairy	$83
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	600	Southern Plains	Dairy	$83
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	1,000	Delta	Dairy	$83
Covering an Existing Lagoon	Liquid/Slurry	150	Southeast	Swine	$83
Covered Lagoon Anaerobic Digester with EG	Deep Pit	1,000	Pacific	Dairy	$84
Plug Flow Digesters	Liquid/Slurry	1,000	Southeast	Beef	$84
Plug Flow Digesters	Liquid/Slurry	1,000	Pacific	Dairy	$85
Complete Mix Digester	Deep Pit	1,000	Northern Plains	Dairy	$86
Complete Mix Digester	Deep Pit	500	Northern Plains	Swine	$86
Complete Mix Digester	Liquid/Slurry	500	Southeast	Beef	$86
Complete Mix Digester	Liquid/Slurry	500	Corn Belt	Swine	$86
Complete Mix Digester	Liquid/Slurry	500	Northern Plains	Swine	$86
Complete Mix Digester	Liquid/Slurry	500	Pacific	Swine	$86
Complete Mix Digester	Liquid/Slurry	600	Pacific	Dairy	$87
Complete Mix Digester	Liquid/Slurry	300	Southern Plains	Dairy	$87
Complete Mix Digester	Deep Pit	500	Corn Belt	Swine	$87
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	600	Southeast	Dairy	$87
Complete Mix Digester	Anaerobic Lagoon	150	Southeast	Swine	$88
Complete Mix Digester	Anaerobic Lagoon	150	Southern Plains	Swine	$88
Complete Mix Digester	Anaerobic Lagoon	150	Delta	Swine	$88
Complete Mix Digester	Anaerobic Lagoon	150	Appalachia	Swine	$88
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	600	Southern Plains	Dairy	$88
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	5,000	Mountain	Dairy	$88
Plug Flow Digesters	Liquid/Slurry	1,000	Delta	Beef	$88
Plug Flow Digesters	Liquid/Slurry	600	Delta	Dairy	$88
Complete Mix Digester	Anaerobic Lagoon	150	Pacific	Swine	$90
Complete Mix Digester	Liquid/Slurry	500	Delta	Beef	$90

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 \$/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	600	Delta	Dairy	\$90
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	600	Delta	Dairy	\$90
Complete Mix Digester	Liquid/Slurry	300	Delta	Dairy	\$94
Complete Mix Digester	Anaerobic Lagoon	150	Northern Plains	Swine	\$95
Complete Mix Digester	Anaerobic Lagoon	150	Mountain	Swine	\$96
Complete Mix Digester	Anaerobic Lagoon	150	Corn Belt	Swine	\$96
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	600	Southeast	Dairy	\$96
Complete Mix Digester	Deep Pit	600	Pacific	Dairy	\$97
Plug Flow Digesters	Liquid/Slurry	1,000	Mountain	Dairy	\$98
Plug Flow Digesters	Liquid/Slurry	1,000	Southern Plains	Beef	\$98
Complete Mix Digester	Liquid/Slurry	600	Appalachia	Dairy	\$99
Complete Mix Digester	Anaerobic Lagoon	150	Northeast	Swine	\$99
Complete Mix Digester	Anaerobic Lagoon	150	Lake States	Swine	\$99
Covered Lagoon Anaerobic Digester with EG	Deep Pit	1,000	Mountain	Dairy	\$99
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	500	Southeast	Swine	\$99
Plug Flow Digesters	Liquid/Slurry	500	Southeast	Swine	\$99
Complete Mix Digester	Liquid/Slurry	1,000	Mountain	Dairy	\$100
Complete Mix Digester	Deep Pit	500	Northeast	Swine	\$100
Complete Mix Digester	Liquid/Slurry	500	Pacific	Beef	\$100
Complete Mix Digester	Liquid/Slurry	500	Northeast	Swine	\$100
Covered Lagoon Anaerobic Digester with EG	Deep Pit	500	Southeast	Swine	\$100
Covered Lagoon Anaerobic Digester with EG	Deep Pit	500	Delta	Swine	\$100
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	1,000	Appalachia	Dairy	\$100
Complete Mix Digester	Liquid/Slurry	500	Southern Plains	Beef	\$101
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	500	Delta	Swine	\$101
Covering an Existing Lagoon	Liquid/Slurry	150	Mountain	Swine	\$101
Plug Flow Digesters	Liquid/Slurry	500	Delta	Swine	\$101

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Plug Flow Digesters	Liquid/Slurry	1,000	Pacific	Beef	$102
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	500	Southern Plains	Swine	$103
Plug Flow Digesters	Liquid/Slurry	500	Southern Plains	Swine	$103
Complete Mix Digester	Liquid/Slurry	5,000	Northeast	Dairy	$104
Covered Lagoon Anaerobic Digester with EG	Deep Pit	500	Southern Plains	Swine	$104
Complete Mix Digester	Deep Pit	500	Lake States	Swine	$105
Complete Mix Digester	Liquid/Slurry	500	Lake States	Swine	$105
Covered Lagoon Anaerobic Digester with EG	Deep Pit	500	Appalachia	Swine	$106
Complete Mix Digester	Deep Pit	1,000	Northeast	Dairy	$106
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	500	Appalachia	Swine	$107
Plug Flow Digesters	Liquid/Slurry	500	Appalachia	Swine	$107
Complete Mix Digester	Deep Pit	500	Mountain	Swine	$108
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	5,000	Mountain	Dairy	$108
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	600	Southern Plains	Dairy	$108
Complete Mix Digester	Deep Pit	600	Corn Belt	Dairy	$111
Complete Mix Digester	Liquid/Slurry	500	Mountain	Swine	$111
Plug Flow Digesters	Liquid/Slurry	1,000	Appalachia	Dairy	$111
Plug Flow Digesters	Liquid/Slurry	1,000	Northern Plains	Dairy	$112
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	1,000	Appalachia	Dairy	$112
Complete Mix Digester	Liquid/Slurry	1,000	Northern Plains	Dairy	$114
Complete Mix Digester	Deep Pit	600	Northern Plains	Dairy	$114
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	600	Delta	Dairy	$116
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	500	Southeast	Swine	$117
Covered Lagoon Anaerobic Digester without EG	Deep Pit	500	Southeast	Swine	$118
Covered Lagoon Anaerobic Digester without EG	Deep Pit	500	Delta	Swine	$118
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	500	Delta	Swine	$119

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Plug Flow Digesters	Liquid/Slurry	1,000	Corn Belt	Dairy	$121
Covered Lagoon Anaerobic Digester with EG	Deep Pit	600	Appalachia	Dairy	$121
Complete Mix Digester	Deep Pit	1,000	Mountain	Dairy	$122
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	500	Southern Plains	Swine	$122
Complete Mix Digester	Liquid/Slurry	1,000	Corn Belt	Dairy	$123
Covered Lagoon Anaerobic Digester without EG	Deep Pit	500	Southern Plains	Swine	$123
Complete Mix Digester	Liquid/Slurry	5,000	Lake States	Dairy	$125
Complete Mix Digester	Deep Pit	1,000	Lake States	Dairy	$125
Covered Lagoon Anaerobic Digester without EG	Deep Pit	500	Appalachia	Swine	$125
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	500	Appalachia	Swine	$126
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	1,000	Pacific	Dairy	$127
Complete Mix Digester	Deep Pit	300	Appalachia	Dairy	$127
Complete Mix Digester	Liquid/Slurry	500	Northern Plains	Beef	$129
Plug Flow Digesters	Liquid/Slurry	600	Pacific	Dairy	$129
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	600	Pacific	Dairy	$130
Complete Mix Digester	Liquid/Slurry	500	Mountain	Beef	$132
Plug Flow Digesters	Liquid/Slurry	1,000	Appalachia	Beef	$132
Plug Flow Digesters	Liquid/Slurry	300	Southeast	Dairy	$133
Complete Mix Digester	Liquid/Slurry	600	Mountain	Dairy	$133
Covered Lagoon Anaerobic Digester with EG	Deep Pit	300	Southeast	Dairy	$134
Complete Mix Digester	Liquid/Slurry	500	Appalachia	Beef	$136
Covered Lagoon Anaerobic Digester with EG	Deep Pit	300	Southern Plains	Dairy	$136
Covered Lagoon Anaerobic Digester with EG	Deep Pit	300	Delta	Dairy	$139
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	1,000	Pacific	Dairy	$142
Complete Mix Digester	Deep Pit	600	Northeast	Dairy	$143
Complete Mix Digester	Liquid/Slurry	500	Corn Belt	Beef	$144

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price
					(2010 \$/ mt CO_2-eq)
Plug Flow Digesters	Liquid/Slurry	1,000	Northern Plains	Beef	\$144
Covered Lagoon Anaerobic Digester with EG	Deep Pit	600	Pacific	Dairy	\$146
Plug Flow Digesters	Liquid/Slurry	1,000	Mountain	Beef	\$147
Plug Flow Digesters	Liquid/Slurry	300	Southern Plains	Dairy	\$148
Complete Mix Digester	Liquid/Slurry	500	Northeast	Beef	\$149
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	300	Southeast	Dairy	\$149
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	300	Southeast	Dairy	\$149
Complete Mix Digester	Liquid/Slurry	300	Pacific	Dairy	\$149
Covered Lagoon Anaerobic Digester with EG	Deep Pit	500	Pacific	Swine	\$150
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	300	Southern Plains	Dairy	\$151
Complete Mix Digester	Liquid/Slurry	600	Northern Plains	Dairy	\$152
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	300	Delta	Dairy	\$154
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	1,000	Appalachia	Dairy	\$154
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	600	Mountain	Dairy	\$155
Plug Flow Digesters	Liquid/Slurry	600	Mountain	Dairy	\$157
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	600	Appalachia	Dairy	\$157
Plug Flow Digesters	Liquid/Slurry	1,000	Corn Belt	Beef	\$160
Plug Flow Digesters	Liquid/Slurry	300	Delta	Dairy	\$160
Complete Mix Digester	Deep Pit	600	Mountain	Dairy	\$163
Plug Flow Digesters	Liquid/Slurry	500	Southeast	Beef	\$163
Plug Flow Digesters	Liquid/Slurry	1,000	Northeast	Beef	\$164
Complete Mix Digester	Liquid/Slurry	600	Corn Belt	Dairy	\$164
Plug Flow Digesters	Liquid/Slurry	600	Appalachia	Dairy	\$165
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	300	Southeast	Dairy	\$165
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	150	Southeast	Swine	\$165
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	150	Southern Plains	Swine	\$165

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	150	Delta	Swine	$165
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	150	Southeast	Swine	$166
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	150	Southern Plains	Swine	$166
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	150	Delta	Swine	$166
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	150	Appalachia	Swine	$166
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	300	Southern Plains	Dairy	$166
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	150	Appalachia	Swine	$166
Complete Mix Digester	Deep Pit	600	Lake States	Dairy	$167
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	600	Appalachia	Dairy	$167
Complete Mix Digester	Deep Pit	300	Pacific	Dairy	$167
Plug Flow Digesters	Liquid/Slurry	500	Corn Belt	Swine	$168
Plug Flow Digesters	Liquid/Slurry	500	Northern Plains	Swine	$168
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	500	Pacific	Swine	$169
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	150	Pacific	Swine	$169
Plug Flow Digesters	Liquid/Slurry	500	Pacific	Swine	$169
Complete Mix Digester	Liquid/Slurry	500	Lake States	Beef	$170
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	150	Pacific	Swine	$170
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	1,000	Mountain	Dairy	$170
Plug Flow Digesters	Liquid/Slurry	500	Delta	Beef	$171
Plug Flow Digesters	Liquid/Slurry	500	Northeast	Swine	$172
Complete Mix Digester	Liquid/Slurry	300	Appalachia	Dairy	$175
Complete Mix Digester	Liquid/Slurry	1,000	Northeast	Dairy	$176
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	600	Pacific	Dairy	$177
Covered Lagoon Anaerobic Digester without EG	Deep Pit	500	Pacific	Swine	$177
Plug Flow Digesters	Liquid/Slurry	1,000	Northeast	Dairy	$179

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price
					(2010 $/ mt CO_2-eq)
Plug Flow Digesters	Liquid/Slurry	600	Northern Plains	Dairy	$179
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	300	Delta	Dairy	$180
Covered Lagoon Anaerobic Digester without EG	Anaerobic Lagoon	150	Mountain	Swine	$180
Complete Mix Digester	Deep Pit	300	Corn Belt	Dairy	$180
Covered Lagoon Anaerobic Digester with EG	Anaerobic Lagoon	150	Mountain	Swine	$181
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	300	Southern Plains	Dairy	$184
Complete Mix Digester	Deep Pit	300	Northern Plains	Dairy	$186
Covered Lagoon Anaerobic Digester with EG	Deep Pit	600	Mountain	Dairy	$189
Plug Flow Digesters	Liquid/Slurry	1,000	Lake States	Beef	$189
Plug Flow Digesters	Liquid/Slurry	500	Southern Plains	Beef	$191
Plug Flow Digesters	Liquid/Slurry	600	Corn Belt	Dairy	$193
Complete Mix Digester	Liquid/Slurry	150	Southeast	Swine	$194
Complete Mix Digester	Deep Pit	150	Southeast	Swine	$195
Complete Mix Digester	Deep Pit	150	Delta	Swine	$196
Complete Mix Digester	Liquid/Slurry	150	Delta	Swine	$197
Plug Flow Digesters	Liquid/Slurry	500	Pacific	Beef	$198
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	600	Pacific	Dairy	$199
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	300	Delta	Dairy	$199
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	500	Pacific	Swine	$199
Complete Mix Digester	Liquid/Slurry	150	Southern Plains	Swine	$202
Complete Mix Digester	Deep Pit	150	Southern Plains	Swine	$204
Plug Flow Digesters	Liquid/Slurry	500	Lake States	Swine	$205
Plug Flow Digesters	Liquid/Slurry	1,000	Lake States	Dairy	$205
Complete Mix Digester	Deep Pit	150	Appalachia	Swine	$207
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	1,000	Mountain	Dairy	$207
Complete Mix Digester	Liquid/Slurry	1,000	Lake States	Dairy	$209
Complete Mix Digester	Liquid/Slurry	150	Appalachia	Swine	$209

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price
					(2010 $/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester with EG	Deep Pit	500	Mountain	Swine	$211
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	600	Appalachia	Dairy	$216
Complete Mix Digester	Liquid/Slurry	300	Mountain	Dairy	$217
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	500	Mountain	Swine	$217
Plug Flow Digesters	Liquid/Slurry	500	Mountain	Swine	$217
Complete Mix Digester	Deep Pit	300	Northeast	Dairy	$234
Complete Mix Digester	Liquid/Slurry	600	Northeast	Dairy	$236
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	600	Mountain	Dairy	$238
Plug Flow Digesters	Liquid/Slurry	300	Pacific	Dairy	$239
Covered Lagoon Anaerobic Digester with EG	Deep Pit	300	Appalachia	Dairy	$243
Complete Mix Digester	Liquid/Slurry	300	Northern Plains	Dairy	$247
Covered Lagoon Anaerobic Digester without EG	Deep Pit	500	Mountain	Swine	$249
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	500	Mountain	Swine	$257
Plug Flow Digesters	Liquid/Slurry	500	Appalachia	Beef	$258
Complete Mix Digester	Deep Pit	300	Mountain	Dairy	$265
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	300	Pacific	Dairy	$267
Complete Mix Digester	Liquid/Slurry	300	Corn Belt	Dairy	$267
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	300	Appalachia	Dairy	$270
Complete Mix Digester	Deep Pit	300	Lake States	Dairy	$271
Complete Mix Digester	Liquid/Slurry	600	Lake States	Dairy	$279
Plug Flow Digesters	Liquid/Slurry	500	Northern Plains	Beef	$281
Plug Flow Digesters	Liquid/Slurry	600	Northeast	Dairy	$285
Plug Flow Digesters	Liquid/Slurry	500	Mountain	Beef	$287
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	600	Mountain	Dairy	$290
Complete Mix Digester	Deep Pit	150	Pacific	Swine	$293
Plug Flow Digesters	Liquid/Slurry	300	Appalachia	Dairy	$298

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester with EG	Deep Pit	300	Pacific	Dairy	$299
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	300	Pacific	Dairy	$304
Plug Flow Digesters	Liquid/Slurry	300	Mountain	Dairy	$305
Plug Flow Digesters	Liquid/Slurry	500	Corn Belt	Beef	$312
Plug Flow Digesters	Liquid/Slurry	500	Northeast	Beef	$320
Complete Mix Digester	Liquid/Slurry	150	Corn Belt	Swine	$328
Plug Flow Digesters	Liquid/Slurry	600	Lake States	Dairy	$329
Complete Mix Digester	Liquid/Slurry	150	Northern Plains	Swine	$329
Complete Mix Digester	Deep Pit	150	Northern Plains	Swine	$330
Complete Mix Digester	Liquid/Slurry	150	Pacific	Swine	$330
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	300	Appalachia	Dairy	$333
Complete Mix Digester	Deep Pit	150	Corn Belt	Swine	$335
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	300	Mountain	Dairy	$339
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	300	Pacific	Dairy	$341
Plug Flow Digesters	Liquid/Slurry	300	Northern Plains	Dairy	$347
Complete Mix Digester	Deep Pit	150	Northeast	Swine	$348
Complete Mix Digester	Liquid/Slurry	150	Northeast	Swine	$348
Plug Flow Digesters	Liquid/Slurry	150	Southeast	Swine	$352
Plug Flow Digesters	Liquid/Slurry	150	Delta	Swine	$358
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	150	Southeast	Swine	$365
Plug Flow Digesters	Liquid/Slurry	150	Southern Plains	Swine	$366
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	150	Southeast	Swine	$367
Covered Lagoon Anaerobic Digester without EG	Deep Pit	150	Southeast	Swine	$367
Plug Flow Digesters	Liquid/Slurry	500	Lake States	Beef	$368
Covered Lagoon Anaerobic Digester with EG	Deep Pit	150	Southeast	Swine	$369
Covered Lagoon Anaerobic Digester without EG	Deep Pit	150	Delta	Swine	$369

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price (2010 $/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	300	Appalachia	Dairy	$370
Covered Lagoon Anaerobic Digester with EG	Deep Pit	150	Delta	Swine	$371
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	150	Delta	Swine	$371
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	150	Delta	Swine	$374
Plug Flow Digesters	Liquid/Slurry	300	Corn Belt	Dairy	$375
Plug Flow Digesters	Liquid/Slurry	150	Appalachia	Swine	$379
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	150	Southern Plains	Swine	$380
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	150	Southern Plains	Swine	$382
Covered Lagoon Anaerobic Digester without EG	Deep Pit	150	Southern Plains	Swine	$384
Complete Mix Digester	Liquid/Slurry	300	Northeast	Dairy	$386
Covered Lagoon Anaerobic Digester with EG	Deep Pit	150	Southern Plains	Swine	$387
Covered Lagoon Anaerobic Digester without EG	Deep Pit	150	Appalachia	Swine	$389
Covered Lagoon Anaerobic Digester with EG	Deep Pit	150	Appalachia	Swine	$391
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	150	Appalachia	Swine	$392
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	150	Appalachia	Swine	$395
Complete Mix Digester	Deep Pit	150	Lake States	Swine	$400
Complete Mix Digester	Liquid/Slurry	150	Lake States	Swine	$401
Covered Lagoon Anaerobic Digester with Flaring	Liquid/Slurry	300	Mountain	Dairy	$408
Complete Mix Digester	Deep Pit	150	Mountain	Swine	$412
Covered Lagoon Anaerobic Digester with EG	Deep Pit	300	Mountain	Dairy	$413
Complete Mix Digester	Liquid/Slurry	150	Mountain	Swine	$425
Complete Mix Digester	Liquid/Slurry	300	Lake States	Dairy	$454
Covered Lagoon Anaerobic Digester with Flaring	Deep Pit	300	Mountain	Dairy	$497
Plug Flow Digesters	Liquid/Slurry	300	Northeast	Dairy	$549

Mitigation Practice	Baseline Management Practice	Farm Size	Region	Animal Type	Break-Even Price
					(2010 $/ mt CO_2-eq)
Covered Lagoon Anaerobic Digester without EG	Deep Pit	150	Pacific	Swine	$551
Covered Lagoon Anaerobic Digester with EG	Deep Pit	150	Pacific	Swine	$554
Plug Flow Digesters	Liquid/Slurry	150	Corn Belt	Swine	$595
Plug Flow Digesters	Liquid/Slurry	150	Northern Plains	Swine	$597
Plug Flow Digesters	Liquid/Slurry	150	Pacific	Swine	$599
Plug Flow Digesters	Liquid/Slurry	150	Northeast	Swine	$610
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	150	Pacific	Swine	$621
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	150	Pacific	Swine	$624
Plug Flow Digesters	Liquid/Slurry	300	Lake States	Dairy	$638
Plug Flow Digesters	Liquid/Slurry	150	Lake States	Swine	$727
Plug Flow Digesters	Liquid/Slurry	150	Mountain	Swine	$771
Covered Lagoon Anaerobic Digester without EG	Deep Pit	150	Mountain	Swine	$775
Covered Lagoon Anaerobic Digester with EG	Deep Pit	150	Mountain	Swine	$779
Covered Lagoon Anaerobic Digester without EG	Liquid/Slurry	150	Mountain	Swine	$799
Covered Lagoon Anaerobic Digester with EG	Liquid/Slurry	150	Mountain	Swine	$804

CHAPTER 3: REFERENCES

Aguerre, M.J., M.A. Wattiaux, J.M. Powell, and G.A. Broderick. 2011. Effect of forage to concentrate ratio in dairy cow diets on emission of methane, carbon dioxide and ammonia, lactation performance and manure excretion. *Journal of Dairy Science*, 94:3081–3093.

