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Managing Agricultural Land for Greenhouse Gas Mitigation within the United States

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Introduction

This report presents an analysis of the greenhouse gas (GHG) mitigation potential associated with changes in U.S. agricultural management practices. Marginal abatement cost curves (MACCs) are developed that illustrate how much GHG mitigation various sets of U.S. crop and livestock producers could supply across a schedule of mitigation incentives. Separate MACCs focus on incentivizing specific changes in technologies and practices in animal production systems, cropland systems, land management, and rangeland and pastureland management. The mitigation options included in this analysis are listed in the adjacent textbox.

Analytical Approach to Developing Marginal Abatement Cost Curves (MACCs)

A MACC traces out the quantities of GHG mitigation (i.e., either reduced GHG emissions or increased carbon sequestration) that U.S. farms could supply, in aggregate, across a schedule of carbon dioxide (CO_2) prices. Mitigation is expressed in metric tons (mt) and teragrams (Tg) carbon dioxide equivalents (CO_2e) and CO_2 prices are expressed in 2010 dollars per mt CO_2e mitigated. For any farm and mitigation practice combination, there is a CO_2 price that when multiplied by the associated mitigation level will yield a dollar value that just equals that farm's adoption cost. These CO_2 prices will be referred to as "break-even prices." With respect to GHGs, this analysis evaluates the potential to reduce methane (CH_4) and nitrous oxide (N_2O) emissions from manure management and crop production systems, and the potential to reduce CO_2 emissions or increase carbon sequestration through changes in tillage and land management practices. The general approach has four key steps:

Step 1: Define a set of farm-level technologies and practices that reduce GHG emissions or increase carbon sequestration. This analysis is based on the mitigation technologies and practices identified in the report, *Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production Within the United States* (ICF, 2013). ICF (2013) identifies a diverse set of about 20 well-established farm-level mitigation options for which adoption costs and mitigation values are available in the scientific literature, published government reports, and other sources. For some mitigation options, it is

Practices Covered in This Analysis

- Animal Production Systems
  - Anaerobic Digesters (3 Systems)
  - Solid Separators
  - Tank/Pond/Lagoon Cover
  - Nitrification-Denitrification System
- Nutrient Management Systems
  - 10% Reduction in Nitrogen Application
  - Switch From Fall to Spring Application
  - Nitrification Inhibitors
  - Variable Rate Technology
- Tillage Management
  - Switch From Conventional Tillage to Long-term No-Till
  - Switch From Conventional Tillage to Reduced Till
  - Switch From Reduced till to Long-term No-Till
- Land Retirement
  - Retire Organic Soils
  - Retire Marginal Cropland
  - Restore Wetlands (Grass and Forested)
  - Establish Windbreaks
  - Plant Riparian Forest Buffers
- Legume Interseeding

possible to distinguish adoption costs and mitigation potential by geographic region, farm size, and/or commodity produced.[1] Where this is the case, the break-even prices are also distinguished by region, farm size, and/or commodity produced, and each is considered separately in the MACC analysis.

Step 2: Identify CO_2 break-even prices. CO_2 break-even prices for the technologies and practice included in the MACC analysis are obtained from ICF (2013). A positive break-even price represents the minimum incentive level needed to make adoption economically rational from a farm perspective. For some farm-mitigation option combinations, ICF (2013) reports a negative break-even price. Conceptually, a negative break-even price suggests that no additional incentive should be required to make adoption cost effective. Negative break-even prices can make sense in cases where non-pecuniary factors exist that discourage adoption (e.g., various types of risk or a burdensome learning curve). They may also indicate situations where existing data do not accurately convey the full set of adoption costs that farmers would incur. Farm-mitigation option combinations in ICF (2013) that have negative break-even prices are not included in the MACC analysis. For more on the derivation of the break-even prices, see ICF (2013).

Step 3: Describe how crop and livestock production practices and technologies in use on U.S. farms are distributed by region and nationally. At the farm-level, the economic feasibility of an incentive to adopt a given GHG-mitigating technology or practice depends on the set of technologies and practices that are currently in place on the farm (hereafter, the farm's baseline technologies and practices). For example, solids separators and lagoon covers have no manure management applications on dairies that keep their cows in pastures. For pasture-based dairies, these technologies have no GHG mitigation potential. Scaling up to a region or on the national level, the mitigation potential of a given GHG-mitigating technology or practice depends on how baseline

production technologies and practices are distributed across the region or the Nation. Data showing how crop and livestock production technologies and practices are distributed across the country are relatively limited and so these distributions (i.e., baseline distributions) had to be constructed. The processes for constructing the baseline distributions for manure management, nutrient management, tillage, and land-use technologies and practices differ somewhat, and each process is described in its respective chapter. Due to data limitations and the timing of the ICF (2013) report, the baseline distributions of management practices in this report are developed from data and other information covering the 2007–2010 timeframe.

Step 4: Generate MACCs. The MACC framework combines the farm-level GHG mitigation practices and technologies (along with their associated CO_2 break-even prices and GHG mitigation values) in ICF (2013) with the baseline distributions

[1] The contiguous United States is divided into 10 U.S. Department of Agriculture (USDA) regions: Northeast, Lake States, Corn Belt, Northern Plains, Appalachia, Southeast, Delta, Southern Plains, Mountain, and Pacific.

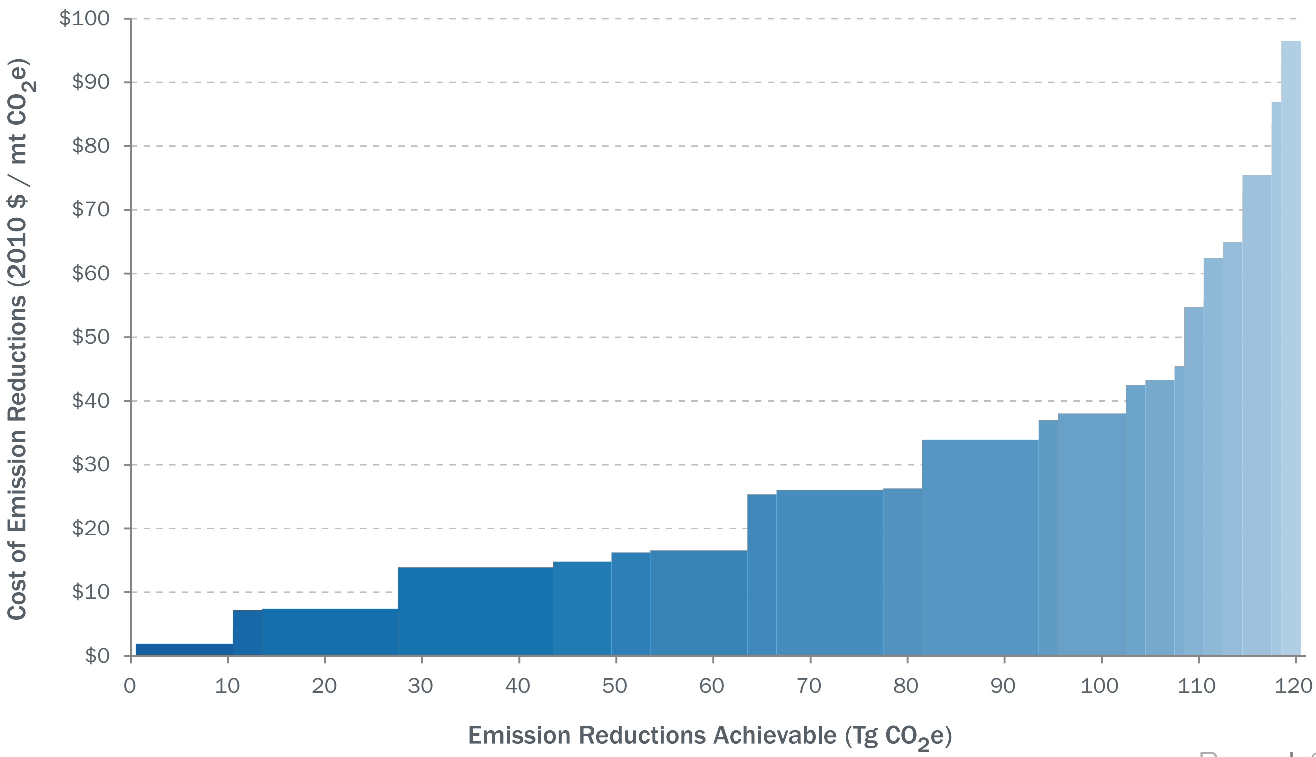
of crop and livestock production practices to assess the aggregate quantity of GHG mitigation that various parts of the farm sector could supply at a given CO_2 incentive level. Conceptually, U.S. agriculture is disaggregated into a set of "representative farms" that are distinguished, to the extent possible and practical, by U.S. Department of Agriculture (USDA) production region, farm size, and commodity produced. In the MACC framework, all actual farms associated with a given "representative" farm are assumed to adopt a mitigation technology or practice when the CO_2 incentive level exceeds the CO_2 break-even price for that farm and that technology; with respect to manure and nitrogen management, however, any one farm can only adopt one mitigation technology or practice. By aggregating all the mitigation that would result from all farms adopting those GHG-mitigating technologies and practices whose CO_2 break-even prices are less than or equal to a specified incentive level, the MACC framework quantifies the GHG mitigation that all farms could supply at that incentive level. Repeating this process across a schedule of incentives traces out a supply curve (i.e., a MACC) for GHG mitigation for the selected set of U.S. farm operations. MACCs can be generated for numerous sets of U.S. farms (e.g., by commodity type, size of farm, region), as well as for U.S. agriculture as a whole. In the chapters that follow, MACCs are presented for livestock production systems, crop production systems, land management practices, and all U.S. farms.