Allard, V., J.F. Soussana, R. Falcimagne, P. Berbigier, et al. 2007. The role of grazing management for the net biome productivity and greenhouse gas budget (CO_2, N_2O and CH_4) of semi-natural grassland. *Agriculture Ecosystems and Environment*, 121:47–58.

American Society of Agricultural and Biological Engineers. 2005. Manure Production and Characteristics ASAE D384.2.

Beauchemin, K.A., L. Eriksen, P. Norgaard, and L.M. Rode. 2008. Nutritional management for enteric methane abatement: a review. *Australian Journal of Experimental Agriculture*, 48:21–27.

Benchaar, C., J. Rivest, C. Pomar, and J. Chiquette. 1998. Prediction of methane production from dairy cows using existing mechanistic models and regression equations. *Journal of Animal Science*, 76:617–627.

Benchaar, C., C. Pomar, and J. Chiquette. 2001. Evaluation of dietary strategies to reduce methane production in ruminants: A modeling approach. *Canadian Journal of Animal Science*, 81:563–574.

Birkelo, C.P., D.E. Johnson, and G.M. Ward. 1986. Net energy value of ammoniated wheat straw. *Journal of Animal Science*, 63:2044–2052.

Boadi, D., C. Benchaar, J. Chiquette, and D. Massé. 2004. Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review. *Canadian Journal of Animal Science*, 84:319–335.

Briske, D.D., J.D. Derner, J.R. Brown, S.D. Fuhlendorf, et al. 2008. Rotational Grazing on Rangelands: Reconciliation of Perception and Experimental Evidence. *Rangeland Ecology and Management*, 63(1):3–16.

Briske, D.D., N.F. Sayre, L. Huntsinger, M. Fernandez-Gimenez, et al. 2011. Origin, Persistence, and Resolution of the Rotational Grazing Debate: Integrating Human Dimensions Into Rangeland Research. *Rangeland Ecology and Management*, 64:325–224.

Briske, D.D., (ed.) 2011. *Conservation Benefits of Rangeland Practices: Assessment, Recommendations, and Knowledge Gaps*: U.S. Department of Agriculture, Natural Resources Conservation Service.

California Code of Regulations. 2012. *SWRCB – Confined Animal Facilities*: Title 27, California Code of Regulations (CCR), Division 2, Subdivision 1, Chapter 7, Subchapter 2, Article 1.

Campbell, R. 2011. Personal Communication with Ray Campbell, Terrablue Corporation.

CAST. 2011. *Carbon Sequestration and Greenhouse Gas Fluxes in Agriclture: Challenges and Opportunities*. Ames, IA: Council for Agricultural Science and Technology.

Central Coast Compost, L. 2011. *Personal communication with Tom Ford.* http://www.omri.org/manufacturers/65555/central-coast-compost-llc.

ChemEurope. 2012. *Bovine somatotropin* http://www.chemeurope.com/en/encyclopedia/Bovine_somatotropin.html#Banned_outside_the_United_States.

Cheremisinoff, N., K. George, and J. Cohen. 2009. *Economic Study of Bioenergy Production from Digesters at Dairies in California*. Sacramento, CA: California Energy Commission http://www.energy.ca.gov/publications/displayOneReport.php?pubNum=CEC-500-2009-058.

Climate Action Reserve. 2009. Livestock Calculation Tool, beta version 2.1.3. Los Angeles, CA: Climate Action Reserve.

Conant, R.T., K. Paustian, and E.T. Elliott. 2001. Grassland management and conversion into grassland; Effects on soil carbon. *Ecological Applications*, 11:343–355.

Cooprider, K.L., F.M. Mitloehner, T.R. Famula, E. Kebreab, et al. 2011. Feedlot efficiency implications on greenhouse gas emission and sustainability. *Journal of Animal Science*, (in press).

Crutzen, P.J., I. Aselmann, and W. Seiler. 1986. Methane production by domestic animals, wild ruminants, other herbivorous fauna, and humans. *Tellus*, 38B:271–284.

Daritech Inc. 2012a. Personal communication regarding improved solids separators.

Daritech Inc. 2012b. DT360 Brochure.

Daritech Inc. 2011. *DT360 Separator*. http://www.daritech.com/categories/manure/separation/dt360%20separator/.

Denef, K., S. Archibeque, and K. Paustian. 2011. *Greenhouse Gas Emissions from U.S. Agriculture and Forestry: A Review of Emission Sources, Controlling Factors, and Mitigation Potential*: Interim report to USDA under Contract #GS-23F-8182H. http://www.usda.gov/oce/climate_change/techguide/Denef_et_al_2011_Review_of_reviews_v1.0.pdf.

Derner, J.D., T.W. Boutton, and D.D. Brisk. 2006. Grazing and ecosystem carbon storage in the North American Great Plains. *Plant and Soil*, 280(14):77–90.

Derner, J.D., and G.E. Schuman. 2007. Carbon sequestration and rangelands: A synthesis of land management and precipitation effects. *Journal of Soil and Water Conservation*, 62(2):77–85.

Dijkstra, J., E. Kebreab, J.A.N. Mills, W.F. Pellikaan, et al. 2007. Predicting the profile of nutrients available for absorption: from nutrient requirement to animal response and environmental impact. *Animal*, 1:99–111.

Dixon, R.K. 1995. Agroforestry systems: sources or sinks of greenhouse gases? *Agroforestry Systems*, 31:99–116.

Dunn, B.H., A.J. Smart, R.N. Gates, P.S. Johnson, et al. 2010. Long-Term Production and Profitability From Grazing Cattle in the Northern Mixed Grass Prairie. *Society for Range Management*, 63(2):233–242.

Eagle, A.J., L.P. Olander, L.R. Henry, K. Haugen-Kozyra, et al. 2012. *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States A Synthesis of the Literature*. Durham, NC: Nicholas Institute for Environmental Policy Solutions, Duke University.

Eckard, R.J., C. Grainger, and C.A.M.d. Klein. 2010. Options for the abatement of methane and nitrous oxide from ruminant production: A review. *Livestock Science*, 130(1):47–56.

EIA. 2012. *Average Retail Price of Electricity to Ultimate Consumers by End-Use*. Washington, DC: U.S. Energy Information Administration,. http://www.eia.doe.gov/electricity/epm/table5_6_b.html.

Emmerich, W.E. 2003. Carbon dioxide fluxes in a semiarid environment with high carbonate soils. *Agricultural and Forest Meteorology*, 116:91–102.

Environmental Fabrics Inc. 2011a. *BilMar Foods, Inc.* http://www.environmentalfabrics.com/case-studies-liners/bilmar-foods.

Environmental Fabrics Inc. 2011b. Personal communication.

EPA. 2002. *Development Document for the Final Revisions to the National Pollutant Discharge Elimination System Regulation and the Effluent Guidelines for Concentrated Animal Feeding Operations* Washington, DC: U.S. Environmental Protection Agency.

EPA. 2006a. *Managing Manure with Biogas Recovery Systems* Climate Leaders, Draft Offset Protocol. Washington, DC: U.S. Environmental Protection Agency. http://www.climateregistry.org/resources/docs/protocols/project/livestock/ClimateLeaders_DraftManureOffsetProtocol.pdf.

EPA. 2006b. *Global Mitigation of Non-CO_2 Greenhouse Gases - Section V Agriculture*. Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs.

EPA. 2009. *AgSTAR FarmWare* Washington, DC: U.S. Environmental Protection Agency,. http://www.epa.gov/agstar/tools/project-dev/farmware.html.

EPA. 2010a. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2007: U.S. Environmental Protection Agency.

EPA. 2010b. *AgSTAR Fact Sheet: Anaerobic Digestion Capital Costs for Dairy Farms*. Washington, DC: U.S. Environmental Protection Agency,. http://www.epa.gov/agstar/documents/digester_cost_fs.pdf.

EPA. 2010c. *Operating Anaerobic Digester Projects*: U.S. Environmental Protection Agency,. http://www.epa.gov/agstar/projects/index.html.

EPA. 2011a. *AgSTAR Anaerobic Digestion: Gas Use Devices*: U.S. Environmental Protection Agency. http://www.epa.gov/agstar/anaerobic/ad101/gas-use.html.

EPA. 2011b. *AgSTAR Anaerobic Digestion: Anaerobic Digesters*: U.S. Environmental Protection Agency. http://www.epa.gov/agstar/anaerobic/ad101/anaerobic-digesters.html.

EPA. 2011c. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2009*. Washington, DC: U.S. Environmental Protection Agency. http://epa.gov/climatechange/emissions/usinventoryreport.html.

EPA. 2012. *Operating Anaerobic Digester Projects*: U.S. Environmental Protection Agency. http://www.epa.gov/agstar/projects/index.html.

Ferket, P.R., E. van Heugten, T.A.T.G. van Kempen, and R. Angel. 2002. Nutritional strategies to reduce environmental emissions from nonruminants. *Journal of Animal Science*, 80:E168–E182.

Firkins, J.L., J.G. Bowman, W.P. Weiss, and J. Naderer. 1991. Effects of protein, carbohydrate, and fat sources on bacterial colonization degradation of fiber in vitro. *Journal of Dairy Science*, 74:4273–4283.

Follett, R.F. 2001. Soil management concepts and carbon sequestration in cropland soils. *Soil and Tillage Research*, 61(1–2):77–92.

Franzluebbers, A.J., and J.A. Stuedemann. 2010. Surface Soil Changes curing Twelve Years of Pasture Management in the Southern Piedmont USA. *Soil and Water management and Conservation*, 74:2131–2141.

Giger-Reverdin, S., P. Morand-Fehr, and G. Tran. 2003. Literature survey of the influence of dietary fat composition on methane production in dairy cattle. *Livestock Production Science*, 82(1):73–79.

Government of Saskatchewan. 2008. *Composting Solid Manure*. http://www.agriculture.gov.sk.ca/Composting_Solid_Manure.

Grainger, C., T. Clarke, K.A. Beauchemin, S.M. McGinn, et al. 2008. Supplementation with whole cottonseed reduces methane emissions and can profitably increase milk production of dairy cows offered a forage and cereal grain diet. *Australian Journal of Experimental Agriculture*, 48:73–76.

Guan, H., K.M. Wittenberg, K.H. Ominski, and D.O. Krause. 2006. Efficiency of ionophores in cattle diets for mitigation of enteric methane. *Journal of Animal Science*, 84:1896–1906.

Hales, K.E., N.A. Cole, and J.C. MacDonald. 2011. Effects of corn processing method and dietary inclusion of wet distillers grain with solubles on energy metabolism and enteric methane emissions of finishing cattle. *Journal of Animal Science*, 89(E-Supplement):196 (abstr.).

Hamilton, D.W. 2010. *Solids separation in manure handling systems*. http://www.extension.org/pages/27470/solids-separation-in-swine-manure-handling-systems#Introduction.

Hamilton, S., and F. Mitloehner. 2008. Environmental Responses to Dietary Monensin in Lactating Cows. Proceedings of the Mitigating Air Emissions from Animal Feeding Operations Conference, Iowa State University, Ames, IA.

Harper, L.A., O.T. Denmead, J.R. Freney, and F.M. Byers. 1999. Direct measurement s of methane emissions from grazing and feedlot cattle. *Journal of Animal Science*, 77:1391–1401.

Havstad, K.M., D.P.C. Peters, R. Skaggs, J. Brown, et al. 2007. Ecological Services to and from Rangelands of the United States. *Ecological Economics*, 64:261–268.

Heckman, E., S. Hinds, K. Johnson, J. Perkins, et al. 2007. *Management-Intensive Grazing in Indiana*. Wet Lafayette, IN: U.S. Department of Agriculture, Natural Resources Conservation Service, Purdue Extension. http://www.extension.purdue.edu/extmedia/AY/AY-328.pdf.

Hendrickson, J., M.A. Liebig, and J. Berdhal. 2008. Responses of Medicago sativa and M. falcata type alfalfas to different defoliation times and grass competition. *Canadian Journal of Plant Science*, 88:61–69.

Hindrichsen, I.K., H.R. Wettstein, A. Machmüller, and M. Kreuzer. 2006. Methane emission, nutrient degradation and nitrogen turnover in dairy cows and their slurry at different milk production scenarios with and without concentrate supplementation. *Agriculture, Ecosystems and Environment*, 113(1–4):150–161.

Hogan, R., S. Stiles, P. Tacker, E. Vories, et al. 2007. *Estimating Irrigation Costs*. Little Rock, AR: University of Arkansas, Division of Agriculture, Cooperative Extension Service. http://www.uaex.edu/Other_Areas/publications/PDF/FSA-28.pdf.

Holter, J.B., and A.J. Young. 1992. Methane prediction in dry and lactating Holstein cows. *Journal of Dairy Science*, 75:2165–2175.

Indiana Department of Natural Resources. 2005. *Legume Inter-Seeding*. Indianapolis, IN: Indiana Department of Natural Resources, Division of Fish and Wildlife,. http://www.in.gov/dnr/fishwild/files/HMFSLegumeInterSeed.pdf.

Ingram, L.J., G.E. Schuman, J.S. Buyer, G.F. Vance, et al. 2008. Grazing Impacts on Soil Carbon and Microbial Communities in a Mixed-Grass Ecosystem. *Soil Science Society of America Journal*, 72(4):939–948.

Iowa State University Extension and Outreach. 2012. Estimated Costs of Pasture and Hay Production. In *Ag Decision Maker*. Ames, IA: Iowa State University.

IPCC. 1996. *Climate change 1995: the science of climate change*. Cambridge, UK: Intergovernmental Panel on Climate Change.

IPCC. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*. Japan: Intergovernmental Panel on Climate Change. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html.

Izaurralde, R.C., A.M. Thomson, J.A. Morgan, P.A. Fay, et al. 2011. Climate Impacts on Agriculture: Implications for Forage and Rangeland Production. *Agronomy Journal*, 103(2):371–381.

Johnson, K.A., and D.E. Johnson. 1995. Methane emissions from cattle. *Journal of Animal Science*, 73:2483–2492.

Kahn, S.A., R.L. Mulvaney, T.R. Ellsworth, and C.W. Boast. 2007. The Myth of Nitrogen Fertilization for Soil Carbon Sequestration. *Journal of Environmental Quality*, 36:1821–1832.

Key, N., and S. Sneeringer. 2011. *Climate Change Policy and the Adoption of Methane Digesters on Livestock Operations*. Washington, DC: U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/publications/err-economic-research-report/err111.aspx.

Knapp, D.M., R.R. Grummer, and M.R. Dentine. 1991. The response of lactating dairy cows to increasing levels of whole roased soybeans. *Journal of Dairy Science*, 74:2563–2579.

LeCain, D.R., J.A. Morgan, G.E. Schuman, J.D. Reeder, et al. 2000. Carbon exchange rates in grazed and ungrazed pastures of Wyoming. *Journal of Range Management*, 53(2):199–206.

Liebig, M.A., J.A. Morgan, J.D. Reeder, B.H. Ellert, et al. 2005. Greenhouse gas contributions and mitigation potential of agricultural practices in northwestern USA and western Canada. *Soil and Tillage Research*, 83:25–52.

Liebig, M.A., J.R. Gross, S.L. Kronberg, R.L. Phillips, et al. 2010a. Grazing Management Contributions to Net Global Warming Potential: A Long-term Evaluation in the Northern Great Plains. *Journal of Environmental Quality*, 39:799–809.

Liebig, M.A., J.R. Hendrickson, and J.D. Berdahl. 2010b. Response of soil carbon and nitrogen to transplanted alfalfa in North Dakota rangeland. *Canadian Journal of Soil Science*:523–526.

Liebig, M.A., A.J. Franzluebbers, and R.F. Follett, (eds.). 2012. *Managing Agricultural Greenhouse Gases Coordinated Agricultural Research through GRACEnet to Address Our Changing Climate*. Waltham, MA: Elsevier.

Lovett, D., S. Lovell, L. Stack, J. Callan, et al. 2003. Effect of forage/concentrate ratio and dietary coconut oil level on methane output and performance of finishing beef heifers. *Livestock Production Science*, 84:135–146.

Lynch, D.H., R.D.H. Cohen, A. Fredeen, G. Patterson, et al. 2005. Management of Canadian prairie region grazed grasslands: Soil C sequestration, livestock productivity and profitability. *Canadian Journal of Soil Science*, 85(2):183–192.

MacDonald, J.M., E.J. O'Donoghue, W.D. McBride, R.F. Nehring, et al. 2007. *Profits, Costs, and the Changing Structure of Dairy Farming*. Economic Research Report Number 47, Washington, DC: U.S. Department of Agriculture, Economic Research Service.

Machmuller, A., C.R. Soliva, and M. Kreuzer. 2003. Methane suppressing effect of myristic acid in sheep as affected by dietary calcium and forage proportion. *British Journal of Nutrition*, 90:529–540.

Martens, D.A., W. Emmerich, J.E. McLain, and T.N. Johnsen. 2005. Atmospheric carbon mitigation potential of agricultural management in the southwestern USA. *Soil and Tillage Research*, 83:95-119.

Martin, C., D.P. Morgavi, and M. Doreau. 2010. Methane mitigation in ruminants: from microbe to the farm scale. *Animal*, 4:351–365.

McGinn, S.M., K.A. Beauchemin, T. Coates, and D. Colombatto. 2004. Methane emissions from beef cattle. Effects of Monensin, sunflower oil, enzymes, yeast, and fumaric acid. *Journal of Animal Science*, 82:3346–3356.

Mortenson, M.C., G.E. Schuman, and L.J. Ingram. 2004. Carbon Sequestration in Rangelands Interseeded with Yellow-Flowering Alfalfa (Medicago sativa ssp. falcata). *Environmental Management*, 33(Supplement 1):S475–S481.

Mortenson, M.C., G.E. Schuman, L.J. Ingram, V. Nayigihugu, et al. 2005. Forage Production and Quality of a Mixed-Grass Rangeland Interseeded with Medicago sativa ssp. falcata. *Rangeland Ecology and Management*, 58(5):505–513.

National Hog Farmer. 2008. *State of the Industry Report*. http://nationalhogfarmer.com/site-files/nationalhogfarmer.com/files/archive/nationalhogfarmer.com/NHF_SOI_TOTAL_LR.pdf?cid=resources.

Nickerson, C., R. Ebel, A. Borchers, and F. Carriazo. 2011. *Major Uses of Land in the United States, 2007*. Washington DC: U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/media/188404/eib89_2_.pdf.

NRAES. 2001. *Dairy Manure Systems: Equipment and Technology*. Ithaca, NY: Natural Resource, Agriculture and Engineering Service, Cooperative Extension.

Odongo, N.E., R. Bagg, G. Vessie, P. Dick, et al. 2007. Long term effects of feeding Monensin on methane production in lactating dairy cows. *Journal of Dairy Science*, 90:1781–1788.

Ogle, S., S. Archibeque, R. Gurung, and K. Paustian. 2010. *Report on GHG Mitigation Literature Review for Agricultural Systems*. Fort Collins, CO: U.S. Department of Agriculture, Climate Change Program Office.

Pearson, T., S. Walker, K. Paustian, B. Sohngen, et al. 2010. *Analysis of U.S. Agriculture, Forest, and Other Land Use Mitigation Activities: Quantitative Assessment and Ranking of Potential Activities*. Washington DC: U.S. Department of Agriculture.

Pineiro, G., J.M. Paruelo, M. Oesterheld, and E.G. Jobbagy. 2010. Pathways of Grazing Effects on Soil Organic Carbon and Nitrogen. *Rangeland Ecology and Management*, 63(1):109–119.

Ribaudo, M., J. Delgado, L. Hansen, M. Livingston, et al. 2011. *Nitrogen in Agricultural Systems; Implications for Convervation Policy*. Washington DC: U.S. Department of Agriculture.

Rochette, P., D.A. Angers, G. Belanger, M.H. Chantigny, et al. 2004. Emissions of N_2O from alfalfa and soybean crops in eastern Canada. *Soil Science Society of America Journal*, 68(2):493–506.

Russell, J.B., J.D. O'Connor, D.G. Fox, P.J.V. Soest, et al. 1992. A net carbohydrate and protein system for evaluating cattle diets: I. Ruminal fermentation. *Journal of Animal Science*, 70:3551–3561.

Schnabel, R.R., A.J. Franzluebbers, W.L. Stout, M.A. Sanderson, et al. 2001. The Effects of Pasture Management Practices. In *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Gas Effect*, R. F. Follett and J. M. Kimble (eds.). Boca Raton, FL: CRC Press.

Schuman, G.E., J.D. Reeder, J.T. Manley, R.H. Hart, et al. 1999. Impact of Grazing Management on the Carbon and Nitrogen Balance of a Mixed-Grass Rangeland. *Ecological Applications*., 9(1):6.

Sharrow, S.H., and S. Ismail. 2004. Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. *Agroforestry Systems*, 60:123–130.

Smith, R., G. Lacefield, R. Burris, D. Ditsch, et al. 2011. *Rotational Grazing*. Lexington, KY: University of Kentucky, College of Agriculture. http://www.ca.uky.edu/agc/pubs/id/id143/id143.pdf.

Smith, R.R. 2001. Image Number K9515-1. In *Red Clover*. http://www.ars.usda.gov/is/graphics/photos/jul01/k9515-1.htm.

Summers, M., and D.W. Williams. 2012. *Energy, Economic and Environmental Performance of Dairy Bio-Power and Bio-methane Systems*: California Energy Commission Project.

USDA-NRCS. 2009. *Conservation Practice Standard Anaerobic Digester, No. 366*. Washington, DC: U.S. Department of Agriculture- Natural Resource Conservation Service. ftp://ftp-fc.sc.egov.usda.gov/NHQ/practice-standards/standards/366.pdf.