Summary of Findings

Figure 1 shows the MACC for GHG mitigation for all U.S. farms across a schedule of CO_2 prices between $1 and $100 per mt CO_2e. Figure 1 shows that at a CO_2 price of $100 mt CO_2e, the total mitigation potential of U.S. agriculture is about 120 Tg CO_2e.

Figure 1 also shows that GHG mitigation from U.S. agriculture increases relatively gradually up to a CO_2 price of about $40 per mt CO_2e. At this price, total GHG mitigation supplied by U.S farms is a little over 100 Tg CO_2e. Above 100 Tg CO_2e, the MACC turns sharply upwards. Low-end estimates of the social cost of carbon dioxide (SC-CO_2) fall in the range of $30 to $40 per mt CO_2e. The MACC then suggests that incentivizing farms

Figure 1: National Marginal Abatement Cost Curve for Break-even Prices Less Than $100 per mt CO_2e



to mitigate GHG emissions may be cost effective up to the low-end estimates of SC-CO_2. Above the $30 to $40 per mt CO_2e (and 100 Tg CO_2e) range, however, achieving additional mitigation in agriculture will likely not compare well—at least on a cost per mt CO_2e basis—with mitigation options in other sectors.

A second CO_2 price to highlight in Figure 1 is $20 per mt CO_2e. At this CO_2 price, U.S. farms supply GHG mitigation of about 63 Tg CO_2e; the implied total cost is $1.26 billion. In the context of comparing the relative value of pursuing alternative mitigation strategies in different economic sectors, the 63 Tg CO_2e can be viewed as a ballpark estimate of the marginal GHG benefits of the next $1 billion spent incentivizing the adoption of GHG-mitigating production and land management practices in the U.S. agriculture sector.

Finally, although not obvious in Figure 1, no one GHG mitigation option is uniquely the best option for all regions, farms, or commodities. For each mitigation option considered in this analysis, there are farms that could economically adopt the technology at relatively low CO_2 prices (e.g., less than $20 per mt CO_2e) and farms that would require a prohibitively high CO_2 price (e.g., over $40 per mt CO_2e). Additionally, for a given CO_2 price, the mitigation potential of almost any policy framework will increase as the number of mitigation options increases. From a policy perspective, the goal should be to allow farms as much flexibility as possible in identifying and adopting the most cost-effective mitigation options for their circumstances.

The remainder of this report presents the approach used to estimate the mitigation potential for animal production systems, cropland production systems, land retirements, and rangeland and pastureland systems. For each of these sectors, the baseline management practices, the potential applicability of each GHG mitigation option, and the resulting MACC are described.

Animal Production Systems

This section synthesizes the data, methods, and key assumptions used to develop the GHG MACC for U.S. animal production systems. The analysis focuses on technology options to reduce CH_4 emissions associated with manure management on confined dairy and swine operations. Figure 2 shows that, in 2010, confined dairy and swine operations that use anaerobic lagoon, deep pit, or liquid/slurry[2] systems accounted for about 85 percent of total CH_4 emissions from livestock manure management in the United States. Farms that employ one of these systems can significantly reduce their CH_4 emissions by decreasing the quantity of volatile solids entering waste

Figure 2: CH_4 Emissions in 2010 by Manure Management System (Source: EPA, 2012)

Animal	Management System	Methane Emissions
DAIRY	Anaerobic Lagoon	32.9%
	Liquid/Slurry	8.0%
	Deep Pit	0.8%
	Solid Storage	0.7%
	Dry Lot	0.4%
	Anaerobic Digester	0.2%
	Pasture	0.1%
	Daily Spread	0.0%
SWINE	Anaerobic Lagoon	26.1%
	Deep Pit	12.1%
	Liquid/Slurry	5.0%
	Solid Storage	0.1%
	Anaerobic Digester	0.1%
	Pasture	0.0%
BEEF	Pasture	4.4%
	Dry Lot	1.0%
	Liquid/Slurry	0.1%
POULTRY	Anaerobic Lagoon	3.7%
	With Bedding	1.7%
	Without Bedding	0.5%
	Pasture	0.0%
OTHER		2.0%

in 2010, confined dairy and swine operations that use anaerobic lagoon, deep pit, or liquid/slurry systems accounted for about 85 percent of total CH_4 emissions from livestock manure management in the United States.

[2] As defined in the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008 (EPA, 2010), liquid/slurry systems store manure as excreted or with some minimal addition of water to facilitate handling, and store it in either tanks or earthen ponds, usually for periods of less than a year.

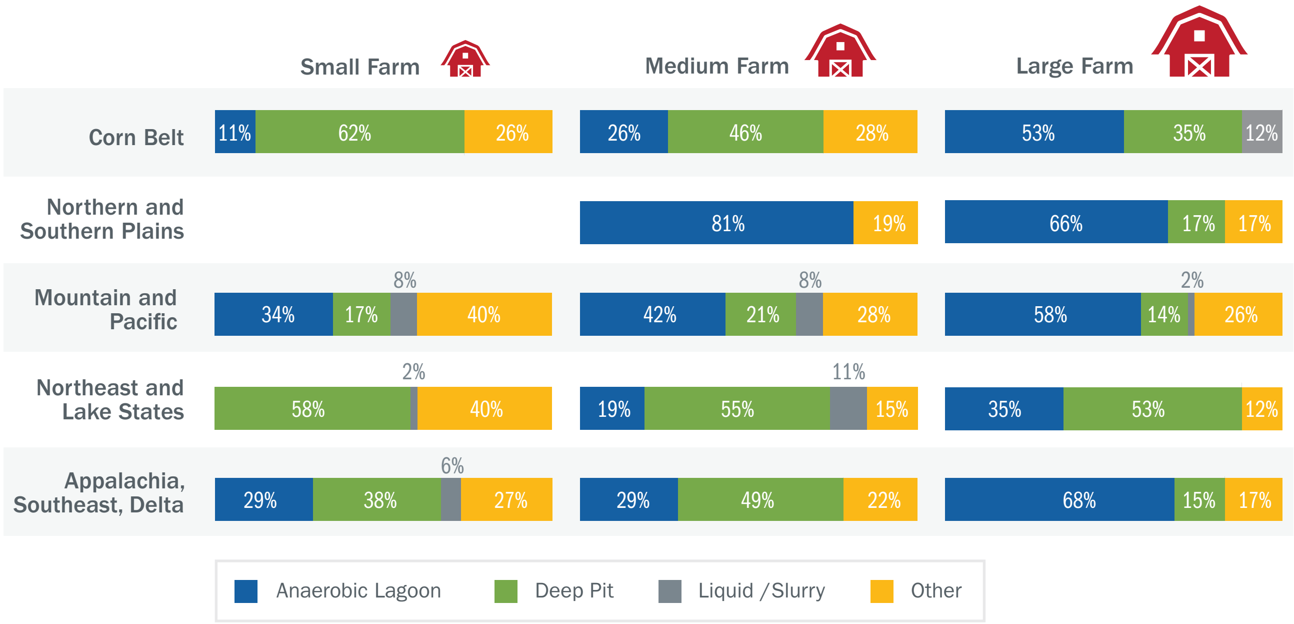
treatment and storage structures, or by capturing CH_4 emitted from the system and converting it to CO_2 through combustion. Seven technology options that accomplish one of these functions are considered in this chapter—specifically, placing impermeable covers on lagoons and liquid/slurry ponds (and either generating electricity or flaring the captured CH_4); adding a solids separator to lagoon systems; adopting one of three anaerobic digester systems (i.e., a covered lagoon, complete mix, or plug flow system); and, for swine operations in the Southeast and Appalachia, adopting a nitrification/denitrification system.

For each of the seven technology options described above, ICF (2013) presents detailed information on the farm-level GHG mitigation that would result from adoption and the CO_2 price that would fully cover the adoption costs for a set of "representative" farms. The representative farms differentiate dairy and swine operations by USDA production region and farm size. To develop a national GHG MACC for manure management systems, the farm-specific GHG mitigation and CO_2 break-even price values need to be viewed in combination with a detailed description of how anaerobic lagoon, deep pit, and liquid/slurry systems on U.S. dairy and swine operations are distributed by region and by farm size. At present, the data needed to characterize these distributions directly are not available and so proxy distributions were constructed using information from various sources and the five-step process described below.

Step 1: Allocate the U.S. populations of dairy cattle and swine by region and farm size. The USDA Census of Agriculture (USDA NASS, 2009) provides data on the total number of dairy cattle and swine by region of the country and farm size. These data were used to allocate the regional populations of (1) dairy cattle to farms with less than 300 head, 300–499 head, 500–999 head, 1,000–2,499 head, and more than 2,500 head; and (2) swine to farm sizes of less than 999 hogs, 1,000–2,499 hogs, 2,500–4,499 hogs, and more than 5,000 hogs.[3]

[3]The 2013 ICF report defined swine farm sizes based on the number of sow places. For this analysis, sow places have been converted into the equivalent number of finished hogs, based on live animal weight. (The method used is described in the text box at the end of this section.)