USDA. 2007. *Census of Agriculture*. Washington, DC: U.S. Department of Agriculture. http://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_2_US_State_Level/index.asp.

USDA. 2011. *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990–2008*. Washington DC: U.S. Department of Agriculture, Climate Change Program Office, Office of the Chief Economist.

USDA. 2012. *Animal Product Manual: Glossary*: U.S. Department of Agriculture,. http://www.aphis.usda.gov/import_export/plants/manuals/ports/apm.shtml.

USDA ARS. 2005. *Interseeded Legumes*: U.S. Department of Agriculture, Agricultural Research Service.

USDA ERS. 2007. *The Changing Economics of U.S. Hog Production*: U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/publications/err-economic-research-report/err52.aspx.

USDA ERS. 2009. *Manure Use for Fertilizer and for Energy: Report to Congress*. Washington, DC: U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/media/377377/ap037fm_1_.pdf.

USDA NASS. 2008. *2007 Census of Agriculture*. Washington, DC: U.S. Department of Agriculture, National Agricultural Statistics Service. http://www.agcensus.usda.gov/Publications/2007/index.php.

USDA NASS. 2011. *A Comparison of U.S. Wage Rates*. Washington, DC: U.S. Department of Agriculture, National Agricultural Statistics Service. http://www.nass.usda.gov/Charts_and_Maps/graphics/data/fl_allwg.txt.

USDA NRCS. 2009. *Summary Report: 2007 National Resources Inventory*: U.S. Department of Agriculture, Natural Resources Conservation Service, Washington DC, and Center for Survey Statistics and Methodology, Iowa State University, Ames, Iowa. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1041379.pdf.

USDA NRCS. 2010a. *Standardized State Average Cost List*. Columbia, MO: U.S. Department of Agriculture, Natural Resources Conservation Service, Missouri State Office.

USDA NRCS. 2010b. *Forage and Biomass Planting code 512*. http://www.nrcs.usda.gov/technical/standards/nhcp.html.

Van Nevel, C.J., and D.I. Demeyer. 1996. Control of rumen methanogenesis. *Environmental Monitoring and Assessment*, 42:73–97.

Vanotti, M.B., A.A. Szogi, and P.G. Hunt. 2003. Extraction of soluble phosphorus from swine wastewater. *Transactions of the American Society of Agricultural Engineers*, 46(6):1665–1674.

Vanotti, M.B., A.A. Szogi, and C.A. Vives. 2008. Greenhouse gas emission reduction and environmental quality improvement from implementation of aerobic waste treatment systems in swine farms. *Waste Management*, 28(4):759–766.

Vanotti, M.B., A.A. Szogi, P.D. Millner, and J.H. Loughrin. 2009. Development of a second-generation environmentally superior technology for treatment of swine manure in the USA. *Bioresource Technology*, 100(22):5406–5416.

Vanotti, M.B. 2011. Personal communication. U.S. Department of Agriculture, Agricultural Research Service, in Florence, SC.

Williams, D.W., and D. Hills. 1981. Effect of Feedlot Manure Collection Techniques on Ultimate Methane Yield. Proceedings of the Proceedings of the Third Symposium on Biotechnology in Energy Production and Conservation.

Williams, D.W. 2011. Schematics. Williams Engineering Associates.

Wilson, D. 2006. Cattle on Rangeland. Washington, DC: U.S. Department of Agriculture, Agricultural Research Service Photo Library.

Wolf, B., Z. Xunhua, N. Bruggermann, W. Chen, et al. 2010. Grazing-induced reduction of natural nitrous oxide release from continental steppe. *Nature*, 464:881–884.

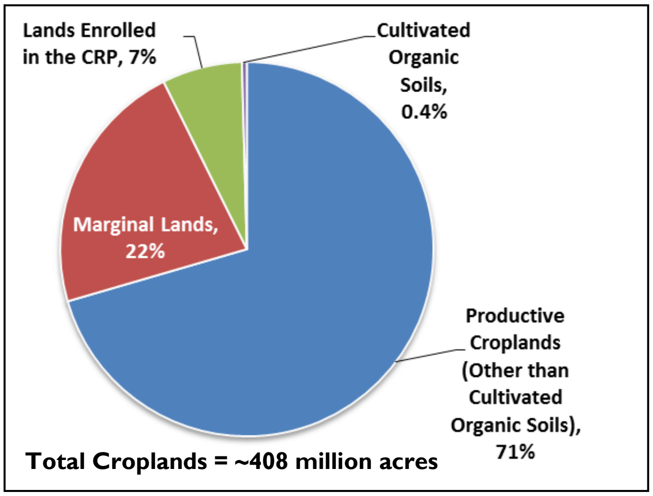
4. LAND RETIREMENT SYSTEMS

Shifting agricultural lands from commodity production to conservation cover can mitigate farm-level GHG emissions in several ways (Denef et al., 2011; Schoeneberger, 2005; USFWS, 2010). If the lands are retired for an extended period of time (from 15 years to more than a century), GHG mitigation benefits can accrue in the form of increased carbon sequestration. For cropland shifted to conservation cover, soil organic carbon will generally accumulate faster than when the land was in cultivation. For cropland, pasture, or range shifted into trees or shrubs, additional carbon will be sequestered in vegetation (CAST, 2011; EPA, 2011).[1] Exhibit 4-1 illustrates the distribution of U.S. cropland in 2007 among productive lands, marginal lands, organic soils, and land in USDA's Conservation Reserve Program. In the past, farmers have generally retired their least productive lands when offered a land retirement incentive. The 22% of croplands classified as marginal suggest that there is significant potential for expanding the adoption GHG-mitigating land retirement options. This chapter describes the five specific farm-level GHG mitigation options that are summarized in the adjacent textbox.

Land Retirement Systems Mitigation Options

- Retire Cultivated Organic Soils and Establish Conservation Cover
- Retire Marginal Croplands and Establish Conservation Cover
- Restore Wetlands
- Establish Windbreaks
- Restore Riparian Forest Buffers

Exhibit 4-1: Distribution of Croplands in the United States



Sources: Nickerson et al. (2011), Ogle (2010), and CAST (2011).

4.1 *Retire Cultivated Organic Soils and Establish Conservation Cover*

4.1.1 Technology Characterization

Establishing conservation cover is a USDA-recognized conservation practice [NRCS Conservation Practice Standard Code 327 (USDA NRCS, 2010e)]. It can help increase quantity of carbon stored in soils and vegetation on lands previously used for commodity production, particularly crop cultivation. Currently, the practice is supported primarily on marginal lands. These lands typically have lower opportunity costs (e.g., loss of commodity-related income) associated with retirement so farmers and/or landowners tend to retire them before more productive lands. However, given appropriate incentives to mitigate GHG emissions, the benefits of retiring more productive lands, such as those with organic soils, could outweigh the loss of commodity or land rent income.

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[1] Current incentive programs, such as USDA's Wildlife Habitats Incentives Program (WHIP) and the Environmental Quality Incentives Program (EQIP), encourage retirement of croplands for conservation purposes unrelated to GHG benefits. These incentives provide payments to landowners in exchange for setting aside the land to implement a number of practices, including the establishment of conservation cover, that aid in soil erosion control, improve water quality, and provide wildlife habitat. For more information on incentives in USDA's various conservation programs, see http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs.

Organic soils (histosols) refer to soils with high organic carbon content from decaying materials (compared with other soil types such as aridisols and entisols); as much as 20-30% of their content is composed of organic material to a depth of at least 40 cm (University of Idaho, 2012). These soils are also called muck, and the crops that are cultivated on them are sometimes called muck crops (MSU, 2011). The soils typically are unsuitable for growing corn or wheat, but are better suited for more profitable crops such as head lettuce, carrots, onions, radishes, sod, mint, and, in the southern United States, sugarcane and rice. Although the rich organic matter provided by these soils allows plentiful crop yields, as soon as the organic content of the soil is exposed to ambient air, it becomes highly erodible as the organic materials begin to decay with oxidation (Kohake et al., 2009).

Key Features of Retiring Organic Soils and Establishing Conservation Cover

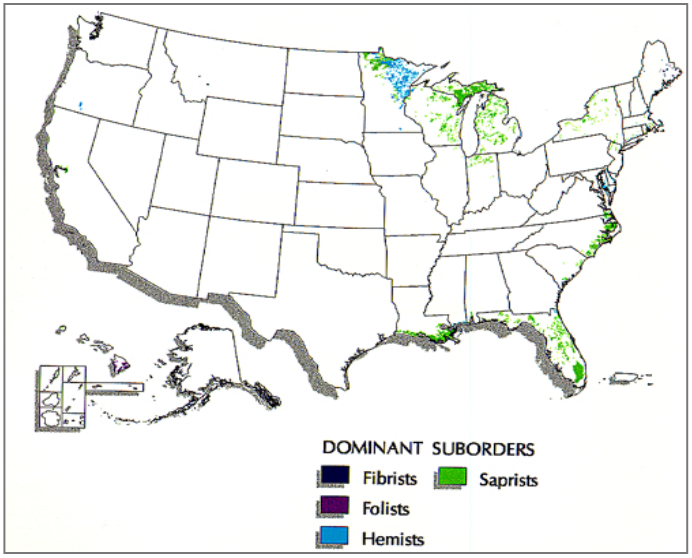
- Sequestration potential per acre for these soils is much higher than that of average soils (Eagle et al., 2011).
- Organic soils break down rapidly when exposed to the atmosphere, such as during farming activities, releasing much of the stored carbon content; retiring these soils from cultivation will slow the carbon loss (Morgan et al., 2010).
- Retiring organic soils from cultivation and establishing native vegetation in place of crops not only fosters additional carbon storage, but also prevents excessive soil erosion and runoff, provides a wildlife habitat, and has the potential to improve air quality (USDA NRCS, 2011).

According to USDA (2011), there are 1.6 million acres of organic soils in the United States that are being used for crop cultivation. Most of the organic soils in the United States are found in the Lake States, Southeast, and Appalachia USDA production regions, as depicted in Exhibit 4-2. Organic soils in the United States belong primarily to the four suborders identified in Exhibit 4-2.[2]

While these lands are typically highly productive for agriculture, they also offer high per-acre GHG mitigation opportunities to land owners if retired and transitioned to permanent grass cover. Specific GHG mitigation benefits accrue from (1) decreases in CO_2 emissions related to the oxidation of soil carbon in commodity production; (2) decreases in use of nitrogen fertilizers; (3) decreases in lime application amendments; and (4) increases in carbon sequestered in soils and perennial vegetation.

Although the costs to landowners (on a per-acre basis) for retiring organic soils are greater than those for marginal lands, the break-even prices (per ton of GHG mitigation) for retiring organic soils for emissions mitigation purposes are generally less than those for marginal soils. The reason is that retiring organic soils provides a per-acre GHG benefit many times higher than the per-acre benefit from retiring marginal soils. This would translate to a significantly higher GHG payment per-acre for retiring organic soils relative to the per-acre payment for retiring marginal land.

Exhibit 4-2: Organic Soils in the United States, by Region and Suborder



Source: USDA NRCS (2012a).

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[2] In this report, the different suborders of organic soils used to cultivate crops are not considered separately.

Current and Potential Adoption

There are no data available to indicate that farmers are currently retiring organic soils for the sole purpose of GHG mitigation. The potential for adoption in each USDA production region is based on the reported cultivated organic soils in each region provided in Table A-204 of the U.S. Inventory of GHG Emissions and Sinks (EPA, 2011); these acreages are provided by USDA production region in Exhibit 4-3, allocated to each region per analysis by Ogle (2011). All cultivated organic soils documented in the U.S. inventory could be potentially available for retirement.

Exhibit 4-3: Cultivated Organic Soils in the United States, by USDA Production Region

Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains	Total
(millions of acres)										
0.11	0.28	-	0.58	-	0.04	-	0.14	0.48	-	1.60

Source: Ogle (2011).

Production and Environmental Impacts

Production Impacts. Establishing permanent grass cover on organic soils can improve the quality of the land remaining in production, due to the reduction in soil erosion.

Other Environmental Impacts. The establishment of permanent grass cover reduces nutrient runoff, enhances plant growth by improving the microclimate, traps airborne particulates, and provides wildlife habitat (CAST, 2011; USDA NRCS, 2010e). Improvements in nearby surface water and groundwater quality due to reduced runoff can reduce risks to human and ecosystem health (USDA NRCS, 1999). Specific quantitative environmental impacts can be calculated for conservation scenarios using several publicly available tools, such as Agricultural Policy Environmental eXtender (APEX) (Steglich and Williams, 2009) and Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1990).

Barriers to Adoption

Some of the barriers to landowners in retiring organic soils and establishing permanent grass cover include those associated with the cost of pulling profitable land out of production, as well as establishing the cover vegetation and maintaining it in accordance with contract requirements. For example, such requirements exist in the USDA WHIP and EQIP programs (USDA NRCS, 2010e).[3] Specific barriers include the following:

- Abandoning annual crops and establishing conservation cover can be technically challenging if the land owner does not have access to the necessary equipment to plant the cover.
- Maintenance requirements for the newly established permanent grass cover vary per grass type and by landowner circumstances. Several of the challenges faced by landowners in maintaining the permanent grass cover are:
  - Preventing invasive plant species from overrunning the native vegetation;
  - Replanting vegetation that dies; and
  - Mowing, as needed or required by agreements.
- The loss of crop-related income (i.e., opportunity cost).
- Contracts between farmers and those buying GHG mitigation (i.e., sequestered carbon) will need to address issues related to the period covered by the agreement, including:

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[3] See footnote 1.

- The duration of the contract;
- Provisions describing how the terms of the contract change with the sale of the affected land; and
- Permanence—specifically, a clear provision describing farmer/landowner liability if sequestered carbon is released, intentionally or unintentionally, during the contract period (perhaps due to fire, disease, or deliberate clearing).

4.1.2 GHG Impacts

Establishing permanent grass cover on organic soils results in greater GHG mitigation than establishing cover on other types of soil due to (1) decreases in CO_2 emissions related to the oxidation of soil carbon when land is in commodity production; and (2) the expected reduction in lime application, which is common for cultivated organic soils.[4] Other impacts that occur in both organic and other types of soils are decreases in use of nitrogen fertilizer and increases in carbon sequestered in soils and perennial vegetation. Establishing vegetation on these soils slows the breakdown and loss of the organic carbon content into the atmosphere. The GHG mitigation benefits associated with retiring organic soils and establishing permanent grass cover are shown in Exhibit 4-4.

Exhibit 4-4: GHG Benefits of Retiring Organic Soils and Establishing Permanent Grass Cover

GHG Category	Net Carbon Benefit (mt CO_2-eq ac^{-1} yr^{-1})
Soil Carbon	11.53
Reduction in Land Emissions, N_2O and CH_4	2.75
Average Net On-Site Impact	14.28[a]

[a] In addition to the on-site sequestration of the soil carbon and the reduced N_2O and CH_4 emissions, other GHG benefits occur from the process and upstream savings in carbon emissions due to reduced need for fertilizer generation, equipment manufacturing, fuel for harvesting equipment, etc. However, these benefits are not evaluated as part of the break-even price estimates in this report.
Source: Eagle, et al. (2011).

4.1.3 Cost Profile

The farm-level costs of retiring organic soils from cultivation and establishing permanent grasses include capital costs, operations and maintenance (O&M) costs, and lost net income related to commodity production (i.e., opportunity cost). These costs vary across regions of the United States based on differences in material costs and labor expenses. State-level capital and O&M costs for establishing permanent grass are reported in the NRCS Field Office Technical Guide (FOTG) database. For estimating the break-even prices, a representative low- and high-cost scenario for the landowner were developed. The low-cost scenario utilizes the lowest combined capital and O&M costs for establishing permanent grass among States in the region; the high-cost scenario utilizes the highest combined value. Opportunity costs are measured by land rent rates. State-level land rent rates are published by USDA NASS (2012). In each region, the average of the State-level land rent rates[5] is used for the 'low" cost scenario. The highest State-level land rent rate is used for the high-cost scenario.

The costs associated with this practice have been calculated for each applicable USDA production region on a per-acre, per-year basis using the following assumptions:

- For the low-cost scenario, average regional land rents for 2010, as provided by USDA NASS (2012), are used.

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[4] Lime is often added to organic soils to reduce acidity. Because lime contains carbonate compounds (such as dolomite and limestone), the interaction between the acidic materials and the lime constitute a "bicarbonate equilibrium reaction," which produces CO_2 (USDA, 2011).

[5] For high-quality soils, such as histosols, land rents are assumed to be higher than average. Consequently, in this analysis, the average land rent rate for the region is used for the low-cost scenario and the region's highest rate (on a statewide basis) is used for the high-cost scenario.

- For the high-cost scenario, the highest statewide land rents for each USDA production region for 2010, as provided by USDA NASS (2012), are used.
- The capital costs are on the front end of the project, while O&M costs occur annually over an assumed 15-year project lifetime.
- No variation in opportunity costs by farm size is assumed.

To determine the costs of establishing permanent grass cover, this analysis used State-level data for NRCS Conservation Practice 327 (Establish Conservation Cover). The level of detail provided for the practice in the FOTG database varies by State. For example, some States include seed costs, labor costs, and equipment rental costs, while others include only one rate for capital costs (which, presumably, includes the complete labor and materials costs). Exhibit 4-5 describes State-level data and information from the FOTG database that were used to develop the low- and high-cost scenarios for each applicable USDA production region. Exhibit 4-6 summarizes capital costs and O&M costs under both the low-cost and the high-cost scenarios. As illustrated, the capital costs and the ranking of the costs by USDA production region are different in the low- and high-cost scenarios.

Exhibit 4-5: Regional Assumptions Based on FOTG Data

Region	Low-Cost Scenario		High-Cost Scenario	
	State Referenced	Vegetation Utilized	State Referenced	Vegetation Utilized
Appalachia	North Carolina	Perennial grass/legume seed mix	Virginia	Warm season grasses
Corn Belt	Ohio	Warm season grasses without fertilizer	Ohio	Tallgrass prairie
Lake States	Wisconsin	Cool season mix	Michigan	Michigan pollinators mix
Northeast	Pennsylvania	Non-native grasses	Vermont	Warm season grass for wildlife
Pacific	Oregon	Non-native grasses	California	Arid native high weeds
Southeast	South Carolina	Warm season grasses	South Carolina	Warm season grasses

Exhibit 4-6: Low- and High-Cost Scenarios per USDA Production Region for Retiring Organic Soils and Establishing Permanent Grass Cover

USDA Production Region	Low-Cost Scenario			High-Cost Scenario		
	Capital Costs[a]	Annual O&M[a]	Annual Opportunity Costs[b]	Capital Costs[a]	O&M[a]	Annual Opportunity Costs[b]
	(2010 $/acre)					
Appalachia	$254	$1	$64	$460	$0	$103
Corn Belt	$193	$7	$137	$410	$16	$176
Lake States	$122	$0	$98	$456	$14	$121
Northeast	$258	$45	$52	$519	$26	$66
Pacific	$201	$6	$191	$1,587	$3	$261
Southeast	$150	$0	$68	$150	$0	$112

Sources: [a] USDA NRCS (2011); [b] USDA NASS (2012).

4.1.4 Break-Even Prices

Exhibit 4-7: Break-Even Prices for Retiring Organic Soils from Cultivation and Establishing Conservation Cover[a]

Low-Cost Scenario	
Region	**Break-Even Price (2010 \$/ mt CO_2-eq)**
Southeast	\$6
Appalachia	\$6
Lake States	\$8
Northeast	\$9
Corn Belt	\$11
Pacific	\$15

High-Cost Scenario	
Region	**Break-Even Price (2010 \$/ mt CO_2-eq)**
Southeast	\$9
Northeast	\$10
Appalachia	\$10
Lake States	\$13
Corn Belt	\$16
Pacific	\$30

[a] Cover is permanent grass.

Exhibit 4-7 presents the break-even prices for retiring organic soils and establishing permanent grass cover as a GHG mitigation option by region for the low- and high-cost scenarios. These prices reflect the CO_2 incentive levels (stated in 2010 dollars per metric ton of CO_2-eq) at which a representative landowner in a given region would view shifting an acre of cultivated organic soils from commodity production to permanent grass cover as economically rational (i.e., the point at which the net present value of the benefits equals the net present value of the costs). The break-even prices shown in Exhibit 4-7 are based on the per-acre costs shown in Exhibit 4-6, the per-acre GHG benefits shown in Exhibit 4-4, and an assumed 15-year project timeframe.

4.2 Retire Marginal Croplands and Establish Conservation Cover

4.2.1 Technology Characterization

This practice entails the conversion of economically marginal lands from crop production to permanent grass cover. Marginal lands are those that have a low potential for crop productivity, and thus a low profit potential for farmers and landowners. These soils can be either naturally marginal, due to regional climate (such as an arid climate), or due to prior land management practices. For example, over-cultivation can lead to highly erodible soils, nutrient depletion, and salinization (CAST, 2011).

While storing less organic carbon than organic soils, marginal land presents a good opportunity for establishment of permanent grass cover due to the relatively low net income loss for the affected soils. This practice is similar in nature to retiring organic soils and establishing grass cover, and has many of the same environmental benefits. USDA currently supports the retirement of targeted marginal croplands in several of its conservation programs.[6]

Key Features of Retiring Marginal Soils and Establishing Conservation Cover

- Less carbon sequestration potential than for organic soils, but feasible since there is lower loss of revenue.
- The introduction of conservation cover, along with the removal of pollution-generating human activities, will benefit local air quality (USDA NRCS, 2010e).
- Abandoning the practices of tilling, planting annual crops, and harvesting the crops, and replacing the annuals with grasslands or other native vegetation helps improve the soil's ability to withstand weathering from wind and water (USDA NRCS, 2010e).