Figure 3: Percent of Dairy Farms Using Anaerobic Lagoon (AL), Deep Pit (DP), Liquid /Slurry (L/S), and Other Manure Management Systems by Region and Farm Size



Step 2: For each region-farm size combination, estimate the number of dairy cattle and swine on farms using each baseline manure management system. USDA periodically collects data on manure management systems in use on dairy and swine operations via the Agricultural Resource Management Survey (ARMS). Surveyed systems include open solid storage, covered solid storage, single-stage lagoon, two-stage lagoon, holding pond, open pit, covered pit, open slurry tank, and covered slurry tank. ARMS data from recent cattle and swine surveys were queried by system, region, and farm size to get estimates of the proportions of small, medium, and large farms in each region that use each baseline manure management system. The surveys allowed responders to select more than one type of manure management system and so the percentages were normalized in order to sum to 100. Figure 3 shows the normalized distribution of anaerobic lagoons (AL), deep pits (DP), liquid/slurry (LS), and other manure management systems used on dairies by region and farm size. The manure management systems in the ARMS data, however, do not match the systems defined by the U.S. Environmental Protection Agency (EPA) in the annual U.S. GHG Inventory. The 2010 U.S. GHG Inventory is the source of emissions data by manure management system, so the ARMS systems were mapped into the EPA systems as shown in Figure 4 (the data obtained from the ARMS queries are provided in Appendix B). The cattle and swine population data in the USDA Census of Agriculture (USDA NASS, 2009) and the proportion of cattle and swine operations by region and farm size using each type of manure management system (derived from the ARMS queries) are used to estimate the number of animals by region and farm size that are managed using each of the baseline manure management practices.

Step 3: Calculate the percent of animals with a given baseline manure management practice in each farm size category. The number of dairy cattle and swine by farm size and baseline manure management practice from Step 2 are used to estimate the percentage of animals managed with each manure management system in each farm size category.

Step 4: Allocate total U.S. CH_4 emissions from manure management on dairy and swine operations by farm size category, manure management system, and region. EPA provides data on CH_4 emissions by livestock type and manure management system (see Figure 2) (EPA, 2010). EPA further breaks down these emissions by region of the country (EPA, 2010). Figure 5 shows how these emissions are distributed by region as indicated in the Inventory of U.S. Greenhouse Gas Emissions and Sinks (EPA, 2010). Assuming that the distribution of CH_4 emissions by farm size category mirrors the distribution of head by farm size category, total CH_4 emissions for a manure management practice are distributed according to the percentage of animals managed in each farm size category and USDA region. Figure 5 illustrates how CH_4 emissions from dairy anaerobic lagoons, which account for approximately 33 percent of total CH_4 from manure management, are distributed first by region and then by farm size (for readability, Figure 5 only shows how CH_4 emissions from dairies in the Pacific region are distributed by farm size).

Step 5: Exclude very small farms as potential adopters of CH_4 mitigation technologies. In this analysis, operations with fewer than 300 dairy cattle or 825 finished hogs are assumed to be too small for the adoption of the GHG mitigation technologies considered in the MACC to be economically feasible. Hence, the CH_4 emissions associated with manure management from these farms are not included as part of the total GHG mitigation potential.

Figure 4: Mapping USDA ARMS Manure Classification to U.S. EPA Categories

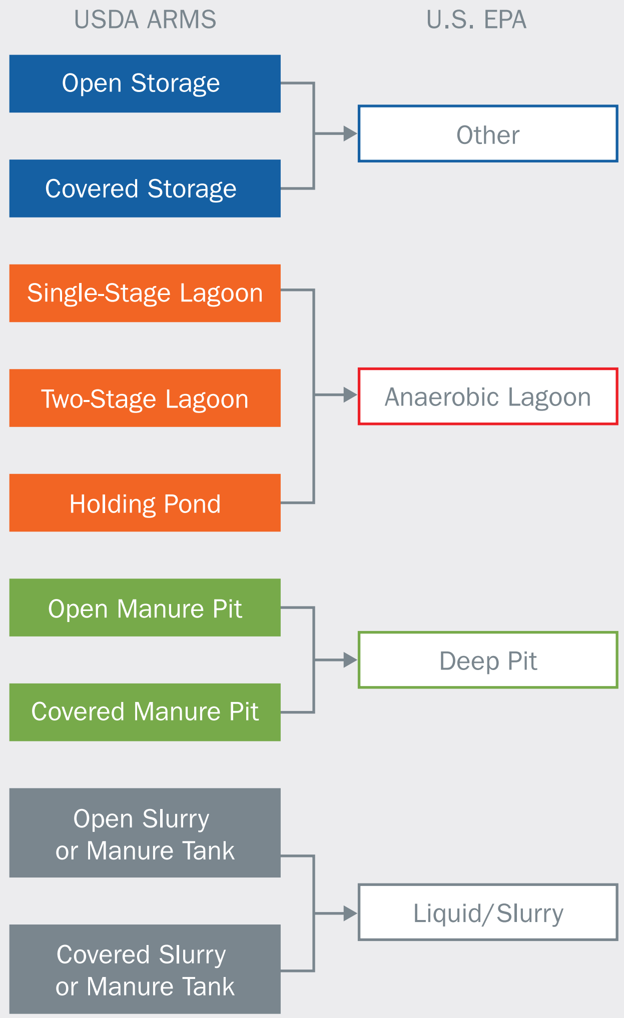
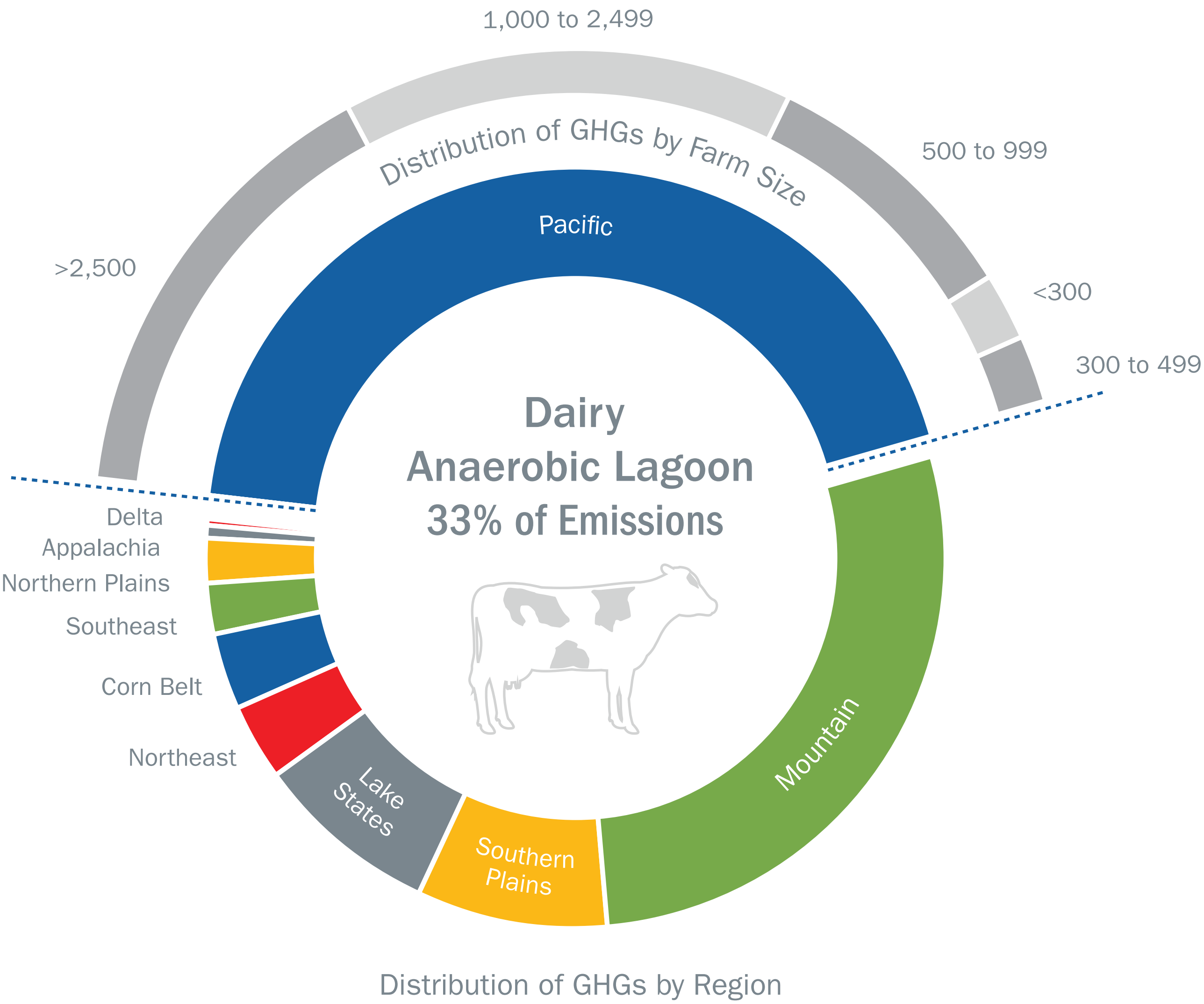


Figure 5: Distributing Dairy GHG Emissions by Farm Size Using U.S. EPA and USDA ARMS Data



GHG emissions from anaerobic lagoons account for 33 percent of the emissions from manure management systems. These emissions are further disaggregated by farm size.

Figure 6 provides an illustrative example of the process used to allocate CH_4 emissions from dairy anaerobic lagoon systems in a given region to farms of different sizes.

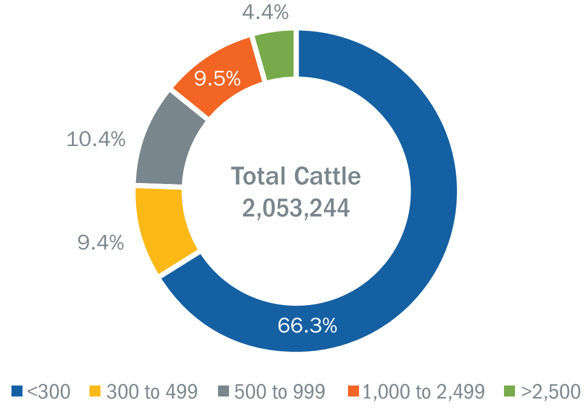
Figures 7 and 8 present the distribution of CH_4 emissions by animal type, manure management system, region, and farm size for dairy and swine farms, respectively. The distribution helps highlight those areas, systems, and farm sizes with the largest technical potential to reduce CH_4 emissions associated with manure management. For example, for dairy anaerobic lagoons, the majority of CH_4 emissions are emitted in the Pacific and Mountain regions, particularly on farms with more than 1,000 head. Conversely, for dairy deep pit systems, a large portion of emissions occur in the Lake States, Corn Belt, and Northeast regions and on small farms.

Figure 6: Illustrative Example of Allocating the Regional Methane Emissions From Anaerobic Lagoons on Dairy Operations to Categories of Farm Sizes (the example uses the Lake States)

1 Allocate the U.S. populations of dairy cattle and swine by region and farm size.

The USDA Census of Agriculture provides information on the population of dairy cattle by region and farm size.

Example: In 2007, there were 2,053,244 head of dairy cattle in the Lake States, with 66 percent (1,361,959 head) managed on farms with fewer than 300 head.



2 For each region-farm size combination, estimate the number of dairy cattle and swine on farms using each baseline manure management system.

The USDA ARMS data provide estimates of the percent of dairy cattle where a particular baseline manure management practice is used for different farm size categories.

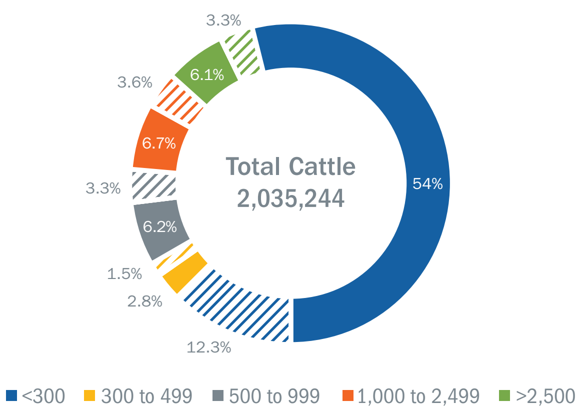
Example: In the Lakes States, anaerobic lagoons are used to manage (1) the manure from 19 percent of attle on dairy farms with 100–499 head, and (2) the manure from 35 percent of cattle on dairy farms with 500 or more head.

Farm Size (No. of Head)	Use of Anaerobic Lagoons (% of Cattle)
< 100	0%
100 < No. of Head < 499	19%
> 500	35%

3 Calculate the percent of animals with a given baseline manure management practice in each farm size category.

Applying the proportions from USDA ARMS to the Lake States dairy cattle population determines the proportion of dairy cattle in each farm size category where manure is managed using anaerobic lagoons systems.

Per step 1 above, 10.4 percent of total dairy cattle (or 212,809 head) are on farms that have 500-999 head. According to USDA ARMS, manure from 35 percent of these cattle is managed in anaerobic lagoons (212,809 x 35% = 74,314). Of the total dairy cattle in the Lake States, manure from 494,136 head is managed with an aerobic lagoon.[4]

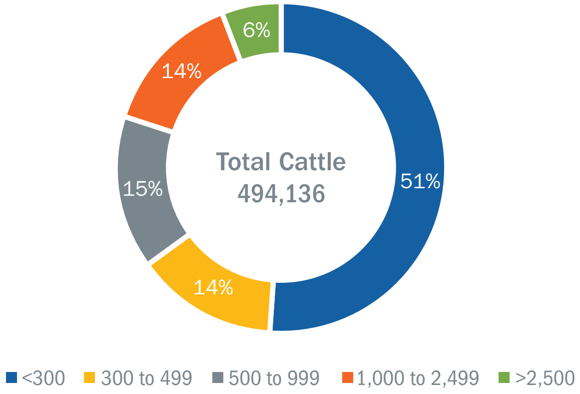


On this graph, the striped pattern indicates that manure is managed using anaerobic lagoons, and the solid pattern indicates that other manure management systems are used.

4 Allocate total U.S. CH_4 emissions from manure management on dairy and swine operations by farm size category, manure management system, and region.

Focusing on the 494,136 head of cattle on farms where manure is manage with anaerobic lagoons, results in the following distribution of the 494,136 head of cattle across the farm sizes:

- 51 percent are on farms with < 300 head
- 14 percent are on farms with 300–499 head
- 15 percent are on farms with 500–999 head
- 14 percent are on farms with 1,000–2,499 head
- 6 percent are on farms with > 2,500 head



5 Exclude very small farms as potential adopters of CH_4 mitigation technologies

The Inventory of U.S. Greenhouse Gas Emissions and Sinks provides estimates of methane emissions from dairy operations by manure management system. For the Lake States, emissions from anaerobic lagoons on dairy operations was 1,189,357 mt CO_2e in 2007. Based on the above analysis, manure from 494,136 head of cattle is assumed to be managed in anaerobic lagoons and 51 percent of the cattle (i.e., 252,009 head) are on small farms.

For the MACC analysis, it is assumed that the adoption costs for anaerobic digesters are prohibitively high for farms with fewer than 300 head. For these dairies, digesters are not a mitigation option. This implies that 51 percent of the total methane emissions associated with anaerobic lagoons in the Lake States (606,572 mt CO_2e) is not part of the mitigation potential for anaerobic digesters. Therefore, the total methane emissions that could potentially be mitigated in the Lake States by installing additional digesters is 582,785 mt CO_2e (i.e., the quantity of methane from anaerobic lagoons used to manage manure are on farms that have more than 300 head).

Total Mitigation Potential of Lakes States

= Total CH_4 Emissions for Lake States
— CH_4 Emissions from Small Farms

= 1,189,357 mt CO_2e
— (51%×1,189,357 mt CO_2e)

= **582,785** mt CO_2e

[4]Based on USDA Census of Agriculture data, there are 1,361,959 head of dairy cattle that are managed on farms with fewer than 300 head. It is assumed that manure from 19 percent of these cattle (equivalent to 252,735 head) are managed with anaerobic lagoons. The remaining 691,285 head of dairy cattle in the Lake States are on farms that have more than 300 head. It is assumed that manure from 35 percent of these cattle (equivalent to 241,401 head) are managed in anaerobic lagoons. Together, this equals 494,136 head of dairy cattle with manure managed by an anaerobic lagoon.

Figure 7: Distribution of GHG Emissions Across Baseline Management Practices and Farm Sizes for Dairy Operations