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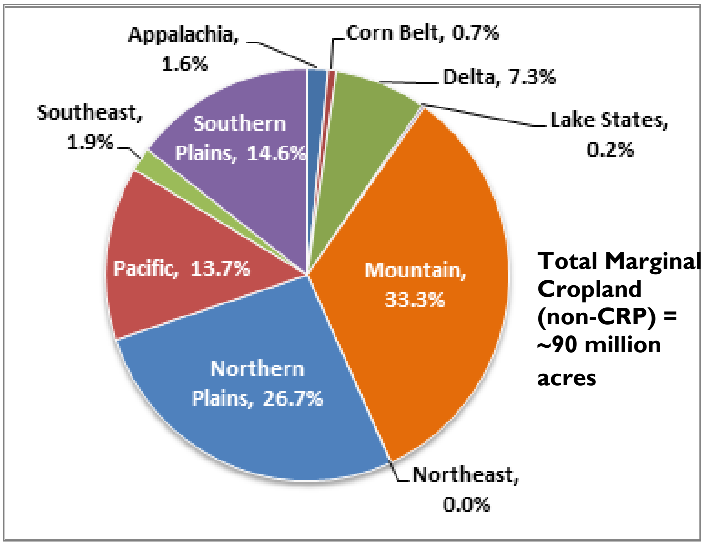
[6] See footnote 1.

Current and Potential Adoption

No data are available to indicate that farmers are retiring marginal soils for the sole purpose of GHG mitigation. Approximately 22% of all cropland in the United States is considered to be of marginal quality (Ogle, 2010).[7] Exhibit 4-8 illustrates the distribution of these marginal croplands by USDA production region.

In an assessment of marginal cropland, Ogle (2010) categorized approximately 84 million acres as "low input" lands.[8] Exhibit 4-9 shows how these lands are distributed by USDA production region. Conceptually, the acres shown in Exhibit 4-9 are reasonable upper bounds (both regionally and nationally) for the quantity of marginal land that could be retired in response to GHG mitigation incentives.

Exhibit 4-8: Distribution of Marginal Cropland in the United States



Sources: Nickerson et al. (2011); Ogle (2010).

Exhibit 4-9: Retiring Marginal Soils to Establish Conservation Cover by USDA Production Region

Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains	TOTAL
(millions of acres)										
1.4	0.6	6.1	0.2	27.9	0.03	22.3	11.4	1.6	12.2	83.7

Source: Ogle (2010).

Production and Environmental Impacts

Production Impacts. Establishing permanent grass cover of marginal lands can improve the quality of the land remaining in production due to the reduction in soil erosion.

Other Environmental Impacts. The establishment of permanent grass cover reduces nutrient runoff, enhances plant growth by improving the microclimate, traps airborne particulates, and provides wildlife habitat (USDA NRCS, 2010e). Improvements in nearby surface water and groundwater quality due to reduced runoff can decrease risks to human and ecosystem health (USDA NRCS, 1999). Specific quantitative environmental impacts can be calculated for conservation scenarios using several publicly available tools, such as Agricultural Policy Environmental eXtender (APEX) (Steglich and Williams, 2009) and Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1990).

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[7] Not including land not already enrolled in USDA's CRP.
[8] Excluding those enrolled in USDA's CRP.

Barriers to Adoption

The barriers for this practice are similar to those for retiring organic soils and establishing permanent grass cover (see page 4.3 of this report).

4.2.2 GHG Impacts

Although the carbon sequestration benefit per acre is lower than for organic soils, retiring marginal lands could be a feasible farm-level GHG mitigation option and have a greater overall mitigation potential due to the large amount of marginal (low-input) lands that are potentially available throughout the United States. Exhibit 4-10 presents the GHG benefits for retiring marginal soils.

Exhibit 4-10: Greenhouse Gas Impacts for Retiring Marginal Soils and Establishing Permanent Grass Cover

GHG Category	Net Carbon Benefit (mt CO_2-eq ac^{-1} yr^{-1})
Carbon sequestration (converting cropland to grass)	0.95
Reduced N_2O Emissions	0.14[a]
Average Net On-Site Impact	1.09

[a] Reduced N_2O emissions are based on nationwide GHG emissions estimate of 5.30 million metric tons of CO_2-eq, split among 37 million acres in the CRP (distributed evenly, this equates to 0.14 mt CO_2-eq per acre).

Source: USDA (2007).

4.2.3 Cost Profile

The farm-level costs of retiring marginal soils from cultivation and establishing permanent grasses include capital costs, operations and maintenance (O&M) costs, and lost net income related to commodity production (i.e., opportunity costs). These costs vary across regions of the United States based on differences in material costs and labor expenses. State-level capital and O&M costs for establishing permanent grass are reported in the NRCS Field Office Technical Guide (FOTG) database. For estimating the break-even prices, a representative low- and high-cost scenario for the landowner were developed. The low-cost scenario utilizes the lowest combined capital and O&M costs for establishing permanent grass among States in the region; the high-cost scenario utilizes the highest combined value. Opportunity costs are measured by land rent rates. State-level land rent rates are published by USDA NASS (2012). In each region, no loss in land rent rates is used for the 'low" cost scenario and the lowest State-level land rent rate is used for the high-cost scenario.[9]

The opportunity costs associated with this practice were calculated for each applicable USDA production region on a per-acre, per-year basis. For estimating opportunity costs, no variation in opportunity costs by farm size is assumed. Specifically, in each cost scenario, the same land rent rate is assumed on a per-acre basis, regardless of the land parcel size. The capital and O&M costs associated with this practice were also calculated for each applicable USDA production region on a per-acre, per-year basis, and reflect differences in the costs of labor and materials. The capital costs are on the front end of the project, while O&M costs occur annually over an assumed 15-year project lifetime. To determine the costs of establishing permanent grass cover, this analysis is based on the available cost data for NRCS Conservation Practice 327 (Establish Conservation Cover) (USDA NRCS, 2010e) in the FOTG database. The level of detail provided per State in the database varies by State. For example, some State include costs such as seed costs, labor costs, and equipment rental costs, while other State include only one rate for capital costs (which, presumably, contains the complete labor and materials costs).

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[9] For marginal quality soils, land rents are assumed to be lower than average. Consequently, in this analysis, zero land rent loss is used for the opportunity cost in the low-cost scenario and the region's lowest statewide land rent rate is used for the high-cost scenario.

Exhibit 4-11 describes State-level data and information from the FOTG database that were used to develop the low- and high-cost scenarios for each USDA production region. Exhibit 4-12 summarizes capital costs and O&M costs under both the low-cost and the high-cost scenarios. As illustrated, the capital costs and the ranking of the costs by USDA production region are different for the low- and high-cost scenarios.

Exhibit 4-11: Regional Assumptions Based on FOTG Data

Region	Low-Cost Scenario		High-Cost Scenario	
	State Referenced	Vegetation Utilized	State Referenced	Vegetation Utilized
Appalachia	North Carolina	Perennial grass/legume seed mix	Virginia	Warm season grasses
Corn Belt	Ohio	Warm season grasses without fertilizer	Ohio	Tallgrass prairie
Delta	Louisiana	Native single species grass	Arkansas	No-till non-native grasses
Lake States	Wisconsin	Cool season mix	Michigan	Michigan pollinators mix
Mountain	Colorado	Adapted grass	Wyoming	Pollinator support mix
Northeast	Pennsylvania	Non-native grasses	Vermont	Warm season grass for wildlife
Northern Plains	South Dakota	Tame grass/forb mix	South Dakota	Native grass/forb mix
Pacific	Oregon	Non-native grasses	California	Arid native high weeds
Southeast	South Carolina	Warm season grasses	South Carolina	Warm season grasses
Southern Plains	Texas	Perennial grass/forb mix	Texas	Perennial grass/forb pollinator mix

Exhibit 4-12: Retiring Marginal Soils and Establishing Permanent Grass Cover Low- and High- Cost Scenarios, per USDA Production Region

USDA Production Region	Low-Cost Scenario			High-Cost Scenario		
	Capital Costs[a]	Annual O&M[a]	Annual Opportunity Costs	Capital Costs[a]	Annual O&M[a]	Annual Opportunity Costs[b]
	(2010 $/acre)					
Appalachia	$254	$1	$0	$460	$0	$32
Corn Belt	$193	$7	$0	$410	$16	$99
Delta	$92	$22	$0	$321	$9	$75
Lake States	$122	$0	$0	$456	$14	$81
Mountain	$69	$0	$0	$228	$0	$47
Northeast	$258	$45	$0	$519	$26	$36
Northern Plains	$45	$0	$0	$120	$0	$47
Pacific	$201	$6	$0	$1,587	$3	$137
Southeast	$150	$0	$0	$150	$0	$33
Southern Plains	$53	$2	$0	$113	$3	$30

Sources: [a] USDA NRCS (2011); [b] USDA NASS (2012).

4.2.4 Break-Even Prices

Exhibit 4-13 shows the break-even prices for the practice of retiring marginal soils and establishing permanent grass cover as a GHG mitigation option by region for the low- and high-cost scenarios. These prices reflect the level of carbon incentive, stated in 2010 dollars per metric ton of carbon sequestered, at which a representative farmer in a given region would view shifting a generic acre of marginal land from commodity production to permanent grass cover as economically rational (i.e., the point at which the net present value of the benefits of establishing a permanent grass cover equals the net present value of the costs). The break-even prices shown in Exhibit 4-13 are based on the per-acre costs shown in Exhibit 4-12, the per-acre GHG benefits shown in Exhibit 4-10, and an assumed 15-year project timeframe.

Exhibit 4-13: Break-Even Prices for Retiring Marginal Soils and Establishing Conservation Cover

Low-Cost Scenario		High-Cost Scenario	
Region	Break-Even Price (2010 \$/ mt CO_2-eq)	Region	Break-Even Price (2010 \$/ mt CO_2-eq)
Northern Plains	$4	Southern Plains	$41
Mountain	$6	Southeast	$44
Southern Plains	$7	Northern	$54
Lake States	$11	Mountain	$64
Southeast	$14	Appalachia	$72
Pacific	$24	Northeast	$105
Corn Belt	$24	Delta	$107
Appalachia	$25	Lake States	$130
Delta	$29	Corn Belt	$144
Northeast	$65	Pacific	$276

4.3 Restore Wetlands

4.3.1 Technology Characterization

Between 1954 and 2006, 66% of all wetland loss in the United States (about 24 million acres) was due to conversion to agriculture. Relative to this period, wetland loss has slowed, but it still occurs (USDA ERS, 2006). Converting agricultural lands back to wetlands is a practice currently supported by USDA for the purposes of wildlife habitat restoration, erosion prevention, and water quality improvement (USDA NRCS, 2010a). The practice also provides an opportunity for potentially significant GHG mitigation, especially when converting to forested wetlands. Although restoring wetlands usually increases CH_4 emissions (compared with agricultural activity), the practice results in significant carbon sequestration and reduces on-site emissions associated with commodity production, producing an overall net mitigation of GHG emissions (Euliss Jr. et al., 2006; Gleason et al., 2005). The restoration of wetlands has co-benefits of potentially improving local water quality and providing a habitat for native plant and animal species.

Key Features of Restoring Wetlands

- Wetland soils store as much as 15 times more carbon than vegetation does (IPCC, 2000).
- Restoring wetlands to their natural state (from cultivated cropland) can result in increased methane emissions, but results in significant carbon storage in soils and vegetation, producing an overall GHG benefit (Eagle et al., 2011; USDA NRCS, 2011).
- In addition to GHG mitigation benefits, restoring wetlands reduces soil erosion, improves groundwater and surface water quality, and provides habitat for terrestrial and aquatic animal species (USDA NRCS, 2011).

Restoring wetlands (NRCS Conservation Practice Standard Code 657) (USDA NRCS, 2010a), involves retiring from crop cultivation lands that had previously been wetlands (and were drained).[10] Restorations can be for grassy wetlands, such as marsh, or forested wetlands, such as mangroves. The technical difficulty of restoring a wetland is dependent on the level of effort involved with ceasing activities occurring on the land, the type of wetland to be restored, and the amount of infrastructure in place. Site conditions are the single biggest determinant of practice costs and level of effort (USDA NRCS, 2010a, 2011). Specifically, removing contaminated soils to off-site locations could require up to 50 times the cost as would moving soil to a nearby on-site location. Other factors resulting from site location will involve the ease of transportation, or lack thereof, to and from the site (roads or water); the placement of levees (if applicable); and the local climate (Steere, 2000). For example, levee construction cost ranges from $1 per cubic yard to $100 per cubic yard. According to Steere (2000) and USDA NRCS (2011), the elements in Exhibit 4-14 will impact the level of effort and cost of restoring a wetland.

Exhibit 4-14: Factors in Determining Level of Effort and Costs Required to Restore Wetlands

▪ Quantities of excavation or earthwork required	▪ Access road construction	▪ Clearing and grubbing
▪ Grading	▪ Soil disposal (on-site vs. off-site)	▪ Dike breaching
▪ Number and type of permanent or temporary weirs, pumps, or other controls	▪ Levee repair	▪ New dike/levee construction
▪ Hydro-seeding levees	▪ Planting of low marsh	▪ Irrigation
▪ Permitting and engineering	▪ Vegetation type to be planted	▪ Necessity of removing existing infrastructure

Sources: Steere (2000); USDA NRCS (2011).

Although the steps required to restore a wetland are site-specific and will require research on the part of the landowner, the steps generally include mobilization, demolition of structures (as needed), clearing and grubbing of any unwanted vegetation (including cultivated crops), earthwork excavation and grading, soil preparation, planting and irrigation installation, and demobilization. Ongoing operations may include adjusting weirs, vegetation and water control structures, mosquito control, predator and non-native fauna/flora species control, monitoring site conditions, replanting vegetation, and levee maintenance (Steere, 2000). Exhibit 4-15 depicts a wetland adjacent to cultivated agricultural lands in the United States.

Exhibit 4-15: Wetland Adjacent to Agricultural Land

Source: USDA NRCS (2013).

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[10] Similar USDA recognized conservation practices include: Constructed Wetland (NRCS Conservation Practice 656), Wetland Creation (NRCS Conservation Practice 658), Wetland Enhancement (NRCS Conservation Practice 659), and Wetland Wildlife Habitat Management (Conservation Practice 644). These practices also likely result in net GHG mitigation but are not considered explicitly here.

Current and Potential Adoption

No data are available to indicate that cropland has been retired to restore wetlands for the sole purpose of GHG mitigation. Eagle et al. (2012) assume that the entirety of the land available for restoration is limited to the Prairie Pothole Region in the United States (9.4 million acres). However, according to USDA ERS (2006), at least half of the 200-million-plus acres of wetlands lost since European settlement in the United States can been attributed to agriculture. Hence, the potential for restoration could extend well beyond Eagle et al.'s (2012) estimate for the Prairie Pothole Region.

Production and Environmental Impacts

Production Impacts. Restoring wetlands can improve the quality of the land remaining in production due to the reduction in soil erosion, improvement of water quality, and improvement in microclimate.

Other Environmental Impacts. The restoration of wetlands filters pesticide from runoff, enhances plant growth by improving the microclimate, provides terrestrial wildlife habitat, improves surface water and groundwater quality, and cycles nutrients. Additionally, the reintroduction of wetlands can provide shade and new habitat for sensitive fish species, especially with the introduction of woody debris into adjacent water bodies (USDA NRCS, 2010a). Specific quantitative environmental impacts can be calculated for conservation scenarios using several publicly available tools, such as Agricultural Policy Environmental eXtender (APEX) (Steglich and Williams, 2009) and Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1990).

Barriers to Adoption

Specific adoption barriers to restoring wetlands include the cost and effort required to establish the wetland – that is to remove crops, move earth, and establish wetland vegetation; the technical expertise required (e.g., knowledge of wetlands hydrology and desirable flora/ fauna); and the required long-term monitoring and maintenance. In rare circumstance, there may also be costs associated with installing drainage pipes and carrying out periodic dredging. The following are additional barriers:

- Contracts between farmers and those buying GHG mitigation (i.e., sequestered carbon) will need to address several issues related to the future period covered by the agreement, as summarized on page 4.3 of this report.
- Maintenance requirements can increase, such as those for:
  - Controlling disease vectors that accompany wetlands, such as mosquitoes;
  - Preventing invasive plant species from overrunning the native vegetation;
  - Replanting vegetation that dies; and
  - Providing barriers to passage for unwanted and predatory fauna.

4.3.2 GHG Impacts

Reflecting the large diversity in wetlands types, published estimates of the GHG mitigation benefits of restoring wetlands vary significantly. For example, in a recent synthesis of scientific studies on the GHG mitigation potential of U.S. agriculture, Eagle et al. (2012) note studies by Badiou et al. (2011), Euliss et al. (2006), and Gleason et al. (2009) that indicate the GHG mitigation potential of restored prairie (grass) wetlands in the United States and Canada is between 0.77 and 3.12 mt CO_2-eq ac^{-1} yr^{-1}. The analysis conducted for this report uses the estimates provided by Hansen (2009), which investigates the viability of restoring wetlands for the purpose of generating carbon offsets. The GHG benefits used here vary significantly depending on whether the type of wetland restored is grassy or forested. Exhibit 4-16 below provides estimates of the GHG benefits for both grassy and forested wetlands. As indicated, the primary pool of carbon sequestration for grassy wetlands is in soil (upper 15 cm), while for forested wetlands the primary pool is in the trees.

Exhibit 4-16: Greenhouse Gas Impacts for Restoring Wetlands

GHG Category	Net Carbon Benefit of Restoring Grassy Wetlands (mt CO$_2$-eq ac^{-1} yr^{-1})	Net Carbon Benefit of Restoring Forested Wetlands (mt CO$_2$-eq ac^{-1} yr^{-1})
Biota (Trees and Other Vegetation)	2.10	5.17
Soil Carbon (top 15 cm)	3.62	0
Annual Sequestration, first 5 years	5.72	-
Annual Sequestration, years 6–30	1.25	-
Annual *Average* Sequestration over 30 years	1.99	5.17

Source: Hansen (2009).

4.3.3 Cost Profile

The farm-level costs of retiring cropland and restoring previously drained wetlands include capital costs, operations and maintenance (O&M) costs, and lost net income related to commodity production (opportunity cost). These costs vary across regions of the United States based on based on differences in material costs and labor expenses. However, due to a lack of practice implementation data for grassy and forested wetlands for each region, practice cost data for both practices are assumed to be the same. Consequently, break-even prices for grassy wetlands are likely overestimated and those for forested wetlands are likely underestimated.

For estimating the break-even prices, representative low- and high-cost scenarios were developed for restoring wetlands on a per acre basis. The Wetland Reserve Program (WRP) provides 30-year financial obligation data for its wetlands restoration projects. These data were used to develop the cost scenarios shown in Exhibit 4-17. The costs for this practice vary by State, and reflect the wide variety of wetland restorations that have been carried out under the WRP (USDA NRCS, 2012b). The low-cost scenario utilizes the lowest statewide WRP obligation and the high-cost scenario utilizes the highest WRP obligation. The WRP obligation data are presented in aggregate (i.e. they do not break out O&M, capital costs, and opportunity costs). However, the WRP's cost-benefit analysis indicates that about 13% of costs over a 30-year period are for the initial restoration. Hence, 13% of the total per-acre obligations were allocated to restoration costs and 87% to opportunity costs. Finally, the WRP covers 75–100% of initial restoration costs. The WRP restoration cost estimates were assumed to reflect the 75% value and were adjusted up to reflect the implied full cost of initial restoration activities. As indicated, the O&M and opportunity costs are aggregated.

Exhibit 4-17: Low- and High-Cost Scenarios for Restoring Wetlands per USDA Production Region

Region	Practice: Restore Wetlands—BOTH GRASSY and FORESTED					
	Low-Cost Scenario			High-Cost Scenario		
	Initial Restoration Costs	Combined Annual O&M and Opportunity Costs	State	Initial Restoration Costs	Combined Annual O&M and Opportunity Costs	State
	(2010 $/acre)					
Appalachia	$283	$63	North Carolina	$732	$164	West Virginia
Corn Belt	$425	$95	Missouri	$637	$143	Indiana
Delta	$283	$63	Louisiana	$287	$64	Arkansas
Lake States	$290	$65	Minnesota	$709	$159	Wisconsin
Mountain	$112	$25	Wyoming	$537	$120	Utah

Region	Practice: Restore Wetlands—BOTH GRASSY and FORESTED					
	Low-Cost Scenario			High-Cost Scenario		
	Initial Restoration Costs	Combined Annual O&M and Opportunity Costs	State	Initial Restoration Costs	Combined Annual O&M and Opportunity Costs	State
	(2010 $/acre)					
Northeast	$197	$44	Maine	$977	$219	Rhode Island
Northern Plains	$176	$39	North Dakota	$320	$72	Nebraska
Pacific	$221	$49	Oregon	$944	$211	Washington
Southeast	$153	$34	South Carolina	$688	$154	Florida
Southern Plains	$254	$57	Oklahoma	$286	$64	Texas

Source: USDA NRCS (2012b).