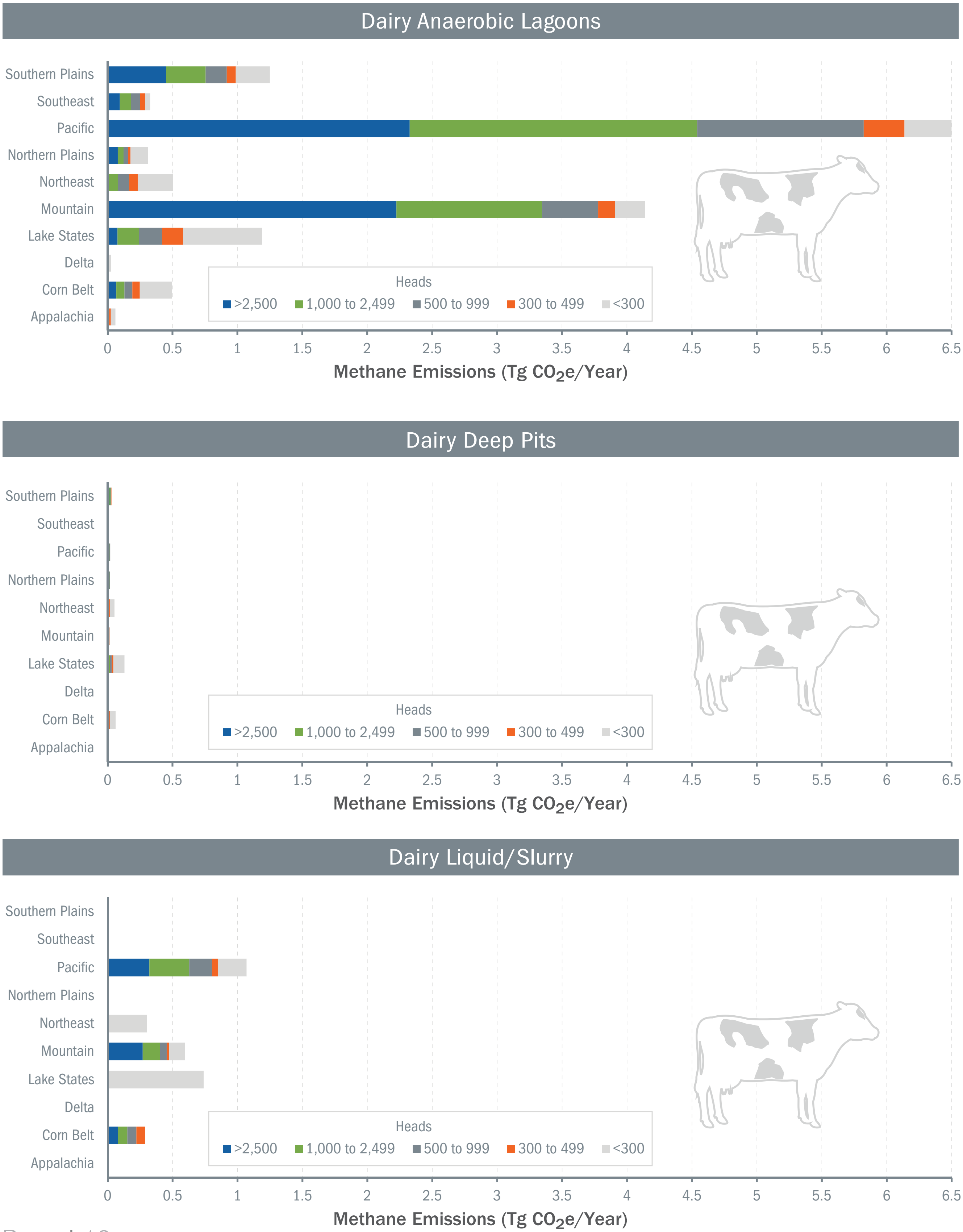
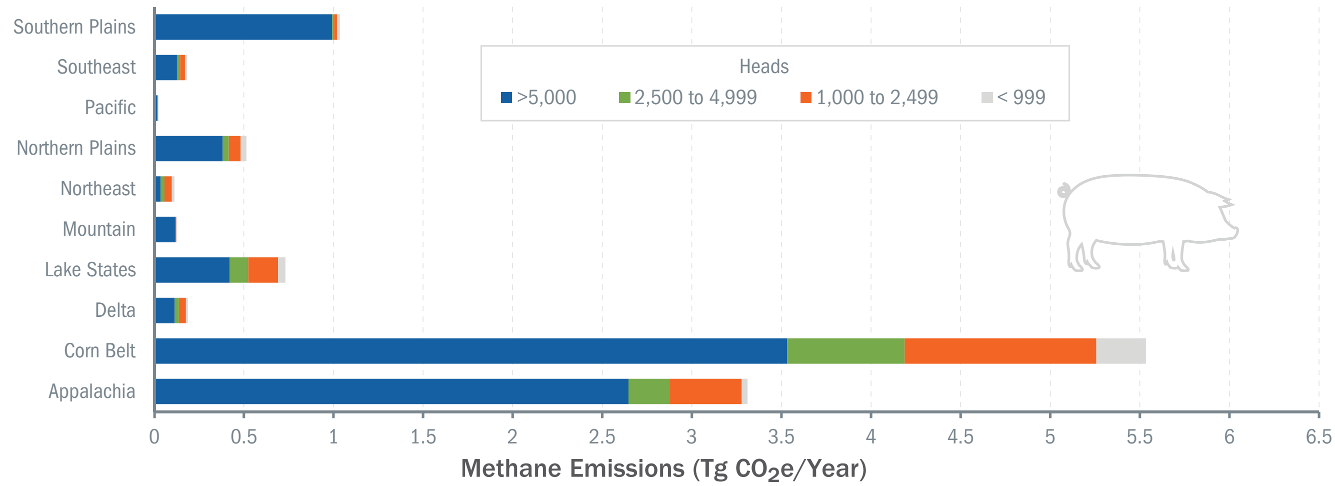
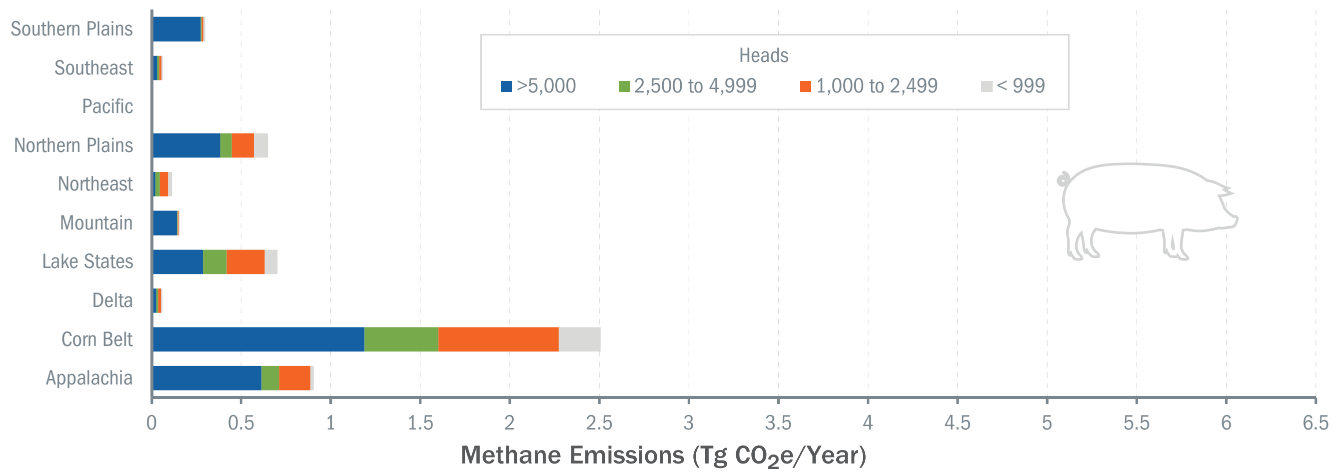


Figure 8: Distribution of GHG Emissions Across Baseline Management Practices and Farm Sizes for Swine Operations

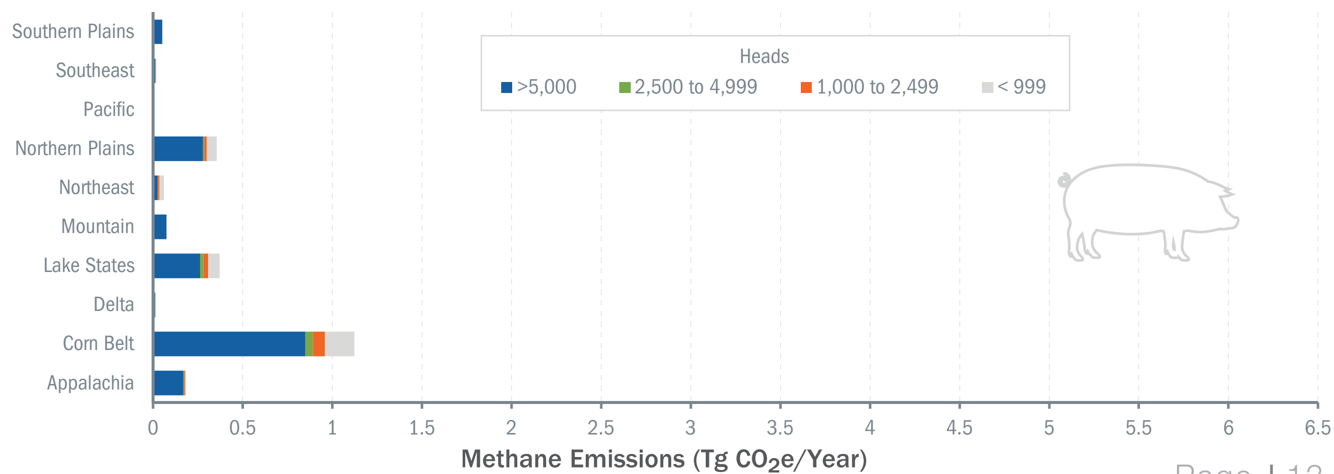
Swine Anaerobic Lagoons



Swine Deep Pits



Swine Liquid/Slurry



Manure Management: Baseline Practices and Potential Adoption of New Practices

The MACC for animal production systems incorporates seven farm-level GHG mitigation options associated with manure management on dairy and swine operations. Digester technologies maintain anaerobic conditions in manure vessels and can produce and capture CH_4-containing biogas. This biogas can be used to generate electricity and/or heat, or it can be flared. Covering an existing tank, pond, or lagoon allows for the capture and destruction of CH_4 gas. Solids separation reduces the quantity of volatile solids in manure storage and treatment structures, which, under anaerobic conditions, would serve as a CH_4 feedstock. For swine operations, the nitrification/denitrification system option also includes a solids separation process.

The applicability of each mitigation option for each baseline manure management system depends on a number of factors. For all mitigation options, a farm size of fewer than 300 dairy cattle or 825 finished hogs is considered to be too small for adoption of any mitigation technology to be economically feasible. Plug flow digesters are designed to operate optimally with manure streams containing 11 to 13 percent solids. Hence, these digesters are only considered feasible for operations using liquid/slurry manure management systems. Covering an existing tank, pond, or lagoon is only considered as a mitigation option for existing anaerobic lagoons and liquid/slurry systems. Solids separation is only considered feasible for operations using anaerobic lagoons. A summary of mitigation options by baseline manure management system is provided in Table 1. For additional details on these GHG-mitigating technologies (including technical descriptions, farm-level adoption costs, mitigation potentials, and CO_2 break-even prices), see ICF (2013).

Table 1: Summary of Manure Management Mitigation Options[a]

Baseline Manure Management Practice	Mitigation Option						
	Covered Lagoon Digester with EG[b]	Covered Lagoon Digester with Flaring	Complete Mix Digester with EG	Plug Flow Digester with EG	Covering Existing Tank, Pond, or Lagoon	Solids Separator	Nitrification / Denitrification System[c]
Dairy Anaerobic Lagoon	●	●	●		●	●	
Swine Anaerobic Lagoon	●	●	●		●	●[d]	●
Dairy Deep Pit	●	●	●				
Swine Deep Pit	●	●	●				
Dairy Liquid/Slurry	●	●	●	●	●		
Swine Liquid/Slurry	●	●	●	●	●		

[a] Source: ICF (2013).

[b] Electricity Generation (EG)

[c] The nitrification/denitrification technology reflects a demonstration system in use on a 5,000+ hog feeder-to-finish operation in North Carolina. Acknowledging that the GHG emissions profile for this system may differ in cooler regions, the MACC analysis considers this technology to be a GHG mitigation option only in the Appalachia, Delta, and Southeast regions, and only on swine operations with more than 5,000 hogs.

[d] In order to separate a significant fraction of the solids from swine manure, separator technologies such as screw presses, fabric filters, or decanting centrifuges are required (solids removal efficiencies range from 20 percent to 40 percent). These are more technically complex than the separators generally used on dairy operations. In the MACC analysis, the solids separator mitigation option for swine farms is limited to those operations that adopt the nitrification/denitrification system.

Translation of Sow Places to Finished Hogs Based on Live Finish Weight

ICF (2013) defines hog numbers per farm in terms of "sow places." In that report, the sow place unit was used to capture the diversity of animal sizes within swine operations and to estimate the capital, operation, and management costs for manure management strategies. In order to identify the appropriate mitigation cost for each USDA Census farm size category, sow places were translated into the number of equivalent finished hogs using average animal weight data for each swine category (EPA, 2004). The process is described below. The use of finished hogs as a unit facilitates the use of available USDA Census of Agriculture data on farm sizes.

Swine Subgroup	Head/Sow Place	Average Weight (lbs)/Head	Live Animal Weight (lbs)/Sow Place
Lactating Sows	0.3	436	145
Gestating Sows	0.7	436	291
Nursing Pigs	3.1	35	110
Weaned Pigs	3.1	90	282
Feeder Pigs	2.7	201	549
		Total	**1,377**

Using the average live animal weight per sow place computed above (i.e., 1,377 lbs) and an average weight of 250 lbs per finished hog (USDA ERS, 2011a), total live animal weight and finished hog equivalents are shown below for swine operation with 150, 500, and 2,500 sow places. For example, this analysis assumes that a 500-sow place farm is equivalent to a 2,754-hog farm, which is representative of the 2,500–4,999 farm size category defined by the USDA Census of Agriculture. The unit cost estimates for small, medium, and large farms (i.e., 150, 500, and 2,500 sow places) were used as the mitigation costs associated with GHG emissions from small, medium, and large farms as defined by the USDA Census of Agriculture (i.e., 1,000–2,499 head, 2,500–4,999 head, and more than 5,000 head). For the small farm size, the unit cost for a farm size of 826 finished hogs is assumed to be representative of the mitigation costs for farms of 1,000–2,499 head.

Parameters	Farm Size (sow places) [a]		
	150	**500**	**2,500**
Total live animal weight per sow place (lbs)	206,550	688,500	3,442,500
Weight of finished hog based on USDA ARMS (lbs)	250	250	250
Equivalent number of finished hogs	826	2,754	13,770
Equivalent Farm Size Category	1,000 < No. of Head < 2,499	2,500 < No. of Head < 4,999	No. of Head > 5,000

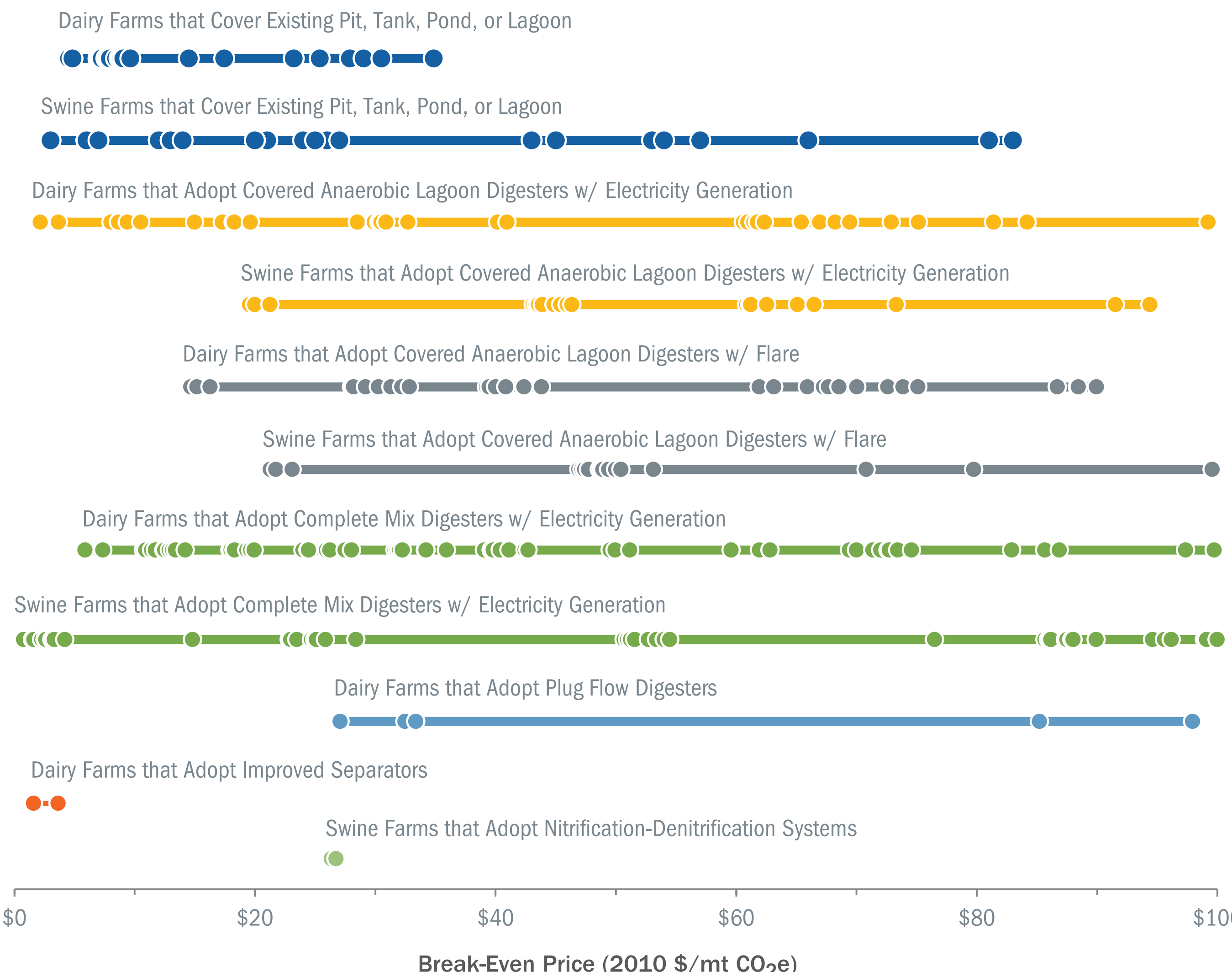
[a] Source: ICF (2013).

Marginal Abatement Cost Curve for Animal Production Systems

Figure 9 shows the distribution of the CO_2e break-even prices for all of the animal production system GHG mitigation options considered in this analysis. Each dot in the figure identifies the CO_2e price at which the mitigation option displayed above the dot becomes economically rational to adopt for at least one representative farm (i.e., at least one unique region, commodity, and farm size combination).

Figure 9 highlights two important points that are relevant to the design of policy frameworks that might be used to increase GHG mitigation in the livestock sector. First, no one GHG mitigation option is uniquely the most cost-effective option for all dairy or swine operations. For each mitigation option, there are farms that could economically adopt the technology at relatively low CO_2e prices (i.e., less than $20 per mt CO_2e) and farms that would require a relatively high CO_2e price (i.e., more than $60 per mt CO_2e). Second, for a given CO_2e price, the mitigation potential of almost any policy framework will increase as the number of mitigation options increases. From a policy perspective, the goal should be to allow farms as much flexibility as possible in identifying and adopting the most cost-effective mitigation option for their circumstances.

Figure 9: CO_2 Break-even Prices for Animal Production Systems by Mitigation Option

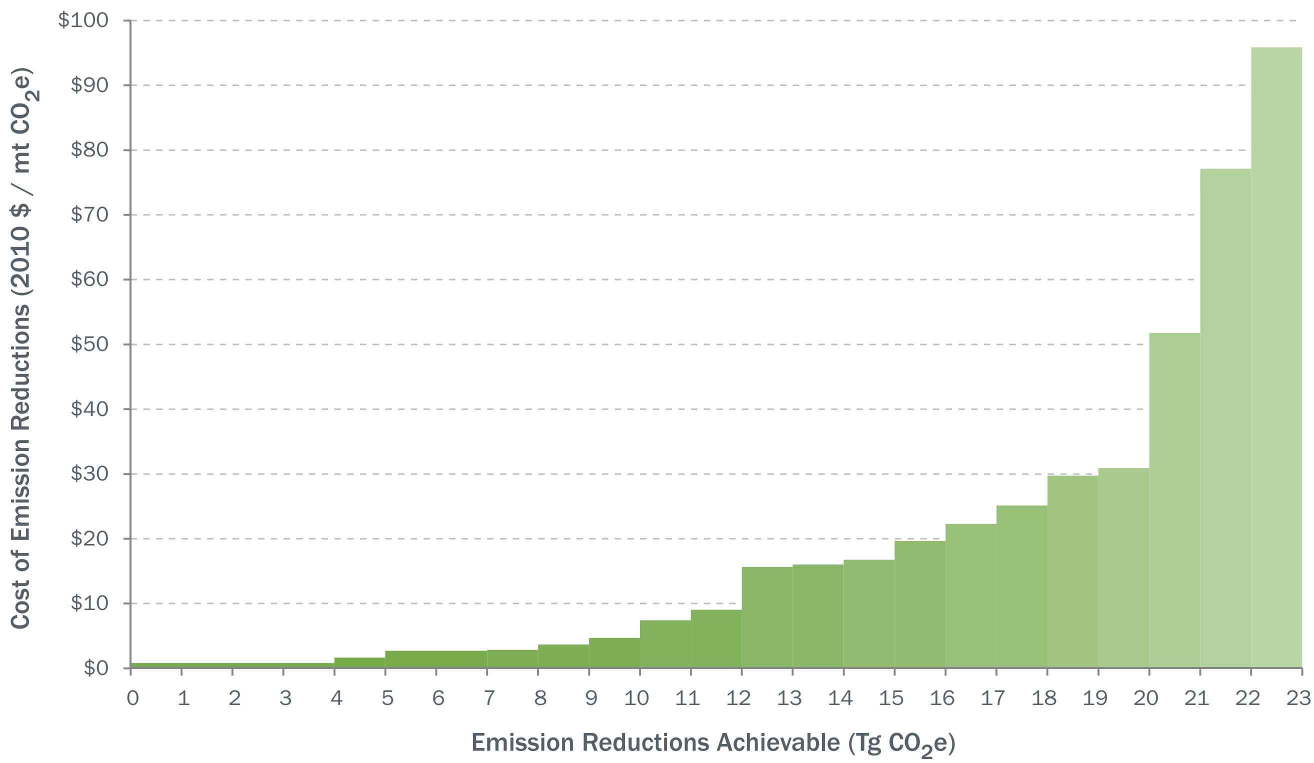


Source: ICF (2013).