4.3.4 Break-Even Prices

Exhibit 4-18 presents break-even prices for the restoration of forested wetlands and grassy wetlands as farm-level GHG mitigation options, by region and by low- and high-cost scenario. The break-even prices vary for any particular scenario due to site conditions and other factors. In general, however, regardless of region, the break-even prices for forested wetlands are less than those for grassy wetlands due to the higher carbon storage capacity of trees. The break-even prices reflect the level of carbon incentive, stated in 2010 dollars per metric ton of CO_2-eq sequestered, at which a representative landowner in a given region would view shifting a generic acre of previously drained wetlands from commodity production to wetland as economically rational (i.e., the point at which the net present value of the benefits of the restored wetland equals the net present value of the costs). The break-even prices are based on the per-acre costs for restoring wetlands shown in Exhibit 4-17 and the per acre GHG benefits shown in Exhibit 4-16. The assumed timeframe for wetlands restoration is 30 years. Hence, in calculating the break-even prices shown in Exhibit 4-18 and Exhibit 4-19 the initial restoration costs shown in Exhibit 4-17 were annualized over a 30-year period.

Exhibit 4-18: Break-Even Prices for Restoring Forested Wetlands

Low-Cost Scenario	
Region	Break-Even Price (2010 $/mt CO_2-eq)
Mountain	$6
Southeast	$9
Northern Plains	$10
Northeast	$11
Pacific	$13
Southern Plains	$14
Appalachia	$16
Delta	$16
Lake States	$17
Corn Belt	$24

High-Cost Scenario	
Region	Break-Even Price (2010 $/mt CO_2-eq)
Southern Plains	$16
Delta	$16
Northern Plains	$18
Mountain	$31
Corn Belt	$36
Southeast	$39
Lake States	$40
Appalachia	$42
Pacific	$54
Northeast	$56

Exhibit 4-19: Break-Even Prices for Restoring Grassy Wetlands

Low-Cost Scenario	
Region	**Break-Even Price (2010 \$/mt CO_2-eq)**
Mountain	\$17
Southeast	\$23
Northern Plains	\$26
Northeast	\$29
Pacific	\$33
Southern Plains	\$38
Appalachia	\$42
Delta	\$42
Lake States	\$43
Corn Belt	\$63

High-Cost Scenario	
Region	**Break-Even Price (2010 \$/mt CO_2-eq)**
Southern Plains	\$42
Delta	\$43
Northern Plains	\$47
Mountain	\$80
Corn Belt	\$94
Southeast	\$102
Lake States	\$105
Appalachia	\$108
Pacific	\$140
Northeast	\$145

4.4 Establish Windbreaks

4.4.1 Technology Characterization

A windbreak (also called a shelterbelt)[11] is a linear strip of vegetation consisting of one or more rows of trees and/or shrubs generally located to protect cultivated crops, livestock, soils, buildings, and/or other property from damages related to wind and other weather events (CAST, 2011; Hanley and Kuhn, 2003; Schoeneberger, 2005; Schoeneberger et al., 2008; USDA NRCS, 2011). Windbreaks can also be designed to provide a number of environmental benefits including reducing soil erosion from wind, enhancing or creating wildlife habitat, improving air quality (by intercepting airborne particulates and chemicals), and providing screens for undesirable views and noises. Because of these benefits, establishing shelterbelts is a recognized USDA conservation practice (see NRCS Conservation Practice Standard Code 380) eligible for cost-share assistance in the context of USDA's Environmental Quality Incentives Program (USDA NRCS, 2009).

Shifting land from commodity production to a windbreak typically results in additional carbon being sequestered in soils and biomass. Assuming the windbreak is a long-term land-use change, the increase in carbon sequestration offsets GHG emissions elsewhere. This makes the establishment of windbreaks a potential farm-level response to the availability of financial incentives to mitigate GHG emissions.

Selecting the location, length, and vegetation mix for a windbreak is dependent on local conditions and the desired purposes. For example, a windbreak established to prevent crop loss, livestock damage, and/or soil would be located on the edge of the

Key Features of Establishing Windbreaks

- Windbreaks protect croplands, livestock, grazing lands, and buildings from potentially damaging winds and heavy precipitation events.
- Additional environmental benefits include preventing soil erosion and reducing agricultural runoff into water resources (USDA NRCS, 2009).
- Establishing windbreaks in place of crops or grazing land increases carbon sequestration in plants and soils (CAST, 2011; Schoeneberger, 2005).
- Windbreaks typically involve several rows of both trees and shrubs for maximum protection and versatility (CAST, 2011; USDA NRCS, 2009, 1999).

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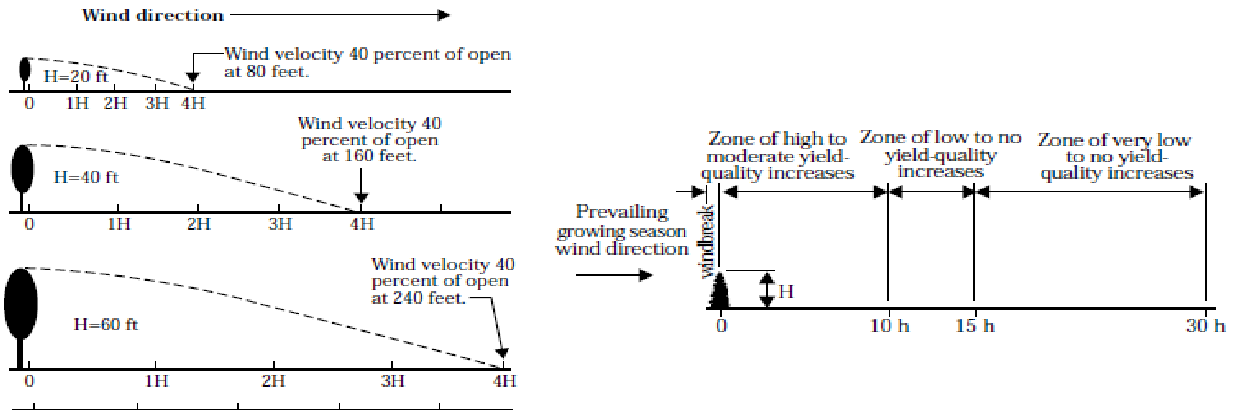
[11] The terms "windbreak" and "shelterbelt" are often used interchangeably; "windbreak" is used throughout this document.

field that is generally upwind during the growing season or most critical grazing period (see Exhibit 4-20). Alternatively, windbreaks established to protect structures or reduce noise would be located close to the structure or source of noise. For purposes of GHG mitigation, windbreaks will consist of tree species with the highest carbon sequestration rates in the region and will be planted close to their maximum stocking density. Regardless of purpose, windbreaks should be positioned to be perpendicular to the winds of concern. While windbreaks are used in all areas of the country, they are most beneficial in areas with flat, wide-open expanses of land that are exposed to frequent strong winds (e.g., the Corn Belt, Lake States, and Northern and Southern Plains).

Exhibit 4-20: Benefits of Windbreaks to Land and Crops, Based on Height of Windbreak

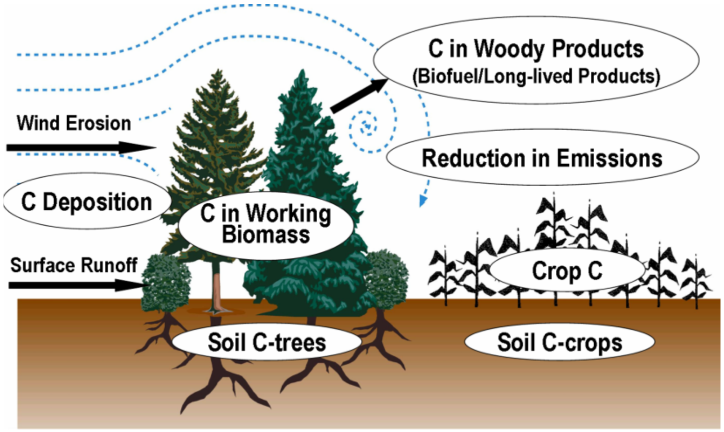


Source: USDA NRCS (1999).

Current and Potential Adoption

As illustrated in Exhibit 4-21, the practice of establishing windbreaks is a potential GHG mitigation option where soil conditions are deteriorated by wind erosion. National Resources Inventory data indicate that in 2007 there were 53.6 million acres of Highly Erodible Land (HEL) cropland and 45.6 million acres of Non-HEL cropland on which soil erosion, due to wind or water, exceeded the applicable soil loss tolerance level (USDA NRCS, 2010g). National Resources Inventory data for 2007 also indicate that wind and water erosion totaled 960 million short tons per year, of which about 80% was related to wind (i.e., 765 million short tons) (USDA NRCS, 2010g). Applying the 80% value to the 99.2 million acres of HEL and non-HEL cropland referred to above, suggests that about 79.4 million acres of cropland are subject to significant wind-related erosion.

Exhibit 4-21: Carbon Sinks and Sources in a Field Windbreak



Source: Schoeneberger (2005).

Production and Environmental Impacts

Production Impacts. Installing windbreaks often improves the quality of the land remaining in production (Maryland Cooperative Extension, 2000; Pearson et al., 2010). Additional stabilization for soils prevents soil and nutrient loss that would result in lower quality land for adjacent crops. The reduction in wind erosion alone can be quite beneficial on otherwise highly erodible land (CAST, 2011; Schoeneberger, 2005).

Other Environmental Impacts. The establishment of windbreaks reduces nutrient runoff, enhances plant growth by improving the microclimate, and provides wildlife habitat (USDA NRCS, 2009). Improvements in nearby surface water and groundwater quality due to decreased runoff can reduce the risks to human and ecosystem health (Schoeneberger, 2005; USDA NRCS, 1999). Specific quantitative environmental impacts can be calculated for conservation scenarios using several publicly available tools, such as Agricultural Policy Environmental eXtender (APEX) (Steglich and Williams, 2009) and Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1990).

Barriers to Adoption

The barriers to landowners in establishing windbreaks include those associated with opportunity cost, establishing the vegetation and maintaining it in accordance with contract requirements. For example, such requirements exist in the USDA WHIP and EQIP programs (USDA NRCS, 2009).[12] The following are additional barriers:

- In dry regions, such as in much of the Great Plains and Southwest, securing adequate water supplies to establish and maintain tree-based windbreaks may be difficult (Pearson et al., 2010). Consequently, opportunities for using this GHG mitigation option may be limited in arid areas.
- Contracts between farmers and those buying GHG mitigation (i.e., sequestered carbon) will need to address several issues related to the future period covered by the agreement, as summarized on page 4.3 of this report.

4.4.2 GHG Impact

Eagle, et al. (2011) estimate the net benefit of agroforestry at 1.40 metric tons CO_2-eq ac^{-1} yr^{-1} (not including a reduction in upstream emissions such as from fertilizer and fuels). The key carbon benefits of a windbreak are shown in Exhibit 4-22.

Exhibit 4-22: On-Site Greenhouse Gas Mitigation Impacts for Establishing Windbreaks

GHG Category	Net Carbon Benefit (mt CO_2-eq ac^{-1} yr^{-1})
Soil Carbon	0.35
Carbon Storage in Trees and Other Vegetation	1.05
Average Net On-Site Impact	1.40

Source: Eagle, et al. (2011) for carbon sequestration estimates for windbreaks. Soil carbon is assumed to be 25% of total on-site sequestration with vegetation accounting for the majority.

4.4.3 Cost Profile

The farm-level costs of retiring portions of cropland and establishing windbreaks include capital costs, operations and maintenance (O&M) costs, and lost net income related to commodity production (i.e., the opportunity cost). These costs vary across regions of the United States based on based differences in material costs and labor expenses, commodity prices, and intended purpose(s) of the windbreak. State-level capital and O&M costs for establishing windbreaks are reported in the NRCS Field Office Technical Guide

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[12] See footnote 1.

(FOTG) database. For each region, a representative low- and high-cost scenario for the landowner are provided. The low-cost scenario utilizes the lowest combined capital and O&M costs for establishing and maintaining windbreaks among the States in each region; the high-cost scenario utilizes the highest combined value. In general, data for NRCS Conservation Practice 380 (Establish Windbreaks) are used. Opportunity costs are measured by land rent rates. State-level land rent rates are published by USDA NASS (2012). In each region, the opportunity cost is assumed to be zero for the 'low' cost scenario (i.e., the affected land is assumed to be truly marginal in commodity production) and the lowest State-level land rent rate is used for the high-cost scenario.

The capital and O&M costs associated with this practice have been calculated for each applicable USDA production region on a per-acre, per-year basis. In estimating these costs, no variation by farm size is assumed. Exhibit 4-23 describes State-level data and information from the FOTG database that were used to develop the low- and high- cost scenarios for each USDA production region. Exhibit 4-24 summarizes capital costs and O&M costs under both the low-cost and the high-cost scenarios.

Exhibit 4-23: Regional Assumptions Based on FOTG Data

Region	State Referenced in Low-Cost Scenario	Assumptions Used in Low-Cost Scenario	State Referenced in High-Cost Scenario	Assumptions Used in High-Cost Scenario
Appalachia	Kentucky	Deciduous trees only (silvopasture cost data); annual O&M cost are assumed to equal 1% of installation cost	Virginia	Hardwoods only
Corn Belt	Indiana	Annual O&M cost are assumed to equal 1% of installation cost	Ohio	No indication of vegetation type is provided
Delta	Arkansas	Multiple rows of shrubs, hardwoods, and conifers	Arkansas	Hardwoods only
Lake States	Michigan	No indication of vegetation type is provided	Wisconsin	Assumed O&M cost is 1% of installation cost based on relationships found between capital costs and O&M costs in other States' data
Mountain	Colorado	No indication of vegetation type is provided	Utah	1,361 trees at $6.50 each, plus $66.58 per acre for seedbed prep w/ fertilizer; assumed O&M cost is 1% of installation cost based on relationships found between capital costs and O&M costs in other States' data
Northeast	New York	Bareroot trees or shrubs	Massachusetts	Assumed O&M cost is 1% of installation cost based on relationships found between capital costs and O&M costs in other States' data
Northern Plains	Kansas	Bareroot seedlings	Kansas	Balled seedlings

Region	State Referenced in Low-Cost Scenario	Assumptions Used in Low-Cost Scenario	State Referenced in High-Cost Scenario	Assumptions Used in High-Cost Scenario
Pacific	California	Single row of deciduous and conifer mix	Oregon	Single row of trees/shrubs, bareroot; assumed O&M cost is 1% of installation cost based on relationships found between capital costs and O&M costs in other States' data
Southeast	Florida	South Florida rockland hardwoods (statewide average)	Florida	Option reflects planting South Florida rockland hardwoods in the Northern Everglades; annual O&M costs are assumed to be 1% of capital costs
Southern Plains	Oklahoma	Tree costs are from Oklahoma; tree density and spacing are from Texas (only State with spacing data); annual O&M costs are assumed to be 1% of capital costs	Texas	Assumed O&M cost is 1% of installation cost, based on relationships found between capital costs and O&M costs in other States' data

Sources: USDA NRCS (2011).

Exhibit 4-24: Regional Low- and High-Cost Scenarios for Establishment of Windbreaks

USDA Production Region	Low-Cost Scenario			High-Cost Scenario		
	Capital Costs[a]	Annual O&M[a]	Annual Opportunity Costs	Capital Costs[a]	Annual O&M[a]	Annual Opportunity Costs[b]
	2010 $/acre					
Appalachia	$177	$16	$0	$910	$9	$32
Corn Belt	$210	$2	$0	$293	$8	$99
Delta	$599	$6	$0	$871	$9	$75
Lake States	$332	$19	$0	$374	$62	$81
Mountain	$191	$19	$0	$328	$3	$47
Northeast	$984	$10	$0	$992	$10	$161
Northern Plains	$330	$3	$0	$1,641	$16	$47
Pacific	$566	$6	$0	$1,473	$15	$137
Southeast	$500	$5	$0	$500	$5	$33
Southern Plains	$231	$2	$0	$576	$6	$30

Source: USDA NRCS (2011).

4.4.4 Break-Even Prices

Exhibit 4-25 presents the break-even prices for the adoption of windbreaks as a GHG mitigation option by region for the low- and high-cost scenarios. These prices reflect the level of carbon incentive, stated in 2010 dollars per metric ton of CO_2-eq sequestered over the project lifetime, at which a representative farm in a given region would view shifting a generic acre of marginal land from commodity production to a windbreak as economically rational (i.e., the point at which the net present value of the benefits of the windbreak equals the net present value of the costs). The break-even prices shown in Exhibit 4-25 are based on the per-acre costs for establishing windbreaks shown in Exhibit 4-24 and the per-acre GHG benefit shown in Exhibit 4-22. In calculating the break-even prices, the capital costs shown in Exhibit 4-24 are annualized over a 15-year period, the presumed project lifestime.

Exhibit 4-25: Break-Even Prices for Establishing Windbreaks

Low-Cost Scenario	
Region	**Break-Even Price (2010 \$/mt CO_2-eq)**
Corn Belt	$17
Southern Plains	$18
Appalachia	$24
Mountain	$27
Northern Plains	$26
Lake States	$38
Southeast	$40
Pacific	$46
Delta	$48
Northeast	$78

High-Cost Scenario	
Region	**Break-Even Price (2010 \$/mt CO_2-eq)**
Mountain	$60
Southeast	$63
Southern Plains	$67
Corn Belt	$97
Appalachia	$95
Lake States	$130
Delta	$123
Northern Plains	$164
Northeast	$194
Pacific	$215

4.5 Restore Riparian Forest Buffers

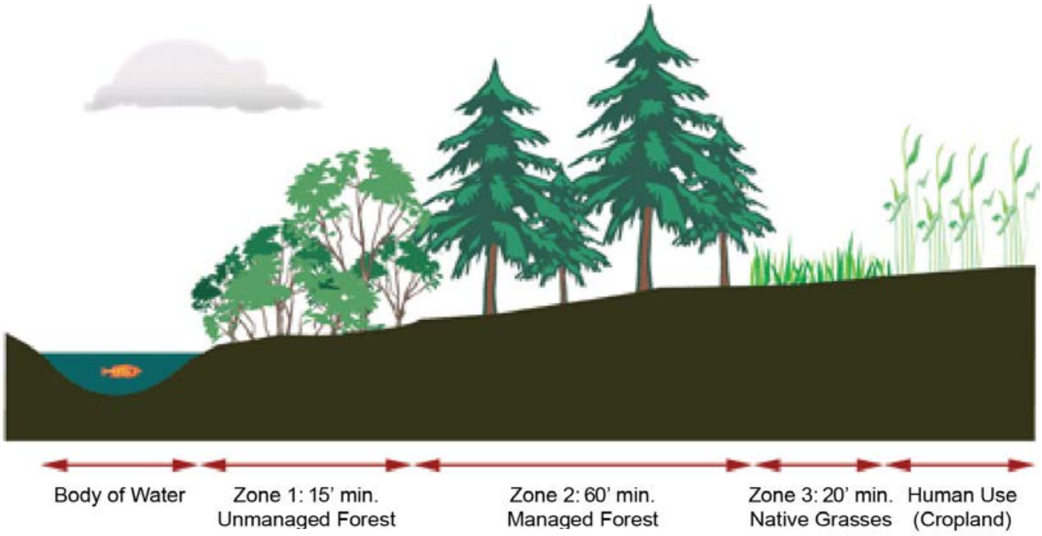
4.5.1 Technology Characterization

A riparian buffer is a vegetated area located between a river or stream and land in commodity production (crops or grazed livestock). Establishing a riparian buffer entails shifting riparian lands from production to a conservation vegetation cover. In practice, buffers may consist of trees, shrubs, and/or grasses. The focus here is on shifting marginal agricultural lands to riparian *forest* buffers due to their larger capacity to sequester carbon. Exhibit 4-26 provides an aerial view of a riparian forest buffer adjacent to croplands as an example of the practical application of this practice. Exhibit 4-27 presents a conceptual model of a three-zone riparian buffer adjacent to cropland; this particular buffer incorporates both woody and herbaceous vegetation.

Exhibit 4-26: Riparian Forest Buffer Adjacent to Agricultural Land in Putnam County, Ohio

Source: USDA NRCS (2012c).

Exhibit 4-27: USDA's Three-Zone Riparian Buffer Model



Source: Virginia Outdoors Foundation (2012).

A variety of equipment is required to remove cultivated crops, re-establish riparian vegetation, mow, seed, and control weeds. For grazing lands, the level of effort required to restore a forest buffer is likely to be less than for croplands; although some annual maintenance will be required for afforested land, more energy is required to work the land throughout a cultivated crop's growing season. Some of the costs for both grazing lands and cropland may be able to be offset by existing USDA programs (such as EQIP and WHIP),[13] which encourage landowners to shift riparian lands from commodity production to long-term vegetation buffers in order to reduce soil erosion, provide habitat for wildlife, and improve water quality.

Key Features of Restoring Riparian Forest Buffers

Riparian forest buffers act as barriers between croplands or grazing lands and adjacent streams (USDA NRCS, 2010f).

In addition to sequestering additional carbon in soils and vegetation, the benefits for agricultural lands include reducing soil erosion and reducing runoff to streams and shallow groundwater (USDA NRCS, 2010f).

The opportunity costs of this option are minimal because the practice requires landowners to retire limited land with respect to their total land area (CAST, 2011; Pearson et al., 2010).

Current and Potential Adoption

The 2004 National Water Quality Inventory: Report to Congress (EPA, 2009) assessed the overall water quality of 16% of all U.S. rivers and streams (measured in miles). The report found that 6% of these rivers and streams were associated with an agricultural use, and 10% of these areas were in an impaired condition. Applying these percentages to all 3.5 million miles of U.S. rivers and streams, about 201,000 miles are associated with an agricultural use and 20,000 miles are impaired. Using a buffer of 35 feet on each bank

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[13] Information on these programs for a particular state can be found by using this map: USDA Service Center Locator, http://offices.sc.egov.usda.gov/locator/app.

(USDA NRCS, 2010g), and assuming restoration of the forest buffer on all impaired miles, suggests a technical potential for this practice to be applied on approximately 810,000 acres.

Production and Environmental Impacts

Production Impacts. Installing riparian forest buffers often improves the quality of the adjacent land remaining in production (Eagle et al., 2011; Wenger, 1999). Grazing livestock that use streams for water are a major source of stream bank destabilization and riparian vegetation damage; repairing banks and restoring vegetation can prevent further damage of adjacent lands. One study of a riparian buffer indicated that 84–90% of the sediment eroded from adjacent agricultural fields was trapped by the buffer, and thus not lost to the stream (Wenger, 1999). Prevention of soil loss will result in higher quality land for farming.

Other Environmental Impacts. Reduced runoff (which carries fertilizers and sediment) due to implementation of this practice can also reduce the risks to human and ecosystem health (USDA NRCS, 1999). The addition of riparian vegetation also provides shade to sensitive fish species; the addition of large woody debris into streams provides habitat for salmon, trout, and other fish (Wenger, 1999). Specific quantitative environmental impacts can be calculated for conservation scenarios using several publicly available tools, such as Agricultural Policy Environmental eXtender (APEX) (Steglich and Williams, 2009) and Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1990).

Barriers to Adoption

Some of the barriers to landowners in establishing riparian forest buffers include the costs and effort associated with establishing and maintain the desired vegetation. The following are additional barriers:

- Dry regions, such as the Southwest, are more likely to face greater water costs until root systems for the vegetation are established (Pearson et al., 2010). Consequently, installing riparian buffers could be more burdensome for landowners in dry regions than it would be in regions with less concern regarding water use.
- Maintenance requirements for the newly established trees and shrubs vary by plant type and by individual circumstances. Several of the challenges faced by landowners in maintaining riparian buffers are:
  - Replanting vegetation that dies (USDA NRCS, 2009); and
  - Ensuring that the trees do not interfere with any other environmental concerns, such as existing wetlands.
- Contracts between landowners and those buying GHG mitigation (i.e., sequestered carbon) will need to address several issues related to the future period covered by the agreement, as summarized on page 4.3 of this report.

4.5.2 GHG Impacts

Several estimates of the mitigation potential associated with riparian buffers have been reported in the literature. The Congressional Budget Office (2007) and EPA (2005) indicate that the carbon sequestration potential from plantings along waterways is between 0.4 and 1.0 metric tons CO_2-eq ac^{-1} yr^{-1}; however, this estimate refers only to grasses. Eagle et al. (2012) provides estimate of 2.79 metric tons CO_2-eq ac^{-1} yr^{-1} that is specific to riparian forest buffers, hence, this estimate is used to estimate the break-even prices. Exhibit 4-28 presents the estimates by soil carbon and carbon stored in trees and other vegetation.

Exhibit 4-28: On-Site Greenhouse Gas Mitigation Impacts for Establishing Riparian Forest Buffers

GHG Category	Benefits of Establishing Riparian Forest Buffers, per acre
Soil Carbon[a] (mt CO_2-eq yr^{-1})	0.70
Carbon Storage in Trees and Other Vegetation (mt CO_2-eq yr^{-1})	2.09
Average Net On-Site Impact (mt CO_2-eq yr^{-1})	2.79

[a] Soil carbon assumed to be 25% of total on-site sequestration with vegetation accounting for the majority.
Source: Eagle, et al. (2012).

4.5.3 Cost Profile

The farm-level costs of shifting riparian land from commodity production to forest buffer include capital costs, operations and maintenance (O&M) costs, and lost net income related to commodity production (i.e., opportunity cost). These costs vary across regions of the United States based on based differences in material costs and labor expenses. State-level capital and O&M costs for establishing riparian buffers are reported in the NRCS Field Office Technical Guide (FOTG) database. For estimating the break-even prices, representative farm-level low- and high-cost scenarios were developed. The low-cost scenario utilizes the lowest combined capital and O&M costs, among the states in each region, for establishing and maintaining riparian buffers; the high-cost scenario utilizes the highest combined value. In general, data for NRCS Conservation Practice 391 (Establish Riparian Forest Buffer) (USDA NRCS, 2010f) are used. The analysis only considers the planting of woody vegetation (rather than other herbaceous buffers, such as grasses). Opportunity costs are measured by land rent rates. State-level land rent rates are published by USDA NASS (2012). In each region, the opportunity cost is assumed to be zero for the 'low" cost scenario (i.e., the affected land is assumed to be truly marginal in commodity production) and equal to lowest State-level land rent rate for the region in the high-cost scenario.

Exhibit 4-29 describes State-level data and information from the FOTG database that were used to develop the low- and high- cost scenarios for each USDA production region. Exhibit 4-30 presents the capital costs, operations and maintenance (O&M) costs, and opportunity costs due to loss of commodity-related income under both the low- and high-cost scenarios by region.

Exhibit 4-29: Assumptions on Land Areas and Vegetation from FOTG Database

Region	State Referenced in Low-Cost Scenario	Assumptions Used in Low-Cost Scenario	State Referenced in High-Cost Scenario	Assumptions Used in High-Cost Scenario
Appalachia	Virginia	110 trees planted in 1 acre; majority of the vegetation used are hardwoods, with pines accounting for up to 20% of total trees/acre planted[a]	Virginia	Hardwood trees at 300 per acre
Corn Belt	Indiana	No indication of vegetation type is provided	Ohio	Hardwoods with weed control
Delta	Arkansas	Per-tree basis (at 302 trees per acre, as suggested in the database, then converted to per-acre cost)	Arkansas	Annual O&M cost are assumed to equal 1% of installation cost
Lake States	Minnesota	Based on relationships between capital costs and O&M in other States, annual O&M cost are assumed to equal 1% of installation cost (no indication of vegetation type is provided)	Michigan	Five rows of large hardwoods, two rows of shrubs, and two rows of medium trees
Mountain	Wyoming	Tree/shrub establishment with rodent protection; based on relationships between capital costs and O&M in other States, annual O&M cost are assumed to equal 1% of installation cost	Colorado	Trees and/or shrubs up-gradient from the water source
Northeast	Vermont	Costs provided for 200 bare-root plantings per acre	New York	Mix of trees, shrubs, and grasses (rather than cost of trees only)

Region	State Referenced in Low-Cost Scenario	Assumptions Used in Low-Cost Scenario	State Referenced in High-Cost Scenario	Assumptions Used in High-Cost Scenario
Northern Plains	North Dakota	No indication of vegetation type is provided	South Dakota	Shrub clumps with tree tubes for wildlife planting, annual O&M costs are assumed to be 1% of capital costs
Pacific	California	Mix of deciduous and coniferous trees	Oregon	No indication of vegetation type is provided
Southeast	Georgia	Based on relationships between capital costs and O&M in other States, annual O&M cost are assumed to equal 1% of installation cost; costs are based on the use of pine trees	Florida	Based on relationships between capital costs and O&M in other States, annual O&M costs are assumed to equal 1% of installation cost; no indication of vegetation type is provided
Southern Plains	Texas	Native trees and shrubs with herbaceous buffer upslope of woody planting	Oklahoma	Bareroot bottomland hardwoods; cost was provided on a per-tree basis, and are assumed to require 16 ft^2 per planting, and then are converted to a per-acre basis

[a] These costs apply for establishments of fewer than 5 total acres. For establishments larger than 5 acres, different costs apply per tree.

Exhibit 4-30: Regional Low- and High-Cost Scenarios for Establishing Riparian Forest Buffers

USDA Production Region	Low-Cost Scenario			High-Cost Scenario		
	Capital Costs[a]	Annual O&M[a]	Annual Opportunity Costs	Capital Costs[a]	Annual O&M[a]	Annual Opportunity Costs[b]
	2010 $/acre					
Appalachia	$765	$8	$0	$1,760	$18	$32
Corn Belt	$673	$68	$0	$835	$16	$99
Delta	$928	$93	$0	$4,211	$42	$75
Lake States	$2,072	$19	$0	$3,472	$174	$81
Mountain	$536	$54	$0	$3,417	$34	$47
Northeast	$1,437	$43	$0	$1,945	$19	$36
Northern Plains	$943	$105	$0	$6,000	$60	$47
Pacific	$710	$7	$0	$2,825	$25	$137
Southeast	$265	$3	$0	$344	$3	$33
Southern Plains	$243	$2	$0	$2,999	$22	$30

Sources: [a] USDA NRCS (2011); [b] USDA NASS (2012).

4.5.4 Break-Even Prices

Exhibit 4-31 shows the break-even prices for installing riparian buffers under the low- and high-cost scenarios. These prices reflect the level of carbon incentive, stated in 2010 dollars per metric ton of CO_2-eq sequestered, at which a representative farmer in a given region would view shifting a generic acre of riparian land from commodity production to a forest buffer as economically rational (i.e., the point at which the net present value of the benefits of the riparian buffer equals the net present value of the costs). The break-even prices are based on the per-acre costs for restoring or establishing riparian forest buffers shown in Exhibit 4-30 and the per-acre GHG benefits shown in Exhibit 4-28. The capital costs shown in Exhibit 4-30 are annualized over a 15-year project lifetime.

Exhibit 4-31: Break-Even Prices for Restoring Riparian Forest Buffers

Low-Cost Scenario	
Region	Break-Even Price (2010 $/ mt CO_2-eq)
Southern Plains	$10
Southeast	$11
Pacific	$28
Appalachia	$31
Mountain	$39
Corn Belt	$49
Delta	$67
Northeast	$68
Northern Plains	$72
Lake States	$82

High-Cost Scenario	
Region	Break-Even Price (2010 $/ mt CO_2-eq)
Southeast	$25
Corn Belt	$72
Appalachia	$82
Southern Plains	$128
Northeast	$136
Pacific	$161
Mountain	$153
Delta	$195
Lake States	$218
Northern Plains	$257

4.6 Summary of Break-Even Prices for Land Retirement Systems Mitigation Options

Given appropriate GHG mitigation incentives, retiring land from crop cultivation or livestock grazing can be an attractive GHG mitigation option for landowners. The mitigation potential for retiring land, as well as the secondary benefits to the remaining agricultural land in terms of increased soil and water quality, can be significant. Exhibit 4-32 presents the break-even prices for all land retirement options developed in this chapter sorted from low to high. As indicated:

- In most regions, the break-even prices for retiring marginal soils and establishing permanent grass cover are higher than for organic soils;
- The break-even prices for restoring forested wetlands are approximately one-third of the levels for restoring grassy wetlands due to increased carbon benefits in forested wetlands; and
- The break-even prices for restoring riparian buffers and establishing windbreaks are similar.

Exhibit 4-32 Break-Even Prices for Land Retirement Systems Mitigation Practices

Management Practice	Region	Break-Even Price (2010 $/ mt CO_2-eq)
Retire Marginal Soils, Establish Conservation Cover (Low-Cost Scenario)	Northern Plains	$4
Retire Organic Soils, Establish Conservation Cover (Low-Cost Scenario)	Southeast	$6
Retire Organic Soils, Establish Conservation Cover (Low-Cost Scenario)	Appalachia	$6
Restore Forested Wetlands (Low-Cost Scenario)	Mountain	$6
Retire Marginal Soils, Establish (Low-Cost Scenario)	Mountain	$6
Retire Marginal Soils, Establish (Low-Cost Scenario)	Southern Plains	$7
Retire Organic Soils, Establish Conservation Cover (Low-Cost Scenario)	Lake States	$8
Retire Organic Soils, Establish Conservation Cover (Low-Cost Scenario)	Northeast	$9
Restore Forested Wetlands (Low-Cost Scenario)	Southeast	$9
Retire Organic Soils, Establish (High-Cost Scenario)	Southeast	$9
Restore Riparian Forest Buffers (Low-Cost Scenario)	Southern Plains	$10
Restore Forested Wetlands (Low-Cost Scenario)	Northern Plains	$10
Retire Organic Soils, Establish Conservation Cover (High-Cost Scenario)	Northeast	$10
Retire Organic Soils, Establish Conservation Cover (High-Cost Scenario)	Appalachia	$10
Restore Riparian Forest Buffers (Low-Cost Scenario)	Southeast	$11
Restore Forested Wetlands (Low-Cost Scenario)	Northeast	$11
Retire Marginal Soils, Establish Conservation Cover (Low-Cost Scenario)	Lake States	$11
Retire Organic Soils, Establish Conservation Cover (Low-Cost Scenario)	Corn Belt	$11
Restore Forested Wetlands (Low-Cost Scenario)	Pacific	$13
Retire Organic Soils, Establish Conservation Cover (High-Cost Scenario)	Lake States	$13
Retire Marginal Soils, Establish Conservation Cover (Low-Cost Scenario)	Southeast	$14
Restore Forested Wetlands (Low-Cost Scenario)	Southern Plains	$14
Retire Organic Soils, Establish Conservation Cover (Low-Cost Scenario)	Pacific	$15
Restore Forested Wetlands (Low-Cost Scenario)	Appalachia	$16
Restore Forested Wetlands (Low-Cost Scenario)	Delta	$16

Management Practice	Region	Break-Even Price (2010 $/ mt CO_2-eq)
Restore Forested Wetlands (High-Cost Scenario)	Southern Plains	$16
Retire Organic Soils, Establish Conservation Cover (High-Cost Scenario)	Corn Belt	$16
Restore Forested Wetlands (High-Cost Scenario)	Delta	$16
Restore Forested Wetlands (Low-Cost Scenario)	Lake States	$17
Restore Grassy Wetlands (Low-Cost Scenario)	Mountain	$17
Establish Windbreaks (Low-Cost Scenario)	Corn Belt	$17
Restore Forested Wetlands (High-Cost Scenario)	Northern Plains	$18
Establish Windbreaks (Low-Cost Scenario)	Southern Plains	$18
Restore Grassy Wetlands (Low-Cost Scenario)	Southeast	$23
Restore Forested Wetlands (Low-Cost Scenario)	Corn Belt	$24
Retire Marginal Soils, Establish Conservation Cover (Low-Cost Scenario)	Pacific	$24
Establish Windbreaks (Low-Cost Scenario)	Appalachia	$24
Retire Marginal Soils, Establish Conservation Cover (Low-Cost Scenario)	Corn Belt	$24
Retire Marginal Soils, Establish Conservation Cover (Low-Cost Scenario)	Appalachia	$25
Restore Riparian Forest Buffers (High-Cost Scenario)	Southeast	$25
Restore Grassy Wetlands (Low-Cost Scenario)	Northern Plains	$26
Establish Windbreaks (Low-Cost Scenario)	Northern Plains	$26
Establish Windbreaks (Low-Cost Scenario)	Mountain	$27
Restore Riparian Forest Buffers (Low-Cost Scenario)	Pacific	$28
Retire Marginal Soils, Establish Conservation Cover (Low-Cost Scenario)	Delta	$29
Restore Grassy Wetlands (Low-Cost Scenario)	Northeast	$29
Retire Organic Soils, Establish Conservation Cover (High-Cost Scenario)	Pacific	$30
Restore Forested Wetlands (High-Cost Scenario)	Mountain	$31
Restore Riparian Forest Buffers (Low-Cost Scenario)	Appalachia	$31
Restore Grassy Wetlands (Low-Cost Scenario)	Pacific	$33
Restore Forested Wetlands (High-Cost Scenario)	Corn Belt	$36

Management Practice	Region	Break-Even Price (2010 $/ mt CO_2-eq)
Restore Grassy Wetlands (Low-Cost Scenario)	Southern Plains	$38
Establish Windbreaks (Low-Cost Scenario)	Lake States	$38
Restore Riparian Forest Buffers (Low-Cost Scenario)	Mountain	$39
Restore Forested Wetlands (High-Cost Scenario)	Southeast	$39
Establish Windbreaks (Low-Cost Scenario)	Southeast	$40
Restore Forested Wetlands (High-Cost Scenario)	Lake States	$40
Retire Marginal Soils, Establish Conservation Cover (High-Cost Scenario)	Southern Plains	$41
Restore Forested Wetlands (High-Cost Scenario)	Appalachia	$42
Restore Grassy Wetlands (Low-Cost Scenario)	Appalachia	$42
Restore Grassy Wetlands (Low-Cost Scenario)	Delta	$42
Restore Grassy Wetlands (High-Cost Scenario)	Southern Plains	$42
Restore Grassy Wetlands (High-Cost Scenario)	Delta	$43
Restore Grassy Wetlands (Low-Cost Scenario)	Lake States	$43
Retire Marginal Soils, Establish Conservation Cover (High-Cost Scenario)	Southeast	$44
Establish Windbreaks (Low-Cost Scenario)	Pacific	$46
Restore Grassy Wetlands (High-Cost Scenario)	Northern Plains	$47
Establish Windbreaks (Low-Cost Scenario)	Delta	$48
Restore Riparian Forest Buffers (Low-Cost Scenario)	Corn Belt	$49
Restore Forested Wetlands (High-Cost Scenario)	Pacific	$54
Retire Marginal Soils, Establish Conservation Cover (High-Cost Scenario)	Northern Plains	$54
Restore Forested Wetlands (High-Cost Scenario)	Northeast	$56
Establish Windbreaks (High-Cost Scenario)	Mountain	$60
Restore Grassy Wetlands (Low-Cost Scenario)	Corn Belt	$63
Establish Windbreaks (High-Cost Scenario)	Southeast	$63
Retire Marginal Soils, Establish Conservation Cover (High-Cost Scenario)	Mountain	$64
Retire Marginal Soils, Establish Conservation Cover (Low-Cost Scenario)	Northeast	$65

Management Practice	Region	Break-Even Price (2010 $/ mt CO_2-eq)
Restore Riparian Forest Buffers (Low-Cost Scenario)	Delta	$67
Establish Windbreaks (High-Cost Scenario)	Southern Plains	$67
Restore Riparian Forest Buffers (Low-Cost Scenario)	Northeast	$68
Restore Riparian Forest Buffers (High-Cost Scenario)	Corn Belt	$72
Restore Riparian Forest Buffers (Low-Cost Scenario)	Northern Plains	$72
Retire Marginal Soils, Establish Conservation Cover (High-Cost Scenario)	Appalachia	$72
Establish Windbreaks (Low-Cost Scenario)	Northeast	$78
Restore Grassy Wetlands (High-Cost Scenario)	Mountain	$80
Restore Riparian Forest Buffers (High-Cost Scenario)	Appalachia	$82
Restore Grassy Wetlands (High-Cost Scenario)	Corn Belt	$94
Establish Windbreaks (High-Cost Scenario)	Appalachia	$95
Establish Windbreaks (High-Cost Scenario)	Corn Belt	$98
Restore Grassy Wetlands (High-Cost Scenario)	Southeast	$102
Restore Grassy Wetlands (High-Cost Scenario)	Lake States	$105
Retire Marginal Soils, Establish Conservation Cover (High-Cost Scenario)	Northeast	$105
Retire Marginal Soils, Establish Conservation Cover (High-Cost Scenario)	Delta	$107
Restore Grassy Wetlands (High-Cost Scenario)	Appalachia	$108
Establish Windbreaks (High-Cost Scenario)	Delta	$123
Restore Riparian Forest Buffers (High-Cost Scenario)	Southern Plains	$128
Establish Windbreaks (High-Cost Scenario)	Lake States	$130
Retire Marginal Soils, Establish Conservation Cover (High-Cost Scenario)	Lake States	$130
Restore Riparian Forest Buffers (High-Cost Scenario)	Northeast	$136
Restore Grassy Wetlands (High-Cost Scenario)	Pacific	$140
Retire Marginal Soils, Establish Conservation Cover (High-Cost Scenario)	Corn Belt	$144
Restore Grassy Wetlands (High-Cost Scenario)	Northeast	$145
Restore Riparian Forest Buffers (High-Cost Scenario)	Mountain	$153

Management Practice	Region	Break-Even Price (2010 $/ mt CO_2-eq)
Restore Riparian Forest Buffers (High-Cost Scenario)	Pacific	$161
Establish Windbreaks (High-Cost Scenario)	Northern Plains	$164
Establish Windbreaks (High-Cost Scenario)	Northeast	$194
Restore Riparian Forest Buffers (High-Cost Scenario)	Delta	$195
Establish Windbreaks (High-Cost Scenario)	Pacific	$215
Restore Riparian Forest Buffers (High-Cost Scenario)	Lake States	$218
Restore Riparian Forest Buffers (High-Cost Scenario)	Northern Plains	$257
Retire Marginal Soils, Establish Conservation Cover (High-Cost Scenario)	Pacific	$276

CHAPTER 4: REFERENCES

Badiou, P., R.L. McDougal, D.J. Pennock, and B. Clark. 2011. Greenhouse Gas Emissions and Carbon Sequestration Potential in Restored Wetlands of the Canadian Prairie Pothole Region. *Wetlands Ecology and Management*, 19(3):237–256.

CAST. 2011. *Carbon Sequestration and Greenhouse Gas Fluxes in Agriculture: Challenges and Opportunities*. Ames, IA: Council for Agricultural Science and Technology.

Congressional Budget Office. 2007. *The Potential for Carbon Sequestration in the United States*: Congressional Budget Office. http://www.cbo.gov/doc.cfm?index=8624.

Denef, K., S. Archibeque, and K. Paustian. 2011. *Greenhouse Gas Emissions from U.S. Agriculture and Forestry: A Review of Emission Sources, Controlling Factors, and Mitigation Potential*: Interim report to USDA under Contract #GS-23F-8182H. http://www.usda.gov/oce/climate_change/techguide/Denef_et_al_2011_Review_of_reviews_v1.0.pdf.

Eagle, A.J., L.R. Henry, L.P. Olander, K. Haugen-Kozyra, et al. 2011. *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States A Synthesis of the Literature* Durham, NC: Nicholas Institute for Environmental Policy Solutions Report.