Figure 10 presents the MACC for all animal production system mitigation options described in ICF (2013) with break-even prices between $1 and $100 per mt CO_2e. Over this range, changes in manure management on confined dairy and swine operations have the potential to mitigate about 24 Tg CO_2e. This is about 50 percent of total CH_4 emissions related to manure management on livestock operations and about 10 percent of CH_4 emissions from all livestock sector sources (i.e., including enteric fermentation and grazing lands). The MACC reflects 331 unique combinations of mitigation option, region, commodity, and farm size. More than half of these combinations are associated with a break-even price of $30 per mt CO_2e or less. About 77 percent of the combinations reflect farms with more than 1,000 animals and 55 percent of the combinations are associated with dairy farms.

With respect to Figure 10, two CO_2e break-even prices merit additional discussion. In the overall agricultural sector MACC presented in the Summary and Conclusions section, a CO_2e price of $20 per mt CO_2e coincides with total GHG mitigation of about 63 Tg CO_2e. The implied cost would be about $1.26 billion. A number of USDA conservation programs have annual budgets in excess of $1.0 billion. Figure 10 indicates that at $20 per mt CO_2e, mitigation from changes in manure management on confined swine and dairy operations would be about 16 Tg CO_2e. So if one were to consider a government framework to incentivize farmers to adopt GHG-mitigating practices and technologies, budgeted on a scale consistent with existing farm sector conservation programs, plausible estimates of the expected total cost and achievable mitigation might be $1.26 billion and 63 Tg CO_2e, respectively. About 25 percent of this mitigation would be derived from dairy and swine operations adopting new manure management technologies.

Figure 10: Marginal Abatement Cost Curve for Dairy and Swine Manure Management for CO_2 Break-even Prices of Less Than $100 per mt CO_2eq



The second break-even price to highlight in Figure 10 is \$30 per mt CO_2e. GHG mitigation from changes in manure management on dairy and swine operations increase gradually up a CO_2 price of about \$30 per mt CO_2e. At this price, U.S. livestock operations supply GHG mitigation of about 20 Tg CO_2e (about 80 percent of the mitigation that would be supplied at \$100 per mt CO_2e). Above \$30 per mt CO_2e, the MACC turns sharply upwards.

The low-end estimates of the social cost of carbon dioxide (SC-CO_2)[5] fall in the range of \$30 to \$40 per mt CO_2 (Interagency Working Group on the Social Cost of Carbon, 2015). The MACC suggests that incentivizing farms to mitigate GHG emissions through changes in manure management practices may be cost effective up to the low-end estimates of the SC-CO_2. Above \$30 per mt CO_2e (and 20 Tg CO_2e), however, achieving additional mitigation in the livestock sector will likely not compare well—at least on a cost per mt CO_2e basis—with mitigation options in other sectors.

Finally, Table 2 presents a more detailed picture of the GHG mitigation that U.S. livestock operations could supply at a CO_2 price of \$30 per mt CO_2e by identifying the top four sources of mitigation by region, mitigation option, and farm type. Among the regions, the Corn Belt and the Pacific regions each supply about 25 percent of all mitigation, while Appalachia and the Mountain regions each supply 14 percent. Given a CO_2 price of \$30 per mt CO_2e, these four regions account for 78 percent of all mitigation supplied by livestock operations. With respect to mitigation options, complete mix and two covered lagoon anaerobic digester options account for almost 90 percent of total mitigation supplied. Finally, with respect to types of farms, large swine operations (more than 5,000 head) and large dairy operations (more than 2,500 head) account for more than 70 percent of all mitigation supplied.

Table 2: Top Livestock Sector GHG Mitigation Sources at \$30 per mt CO_2e by Region, Mitigation Option, and Farm Type

Region	Share of Total Mitigation
Corn Belt	26%
Pacific	24%
Appalachia	14%
Mountain	14%

Mitigation Option	Share of Total Mitigation
Complete mix digester with electricity generation (EG)	51%
Cover existing tank, pond, and lagoon with flaring	16%
Covered lagoon digester with EG or flaring	21%
Solids separation	9%

Farm Type	Share of Total Mitigation
Swine (> 5,000 head)	50%
Dairy (> 2,500 head)	22%
Dairy (1,000–2,499 head)	17%
Dairy (500–999 head)	6%

Note: Total mitigation is approximately 20 Tg CO_2e below \$30 per mt CO_2e.

[5] Empirical estimates of the SC-CO_2 attempt to capture all impacts of CO_2 emissions on society, including health, environmental, and economic impacts.

Crop Production Systems

This section describes construction of the GHG marginal abatement cost curve (MACC) for farmers changing crop production practices for the purpose of mitigating GHG emissions. The MACC incorporates four farm-level GHG mitigation options associated with the application of nitrogen (N) fertilizers to croplands and three farm-level options that reduce the intensity of tillage operations. The changes in nitrogen management reduce nitrous oxide (N_2O) emissions while the reductions in tillage intensity increase carbon sequestration in cropland soils. The specific options considered are shown in the adjacent text box. Where possible and appropriate, each GHG mitigation option is further delineated by region, size of farm (for variable rate technology only), and/or commodity produced.

Mitigation Options for Nitrogen and Tillage Management

- Nitrogen Management Systems
  - 10% Reduction in Nitrogen Application
  - Switch From Fall to Spring Application
  - Nitrification Inhibitors
  - Variable Rate Technology
- Tillage Management
  - Switch From Conventional Tillage to Long-term No-Till
  - Switch From Conventional Tillage to Reduced Till
  - Switch From Reduced till to Long-term No-Till

Conceptually, the MACC for crop production systems summarizes how much GHG mitigation U.S. crop producers would collectively supply at various CO_2e prices (stated in 2010 dollars per mt CO_2e). Underlying the MACC are the decisions of numerous individual farms choosing to adopt alternative nitrogen fertilizer and tillage management practices in response to increasing economic incentives (i.e., increasing CO_2 prices) to mitigate GHG emissions. To develop a MACC that reflects the summation across the sector of these farm-level decisions requires the following five inputs:

1. Estimates of the farm-level cost of adopting each GHG mitigation option to change N application rates and tillage practices;
2. Estimates of the farm-level GHG mitigation that would result from adopting each N and tillage management option;
3. Estimates of the of the CO_2e prices that would make each GHG mitigation option a break-even action on the part of farmers;
4. An assessment of the geographic distribution of baseline commercial nitrogen fertilizer and tillage practices by region, commodity, and size of farm; and
5. A methodology for describing how and when farmers decide to adopt new GHG-mitigating nitrogen and tillage management practices as the incentive to mitigate (i.e., the price of CO_2) increases.

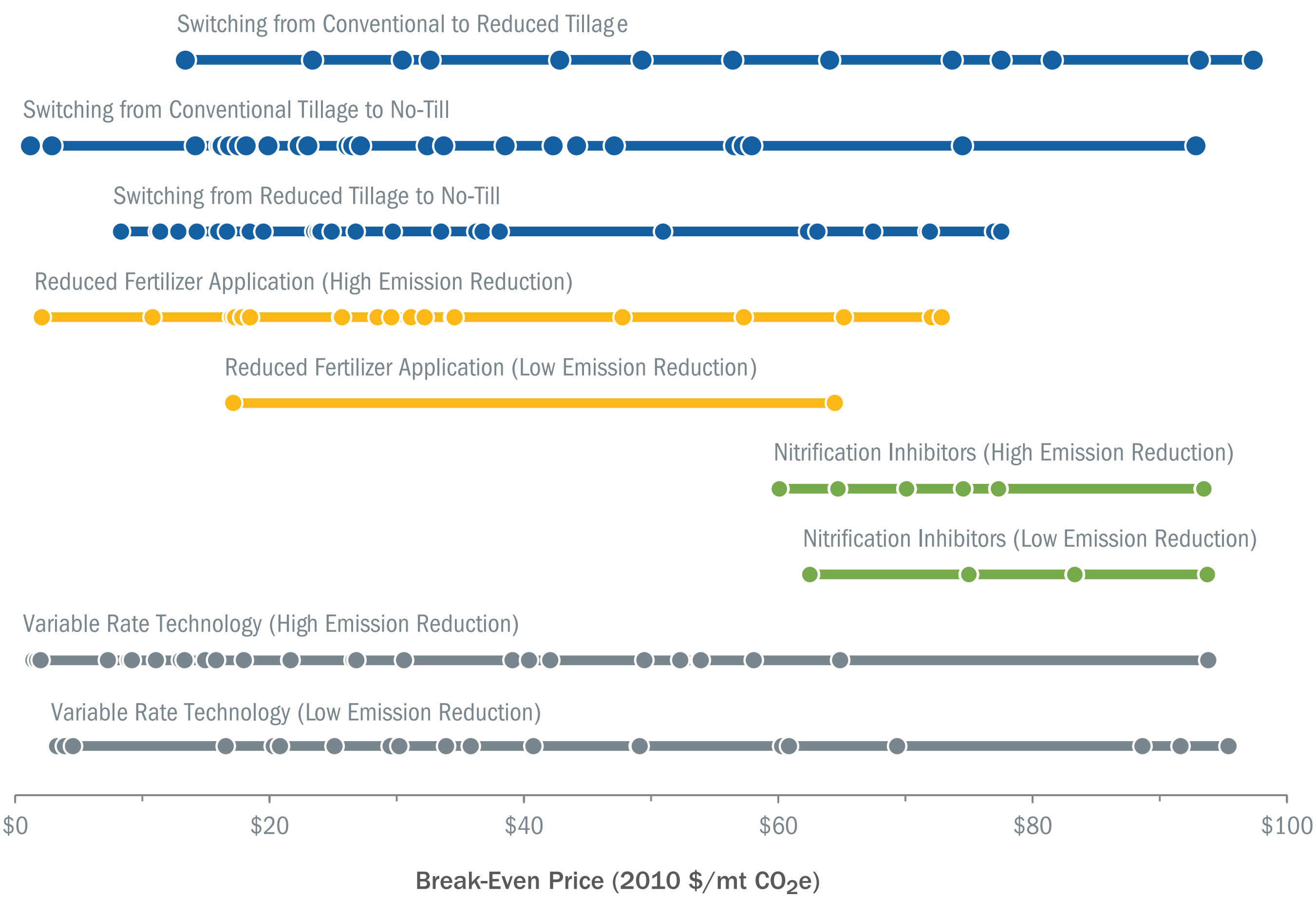
For all nitrogen and tillage management options, numerical values for inputs 1, 2, and 3 above are obtained from ICF (2013). Readers can find more detail on these input values in ICF (2013), as well as a technical description of each mitigation option.