Eagle, A.J., L.P. Olander, L.R. Henry, K. Haugen-Kozyra, et al. 2012. *Greenhouse Gas Mitigation Potential of Agricultural Land Management in the United States A Synthesis of the Literature*. Durham, NC: Nicholas Institute for Environmental Policy Solutions, Duke University.

EPA. 2005. *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture*. Washington, DC: U.S. Environmental Protection Agency. http://www.epa.gov/sequestration/greenhouse_gas.html.

EPA. 2009. *National Water Quality Inventory: Report to Congress: 2004 Reporting Cycle*. Washington, DC: U.S. Environmental Protection Agency. http://water.epa.gov/lawsregs/guidance/cwa/305b/upload/2009_01_22_305b_2004report_2004_305Breport.pdf.

EPA. 2011. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2009*. Washington, DC: U.S. Environmental Protection Agency. http://epa.gov/climatechange/emissions/usinventoryreport.html.

Euliss Jr., N.H., R.A. Gleason, A. Olness, R.L. McDougal, et al. 2006. *North American Prairie Wetlands Are Important Nonforested Land-Based Carbon Storage Sites*. Jamestown, ND: U.S. Geological Survey, Northern Prairie Wildlife Research Center.

Gleason, R.A., J. N.H. Euliss, R.L. McDougal, K.E. Kermes, et al. 2005. *Potential of Restored Prairie Wetlands in the Glaciated North American Prairie to Sequester Atmospheric Carbon*. Jamestown, ND: U.S. Geological Survey, Northern Prairie Wildlife Research Center.

Gleason, R.A., B.A. Tangen, B.A. Browneb, and J. N.H. Euliss. 2009. Greenhouse Gas Flux from Cropland and Restored Wetlands in the Prairie Pothole Region. *Soil Biology & Biochemistry*, 41:2501–2507.

Hanley, D., and G. Kuhn. 2003. *Trees Against the Wind*: Pacific Northwest Extension. http://cru.cahe.wsu.edu/CEPublications/pnw0005/pnw0005.pdf.

Hansen, L.T. 2009. The Viability of Creating Wetlands for the Sale of Carbon Offsets. *Journal of Agricultural and Resource Economics*, 34(2):350–365.

Kohake, D.J., L.J. Hagen, and E.L. Skidmore (USDA ARS). 2009. Wind Erodibility of Organic Soils. *Soil Science Society of America Journal*, 74:250–257.

Maryland Cooperative Extension. 2000. *Fact Sheet 774: When a Landowner Adopts a Riparian Buffer-Benefits and Costs*. http://www.riparianbuffers.umd.edu/PDFs/FS774.pdf.

Morgan, J.A., R.F. Follett, L.H. Allan Jr., S. Del Grosso, et al. 2010. Carbon Sequestration in Agricultural Lands of the United States. *Journal of Soil and Water Conservation*, 65(1):6A–13A.

MSU. 2011. *Muck Crops*: Michigan State University, Department of Geography. http://www.geo.msu.edu/geogmich/muck_crops.htm.

Nickerson, C., R. Ebel, A. Borchers, and F. Carriazo. 2011. *Major Uses of Land in the United States, 2007*. Washington DC: U.S. Department of Agriculture, Economic Research Service. http://www.ers.usda.gov/media/188404/eib89_2_.pdf.

Ogle, S. 2010. Data received in a personal communication with Steven Ogle regarding soil carbon and soil quality per USDA production region.

Ogle, S. 2011. Data on cultivated histosols per USDA region.

Pearson, T., S. Walker, K. Paustian, B. Sohngen, et al. 2010. *Analysis of U.S. Agriculture, Forest, and Other Land Use Mitigation Activities: Quantitative Assessment and Ranking of Potential Activities*. Washington DC: U.S. Department of Agriculture.

Schoeneberger, M.M. 2005. *Agroforestry: Working Trees for Sequestering Carbon on Ag-Lands*. Rochester, MN: University of Minnesota, Department of Forest Resources.

Schoeneberger, M.M., G.B. Bentrup, D. Current, B. Wight, et al. 2008. Building Bigger, Better Buffers for Bioenergy. *Water Resource Impact*, 10:22–24.

Steere, J. 2000. Estimating Wetland Restoration Costs at an Urban and Regional Scale: The San Francisco Bay Estuary Example. Proceedings of the Proceedings of the Salmon Habitat Restoration Cost Workshop, November 14-16, 2000, Gladstone, OR.

Steglich, E.M., and J.W. Williams. 2009. *Agricultural Policy/Environmental eXtender Model User's Manual: Version 0604. BREC Report # 2008-16*. Temple, TX: Blackland Research and Extension Center. http://apex.tamu.edu/media/34652/apex-user-manual.pdf.

University of Idaho. 2012. The Twelve Soil Orders: Soil Taxonomy. Moscow, ID: University of Idaho, College of Agricultural and Life Sciences, Soil and Land Resources Division, .

USDA. 2007. *Greenhouse Gas Benefits of the Conservation Reserve Program (CRP)*. Washington, DC: U.S. Department of Agriculture.

USDA. 2011. *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990–2008*. Washington DC: U.S. Department of Agriculture, Climate Change Program Office, Office of the Chief Economist.

USDA ERS. 2006. *Agricultural Resources and Environmental Indicators, AREI Chapter 2.3: Wetlands: Status and Trends*: U.S. Department of Agriculture, Economic Research Service. http://webarchives.cdlib.org/sw1vh5dg3r/http://www.ers.usda.gov/publications/arei/eib16/Chapter2/2.3/.

USDA NASS. 2012. *2010 Cropland Cash Rent by State*: U.S. Department of Agriculture, National Agricultural Statistics Service. http://www.nass.usda.gov/Charts_and_Maps/Land_Values_and_Cash_Rents/crop_rent_map.asp.

USDA NRCS. 1999. *The CORE4 Conservation Practices Training Guide: The Common Sense Approach to Natural Resource Conservation*: U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA NRCS. 2009. *Conservation Practice Standard: Windbreak/ Shelterbelt Establishment (Code 380)*: U.S. Department of Agriculture, Natural Resources Conservation Service. http://efotg.sc.egov.usda.gov/references/public/MN/380mn.pdf.

USDA NRCS. 2010a. *Conservation Practice Standard: Wetland Restoration (Code 657)*: U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA NRCS. 2010b. *Conservation Practice Standard: Constructed Wetland (Code 656)*: U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA NRCS. 2010c. *Conservation Practice Standard: Wetland Enhancement (Code 659)*: U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA NRCS. 2010d. *Conservation Practice Standard: Wetland Wildlife Habitat Enhancement (Code 644)*: U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA NRCS. 2010e. *Conservation Practice Standard: Conservation Cover (Code 327)*: U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA NRCS. 2010f. *Conservation Practice Standard: Riparian Forest Buffer (Code 391)*: U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA NRCS. 2010g. *2007 National Resources Inventory: Soil Erosion on Cropland*: U.S. Department of Agriculture, Natural Resources Conservation Service. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_012269.pdf.

USDA NRCS. 2010h. *Conservation Practice Standard: Wetland Creation (Code 658)*: U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA NRCS. 2011. *Natural Conservation Practice Standards: Electronic Field Technical Guide (eFOTG) Database of Practice Costs*: U.S. Department of Agriculture, Natural Resources Conservation Service. http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/fotg.

USDA NRCS. 2012a. *Histosols Map*: U.S. Department of Agriculture, Natural Resources Conservation Service. http://soils.usda.gov/technical/classification/orders/histosols_map.html.

USDA NRCS. 2012b. Wetlands Reserve Program (WRP): FY 2010 WRP Data - Contracts and Funding: U.S. Department of Agriculture, Natural Resources Conservation Service.

USDA NRCS. 2012c. *Riparian Buffer in Putnam County, Ohio (Photo)*: U.S. Department of Agriculture, Natural Resources Conservation Service. http://www.oh.nrcs.usda.gov/programs/lake_erie_buffer/riparian.html.

USDA NRCS. 2013. *New Jersey Wetland (Photo)*: U.S. Department of Agriculture, Natural Resources Conservation Service. http://www.nj.nrcs.usda.gov/technical/biology/wetlands.html.

USFWS. 2010. *Carbon Sequestration Benefits of Peatland Restoration: Attracting New Partners to Restore Habitat on National Wildlife Refuges*: U.S. Fish and Wildlife Service.

Virginia Outdoors Foundation. 2012. *USDA 3-Zone Riparian Buffer Planning Model.*

Wenger, S. 1999. *A Review of the Scientific Literature on Riparian Buffer Width, Extent, and Vegetation*. Athens, GA: University of Georgia, Office of Public Service and Outreach, Institute of Ecology.

Williams, J.R., C.A. Jones, and P.T. Dyke. 1990. *The EPIC Model Documentation*. Washington, DC: U.S. Department of Agriculture.

5. CONCLUSION

This report evaluates the farm-level adoption costs and break-even prices of 20 technologies and production practices that farms could implement to mitigate greenhouse gas emissions from crop production systems, animal production systems, and land retirement systems. The break-even prices presented in this report reflect the carbon incentive level at which a given GHG mitigation option becomes economically viable to the landowner (i.e., the point at which the net present value of the benefits equals the net present value of the costs). To account for uncertainty in the estimates, different scenarios were evaluated to develop a range of break-even prices for several of the mitigation options. Some mitigation options have potential co-benefits that may result in additional revenue under some circumstances (e.g., increases in crop yield from use of nitrification inhibitors or shifting from fall to spring fertilizer application, the sale of excess electricity from on-farm collection and combustion of biogas). The existence of such benefits could significantly lower the break-even price of a given technology or practice in a given farm situation. These benefits are not considered in the calculation of break-even prices developed in this report for two reasons. First, the ability of a farm to capture the economic value of these benefits is typically dependent on site-specific factors and, in some cases, is limited. Second, given the uncertainties associated with farmers' abilities to capture the economic value of these benefits, it is important for farmers and policy-makers to know what incentive levels, based only on CO_2 mitigation benefits, would be needed to facilitate broader adoption of these technologies and practices. Below we summarize the major findings for each agricultural system.

5.1 Crop Production Systems

The mitigation categories for crop production systems are field management and nutrient management. Data were gathered primarily from USDA data sets, Land Grant universities, and DAYCENT model outputs. Decreases in yield were accounted for when modeling reduced tillage intensity and reduced fertilizer application. Without decreases in yield, the break-even prices would be negative. This outcome would imply the options are currently cost effective for farmers to adopt and thus no additional incentive is needed.

For the other options (i.e., switch in timing of nitrogen application, use of inhibitors, and variable rate technology), no change in yield is modeled. The underlying assumption is that farmers who adopt these options can reduce the amount of applied nitrogen that is lost to nitrification, denitrification, and leaching (and is thus never available for crop growth). Exhibit 5-1provides an overview of the crop production mitigation practices and corresponding yield considerations that were modeled in this report.

Mitigation Options for Crop Production Systems

Field Management Options

- Reduced Tillage Intensity
  - Switch from Conventional to Reduced Tillage
  - Switch from Conventional Tillage to No-Till
  - Switch from Reduced Tillage to No-Till
- Qualitative Assessments
  - Crop Rotation Changes
  - Field Burning Elimination
  - Reduced Lime Application
  - Rice Cultivation

Nutrient Management Options

- Reduce Application Rate
- Shift From Fall to Spring Fertilizer Application
- Inhibitor Application
  - Nitrification Inhibitors
  - Urease Inhibitors
- Use Variable Rate Technology

Exhibit 5-1: Mitigation Practices and Modeled Yield Scenario

Mitigation Practice	Decrease in Yield	No Change in Yield
Switching from Conventional to Reduced Tillage	✓	
Switching from Conventional to No-Till	✓	
Switching from Reduced Till to No-Till	✓	
10% Reduction in Nitrogen Application Rate	✓	
Switch from Fall to Spring Nitrogen Application		✓
Inhibitor Application		✓
Variable Rate Technology		✓

The break-even prices developed in this report indicate that no one mitigation option is consistently the most cost effective across USDA production regions and crop types (i.e., a particular mitigation option does not have the lowest break-even price across production regions, crop produced, and farm size category). Exhibit 5-2 provides a qualitative assessment of the relative cost effectiveness of different mitigation options by crop type. For example, for corn, GreenSeeker^{TM} has a relatively low break-even price when compared to the use of nitrogen inhibitors. Cotton has the highest commodity price, hence technologies with potential decreases in yield result in relatively high break-even prices. Inhibitors, particularly under the low emissions reduction scenario, have relatively high break-even prices due to their incremental cost with respect to fertilizer costs and the limited N_2O mitigation effectiveness assumed under the low emissions reduction scenario. High break-even prices can be due to the relatively high adoption costs, losses in yield, and/or low emissions reduction potential.

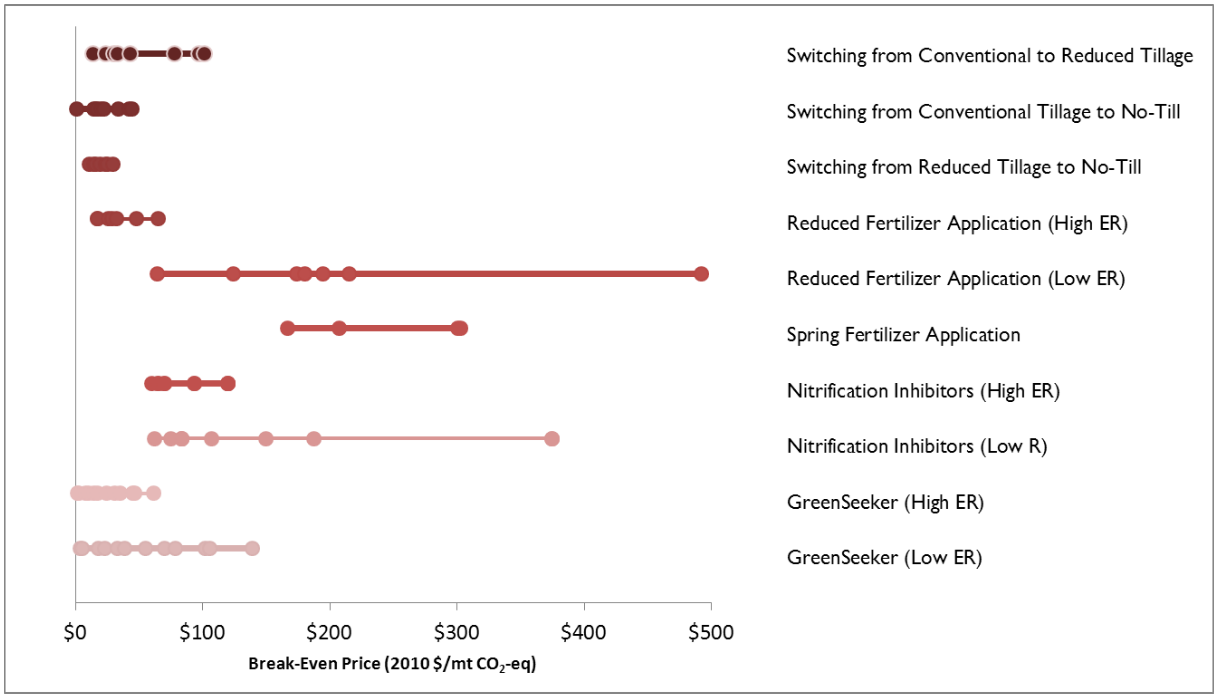
Exhibit 5-2: Relative Break-Even Prices for Each Crop Type

Crop Type	Break-Even Prices	
	Relatively Low	Relatively High
Corn	▪ Switching from Conventional Tillage to No-Till ▪ Switching from Conventional Tillage to Reduced Tillage ▪ 10% Reduction in Nitrogen Application (High Emissions Reduction Scenario) ▪ Variable Rate Technology (e.g., GreenSeeker^{TM})	▪ Nitrogen Inhibitors (Low Emissions Reduction Scenario) ▪ Switching from Fall to Spring Nitrogen Application ▪ 10% Reduction in Nitrogen Application (Low Emissions Reduction Scenario)
Cotton	▪ Switching from Reduced Till to No-Till ▪ Urease Inhibitors (High Emissions Reduction Scenario) ▪ Switching from Conventional Till to No-Till	▪ Urease Inhibitors (Low Emissions Reduction Scenario) ▪ Switching from Conventional Tillage to Reduced Tillage ▪ 10% Reduction in Nitrogen Application (Low Emissions Reduction Scenario)
Sorghum	▪ 10% Reduction in Nitrogen Application (High Emissions Reduction Scenario) ▪ Switching from Conventional Tillage to No-Till ▪ Switching from Reduced Till to No-Till	▪ Nitrogen Inhibitors (Low Emissions Reduction Scenario) ▪ Switching from Fall to Spring Nitrogen Application ▪ Switching from Conventional Tillage to Reduced Tillage

Crop Type	Break-Even Prices	
	Relatively Low	Relatively High
Soybeans	▪ Switching from Conventional Till to No-Till ▪ Switching from Reduced Till to No-Till	▪ Switching from Fall to Spring Nitrogen Application ▪ Nitrification Inhibitors
Wheat	▪ GreenSeeker^{TM} ▪ 10% Reduction in Nitrogen Application (High Emissions Reduction Scenario) ▪ Switching from Conventional Till to No-Till	▪ Nitrogen Inhibitors (Low Emissions Reduction Scenario) ▪ Switching from Fall to Spring Nitrogen Application

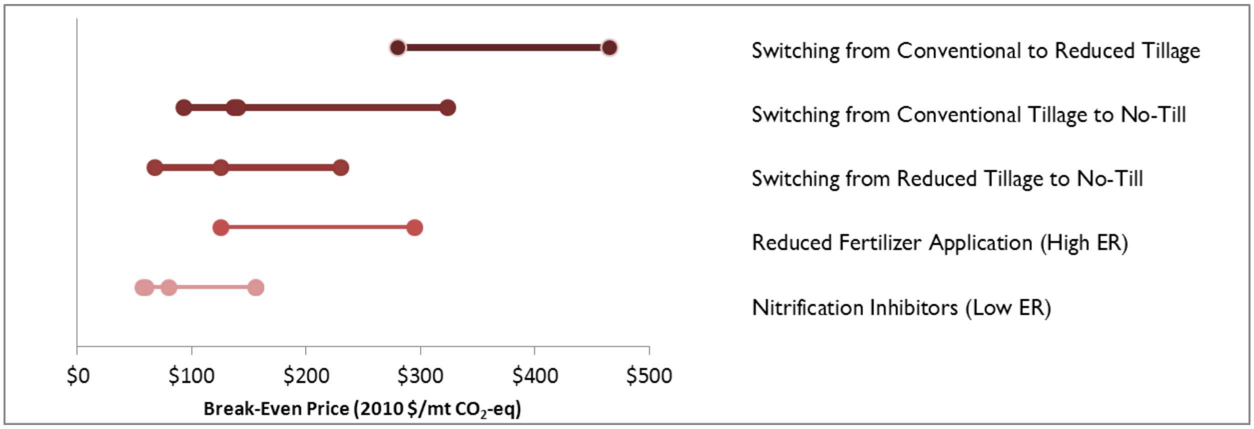
Exhibit 5-3 through 5-7 present break-even prices (limited to \$500/mt CO_2-eq) for various GHG mitigation options for corn, cotton, sorghum, soybeans, and wheat systems, respectively. For each option, the individual dots represent different region- farm size combinations. Exhibit 5-8 summarizes break-even prices for all cropping systems. As evident in the exhibits, the majority of the break-even prices are less than \$100/mt CO_2-eq. Variable rate technology (i.e., GreenSeeker^{TM}) on farms of more than 500 acres was the most cost-effective farm-level option for mitigating GHG emissions related to nutrient management. However, variable rate technology estimates do not include net changes in yield and are based on a small number of studies. Reducing fertilizer application is a simple and cost-effective strategy for reducing N_2O emissions; however, incentivizing reductions in nitrogen application rates would likely need to account for the risk of reduced yields. For a few region-crop type combinations, low yield losses, and high fertilizer savings resulted in negative break-even prices. For these situations, incentives may not be needed to encourage farmers to reduce nitrogen application. For other combinations, high yield losses combined with high crop prices resulted in relative high break-even prices. In particular, cotton crop systems generally have the highest break-even prices across options. These cropping systems will likely require incentives that are too high to be considered realistic in the context of paying farms to mitigate GHG emissions by changing tillage or fertilizer practices.

Exhibit 5-3: Break-Even Prices (less than \$500/mt CO_2-eq) for Corn Production Practices



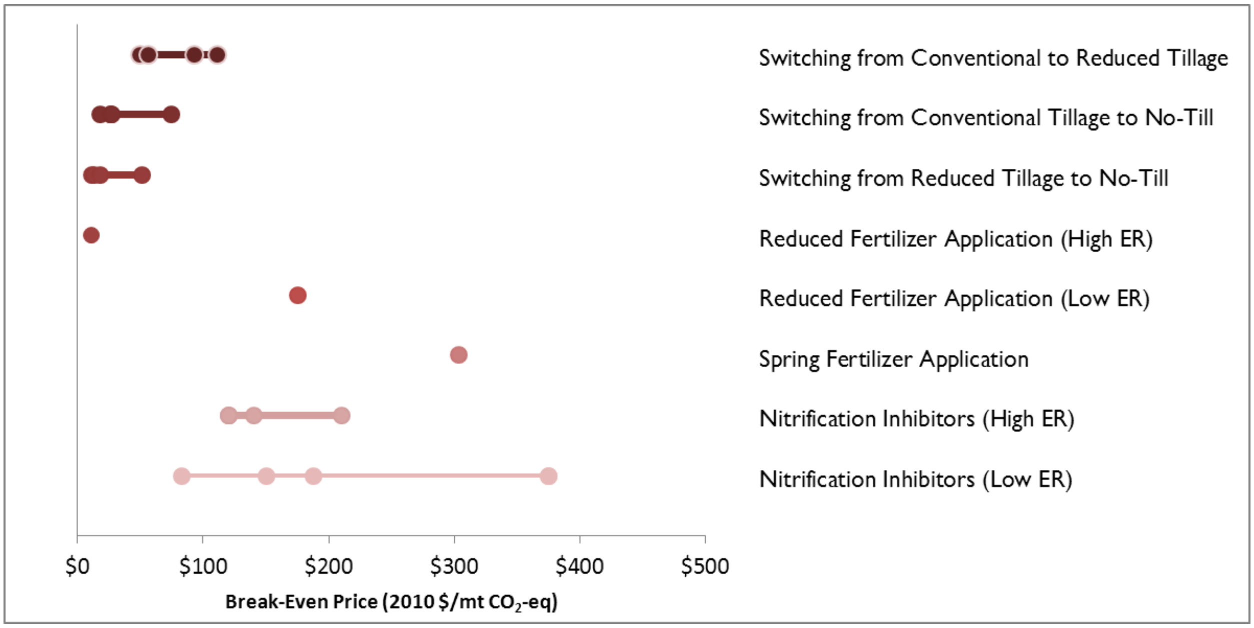
ER = Emissions reduction
Dots represent different region-farm size combinations.

Exhibit 5-4: Break-Even Prices (less than $500/mt CO₂-eq) for Cotton Production Practices



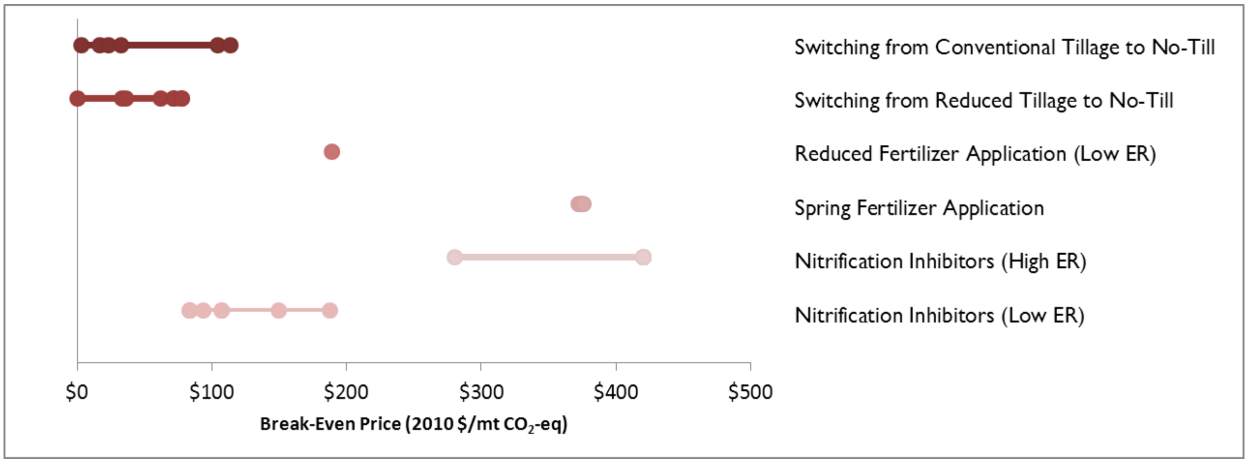
ER = Emissions reduction
Dots represent different region-farm size combinations.

Exhibit 5-5: Break-Even Prices (less than $500/mt CO₂-eq) for Sorghum Production Practices



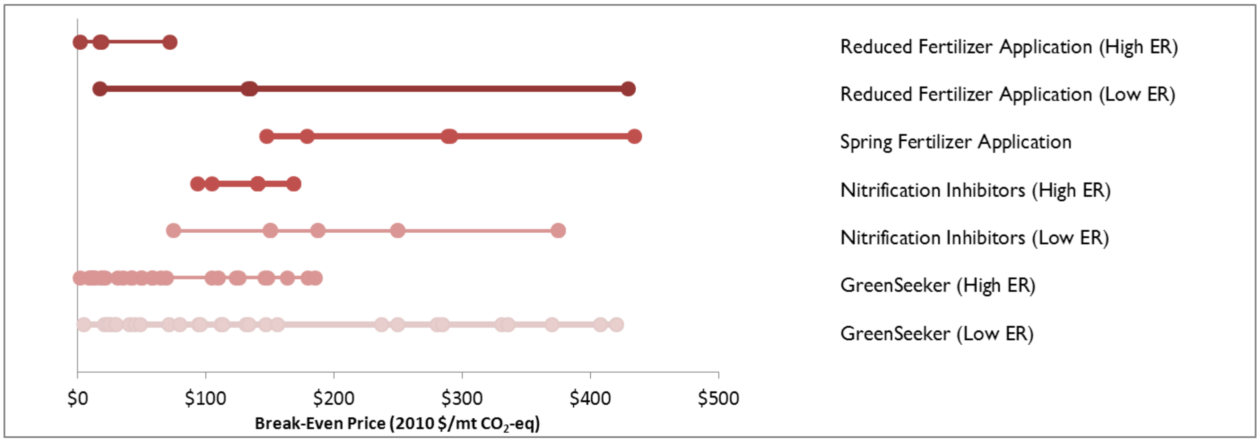
ER = Emissions reduction
Dots represent different region-farm size combinations.

Exhibit 5-6: Break-Even Prices (less than \$500/mt CO_2-eq) for Soybean Production Practices



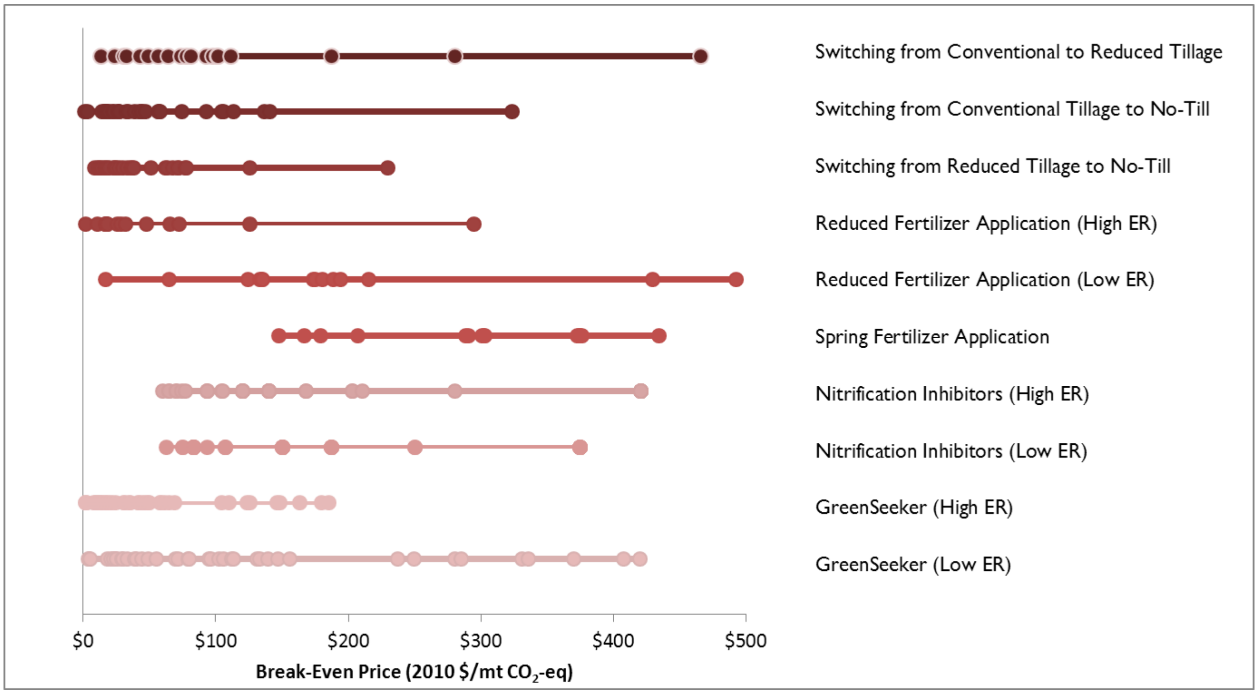
ER = Emissions reduction
Dots represent different region-farm size combinations.

Exhibit 5-7: Break-Even Prices (less than \$500/mt CO_2-eq) for Wheat Production Practices



ER = Emissions reduction
Dots represent different region-farm size combinations.

Exhibit 5-8: Break-Even Prices (less than \$500/mt CO_2-eq) for Transitioning from Current Management Practice to Mitigation Option in Crop Production Systems



ER = Emissions reduction
Dots represent different region-farm size combinations.

5.2 Animal Production Systems

The mitigation categories for animal production systems are (1) manure management, (2) enteric fermentation, and (3) grazing land management. Animal population, activity, and emissions data were obtained primarily from USDA data sets, the U.S. National GHG Inventory, and the EPA AgSTAR program. The adjacent textbox lists the mitigation options evaluated for animal production systems.

5.2.1 Manure Management

The mitigation practices provide alternative ways of managing manure that would reduce the release of methane into the atmosphere. For some options, there is an opportunity for farms to capture methane-containing biogas and use it for generating electricity or heat. Cost savings were evaluated for on-site use of biogas, but not for the sale of excess gas or electricity to a utility.

Exhibit 5-9 summarizes the break-even prices for the analyzed manure management options. Only break-even prices less than \$500/mt CO_2-eq are shown and for each option. The dots represent different region-farm size combinations. Key findings include the following:

- Digester technologies (and other capital-intensive manure management systems) have been demonstrated at scale. At given CO_2 prices, these systems could be cost-effective GHG mitigation options for many confined animal operations, particularly dairy and swine operations:
  - Break-even prices for large operations are generally less than \$50/mt CO_2-eq; and
  - Break-even prices for medium-size operations are generally less than \$100/mt CO_2-eq.

- Accounting for co-products (e.g., mulch, bedding, off-farm sale of electricity/natural gas) could significantly lower the break-even prices.
- Break-even prices for covering anaerobic lagoons and flaring the biogas, and for installing improved solids separators show that relatively small livestock operations have feasible GHG mitigation opportunities at CO_2 prices less than \$50/mt CO_2-eq.
- Swine and dairy cow operations have more mitigation options available than beef operations due to the current methods that are used in each sector to collect and treat manure.
- For covered lagoon digesters, plug flow digesters, covering an existing lagoon, and, in some instances, for complete mix digesters, the regions with the largest potential for GHG reductions are the Southeast, Delta, and Southern Plains. This is because existing manure management practices emit more methane in warmer regions than in cooler regions, resulting in generally lower break-even prices in warmer regions.
- Liquid/slurry systems have lower methane production potential than deep pit or anaerobic lagoons, and thus have higher break-even prices.

An anaerobic lagoon produces the most methane of existing manure management practices, and thus has the greatest mitigation potential for farms transitioning to a lower emitting manure management system. Consequently, the break-even prices for most manure management options consider in this report are lower for transitioning from anaerobic lagoons than from other manure management practices.

Mitigation Options for Animal Production Systems

Manure Management

- Anaerobic Digesters
  - Covered Lagoon Anaerobic Digester
  - Complete Mix Anaerobic Digester
  - Plug Flow Anaerobic Digester
  - Covering Existing Pond, Tank, or Lagoon
- Solids Separator
- Nitrification/Denitrification

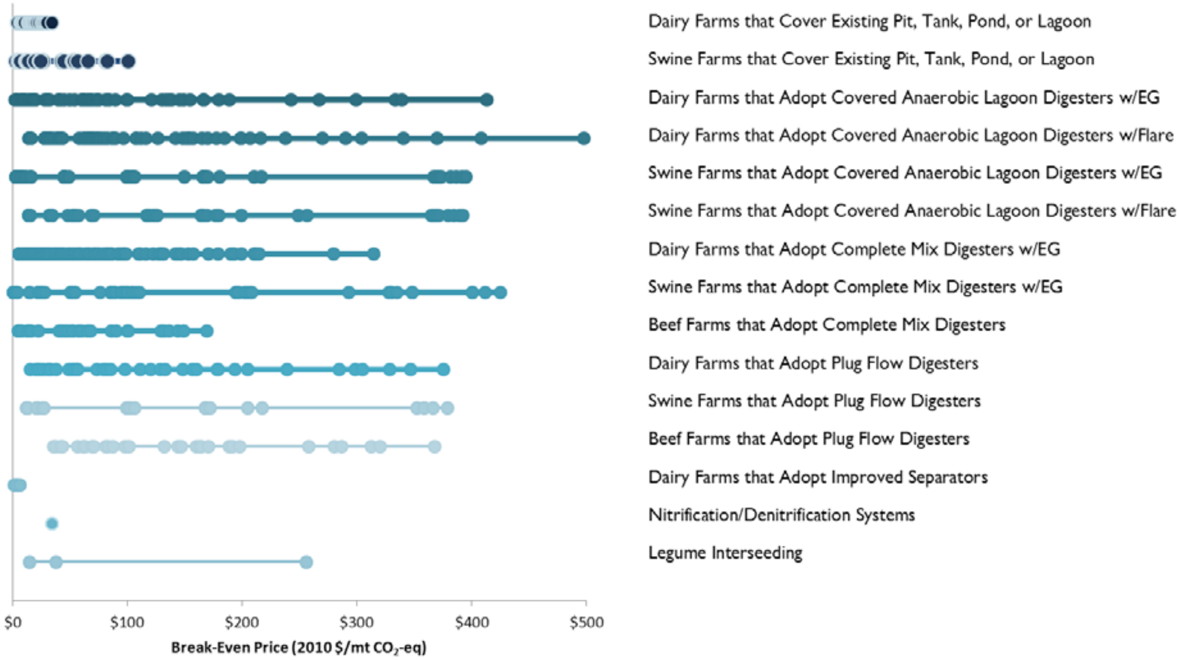
Enteric Fermentation (qualitative assessments)

- Modification of Diet Composition and Level of Intake
  - Increasing Dietary Fat Content
  - Providing Higher Quality Forage
  - Increasing Protein Content of Feed
  - Decreasing the Forage-to-Concentrate Ratio and Adding Supplemental Concentrates
  - Processing/Grinding Feed
- Monensin and Other Feed Additives
- Breeding for Increased Productivity and Decreased Methane Production

Grazing Land Management

- Legume Interseeding
- Qualitative Assessments
  - Rotational Grazing
  - Fertilization
  - Irrigation
  - SilvoPasture

Exhibit 5-9: Break-Even Prices (less than \$500/mt CO_2-eq) for Transitioning from Current Management Practice to Mitigation Option in Animal Production Systems



EG = Electricity generation
Dots represent different region-farm size combinations.

5.2.2 Enteric Fermentation

Emissions from enteric fermentation are highly variable and are dependent on livestock type, life stage, activity, and feeding situation (e.g., grazing, feedlot). Several practices have demonstrated the potential for efficacy in reducing emissions from enteric fermentation. Although diet modification (e.g., increasing fat content, providing higher quality forage, increasing protein content) and providing supplements (e.g., monensin, bovine somatotropin [bST]) have been evaluated for mitigation potential, the effectiveness of each option is not conclusive. For example, the efficacy of monensin in mitigating emissions is still not fully understood. Among studies, the magnitude of the reductions varies by animal type and living/feeding conditions. Additionally, several studies indicate that initial reductions in methane emissions are temporary and emissions return to baseline levels after several months.

5.2.3 Grazing Land Management

Break-even prices were estimated only for legume interseeding because other options have limited quantiative data and/or inconclusive research results. The reported range of potential carbon sequestration associated with legume interseeding is large reflecting the variety of different soil and climatic conditions across the United States. Low and high carbon sequestration potentials were modeled to estimate a range of break-even prices. Break-even prices were higher for high-input legume interseeding (i.e., the inclusion of potash, lime, and phosphorus application) than for low-input legume interseeding. Across regions and input intensities the break-even ranged from \$15 to \$657 per mt CO_2-eq as indicated in Exhibit 5-10.

Exhibit 5-10: Break-Even Price for Legume Interseeding

Management Intensity	Low Carbon Sequestration	High Carbon Sequestration
	Break-Even Price (2010 \$/mt CO_2-eq)	Break-Even Price (2010 \$/mt CO_2-eq)
Low Intensity	\$256	\$15
High Intensity[a]	\$657	\$38

[a] High-input legume interseeding includes the cost of potash, lime, and phosphorus application.

5.3 Land Retirement Systems

Mitigation Options for Land Retirement Systems

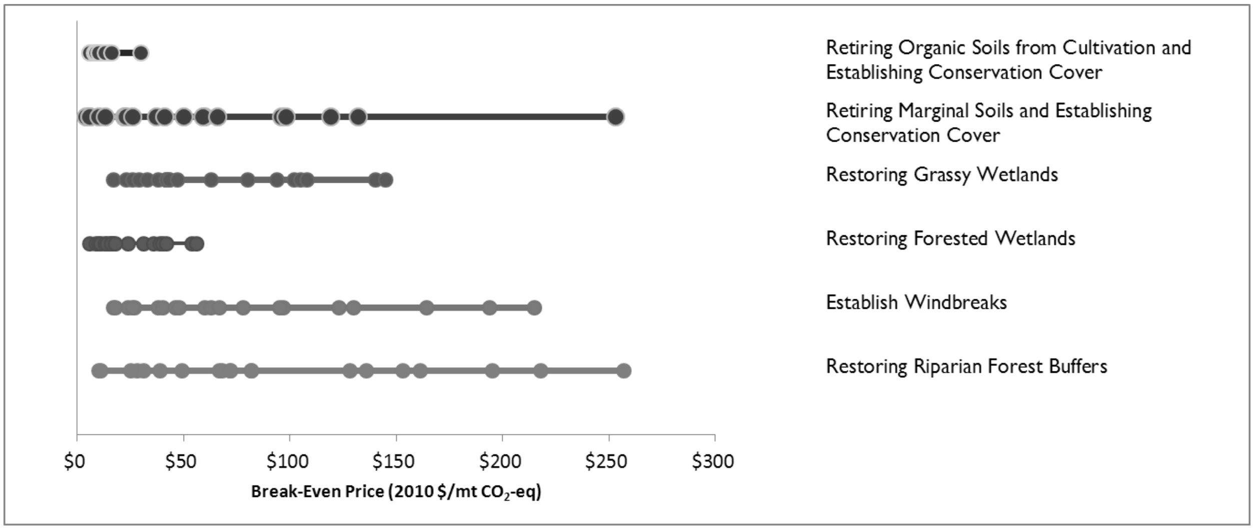
- Retire Cultivated Organic Soils and Establish Conservation Cover
- Retire Marginal Croplands and Establish Conservation Cover
- Restore Wetlands
- Establish Windbreaks
- Restore Riparian Forest Buffers

Break-even prices were developed for five illustrative GHG mitigation options that involve the retirement of both marginal and more productive croplands (organic soils and drained wetlands). Utilizing estimates of CO_2-eq reductions per acre, average land rents per acre (per region), and practice cost data provided by USDA's Field Office Technical Guide (FOTG) and the Wetlands Reserve Program (WRP), a range of break-even prices were developed.

Although retiring marginal lands is generally more attractive for landowners than is retiring higher quality parcels, an exception can be with retiring organic soils (histosols). On an acre-by-acre basis, retiring organic soils has a much greater GHG mitigation potential (i.e., 14.3 mt CO_2-eq per acre per year versus 1.1 mt CO_2-eq per acre per year). Exhibit 5-11 summarizes the break-even prices for each land retirement option. Key findings include the following:

- Taken collectively, the land retirement options could be relatively cost-effective at increasing farm-level GHG mitigation.
- The large majority of the options considered had break-even prices less than \$100/mt CO_2-eq., and at least half of these options had break-even prices less than \$50/mt CO_2-eq.
- In most regions, the break-even prices for retiring marginal soils and establishing conservation cover are higher than for organic soils.
- Incentive levels for restoring forested wetlands are approximately one-third of the levels for restoring grassy wetlands due to increased carbon benefits.
- Incentive levels for restoring riparian forest buffers and establishing windbreaks are similar.
- Additional incentives for other environmental goods and services (e.g., water quality, air quality, reduced runoff) would lower the break-even prices needed to increase adoption rates for land retirement practices.

Exhibit 5-11: Land Retirement Range of Break-Even Prices for Transitioning from Current Management Practice to Mitigation Option



Dots represent different region-farm size combinations.

5.4 Summary

Landowners can implement a number of practices and technologies to significantly reduce GHG emissions and/or to increase carbon sequestration in soils and biomass. To achieve widespread adoption of these practices or technologies, however, farmers must be able to recover the associated implementation costs (including any foregone net income related to commodity production). A proven technological/ implementation track record on other farms will also be important to most farmers. Additionally, practices and technologies that have other environmental benefits (e.g., benefits related to improved water quality, air quality, and wildlife habitat, or decreased soil erosion and nutrient run-off) benefits will be more appealing than those that do not.

This report provides a compendium of demonstrated GHG mitigation options for which data are readily available to estimate the incentive levels that would make implantation of the options by various "representative" farmers and landowners a break-even undertaking. These results will serve as a basis for USDA and other Federal agencies to assess the role of agriculture in GHG mitigation and the level of incentives that are needed to engage landowners. For the options considered, the results indicate a range of incentive levels that vary by farm size, region, and commodity produced (i.e., animal and crop type). As with any report of this nature, more research is needed to refine the costs and GHG mitigation benefits for each mitigation option. This report addresses the uncertainty in the incentive levels by evaluating several scenarios of farm characteristics and GHG mitigation potential.