With respect to input 4, existing data and other information are generally adequate to identify the overall number of acres managed with specific nitrogen or tillage practices but are too limited to construct verifiable representations of how these acres are distributed by geographic region, farm size, or commodity produced. Similarly, with respect to input 5, there is no generally accepted approach to assess how farmers would adopt new practices or technologies in response to economic incentives to produce GHG mitigation.

The following two sections describe, respectively, the processes that were used to determine the applicable acres for adoption of each nitrogen management and tillage mitigation option. These sections include: (1) a description of baseline management practices by crop and region (input 4 above); and (2) the methodology for determining applicable acres for each mitigation option by crop and region (input 5 above). The final section presents the aggregate MACC for GHG mitigation from U.S. crop production systems for incentive levels ranging from $0 to $100 per mt CO_2e.

Figure 11 summarizes the range of break-even prices, up to $100 per mt CO_2e, for each nutrient and tillage management practice reflected in the MACC for crop production systems. For a given mitigation option, each dot reflects the CO_2e break-even price associated with a specific representative farm distinguished by USDA production region and commodity. Figure 11 shows that there is considerable variation in the incentive levels that would be required to get different types of farms in different regions of the country to adopt a given nitrogen or tillage management. Figure 11 also provides a basis for comparing the range of break-even prices of one GHG mitigation option with the range of break-even prices of the other options. The actual CO_2e break-even prices are in Chapter 2 of ICF (2013).

Figure 11: CO_2 Break-even Prices for Crop Production Systems by Mitigation Option

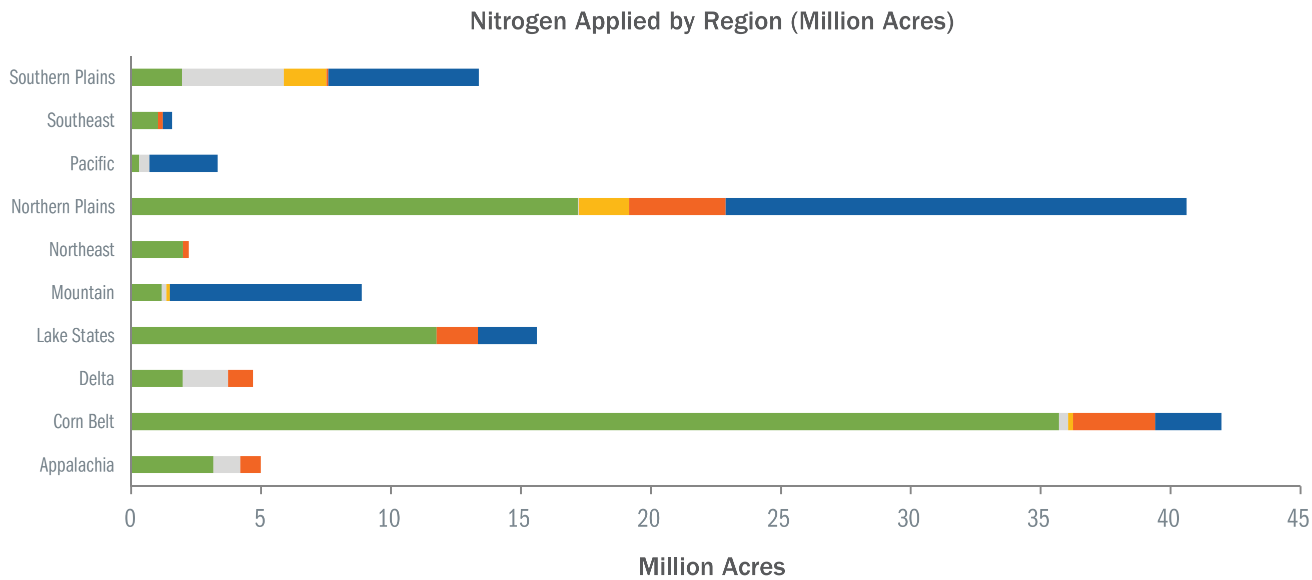


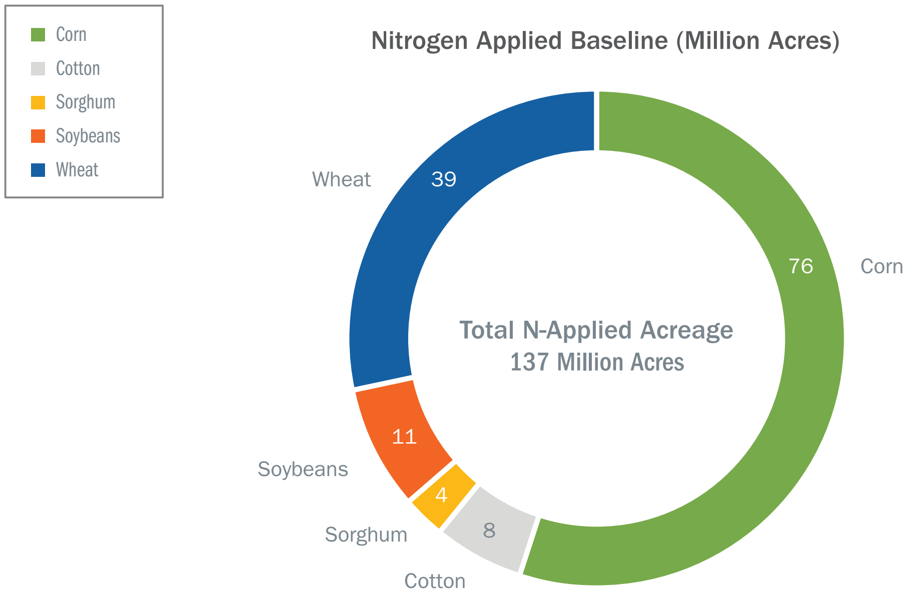
Note: See ICF (2013) for definition of high and low emission reduction (ER) scenarios for reduced fertilizer application and use of nitrification inhibitors and variable rate technology.

Nitrogen Management: Baseline Management Practices and Potential Adoption of New Practices

Baseline nitrogen management practices are derived from USDA ARMS data (USDA ERS, 2011b) and the 2007 USDA Census of Agriculture (USDA NASS, 2009). ARMS data provide the percent of acres treated with nitrogen by crop and farm size for the 10 USDA regions. These percents are applied to the USDA Census of Agriculture acres by crop (i.e., corn, cotton, sorghum, soybeans, and wheat) and region to estimate the number of acres where nitrogen is applied by crop and region (Figure 12). In some instances, USDA ARMS data indicate that certain crops and regions had no acres treated with nitrogen. In these instances, it is assumed that there are no opportunities to manage nitrogen for additional GHG mitigation, and the associated acres are not considered in developing the MACC (e.g., cotton in the Lake States or soybeans in the Mountain States).

Figure 12: Acres Treated With Nitrogen by Crop and Region





Estimates of the potential applicability of each nutrient management practice (i.e., a 10 percent reduction in N application, switching from fall to spring N application, adding a nitrification inhibitor, and using variable rate technology) are derived from the total number of acres where nitrogen is applied and the three-step process described below:

Step 1: Exclude all farms smaller than 100 acres. It is assumed that farms with less than 100 harvested acres are too small for the adoption of the GHG mitigation technologies considered in the MACC to be economically feasible. These farms are removed from the analysis and only farms with 100 harvested acres or more are considered potential adopters of the GHG-mitigating nitrogen management practices.

Step 2: Determine where baseline nitrogen management practices could be improved. A report by USDA ERS titled, *Nitrogen in Agricultural Systems: Implications for Conservation Policy,* identifies the percent of acres where nitrogen application is not meeting USDA Natural Resources Conservation Service (NRCS)-derived specifications for application rate and timing (Ribaudo et al., 2011). Table 3 shows the percent of acres not meeting the rate or timing criteria specified by commodity. Acres not meeting the rate criterion indicate that managers applied nitrogen (commercial and manure) at a rate of 50 percent more than that removed with the crop or harvest based on the stated yield goal, including any carryover from the previous crop. Acres not meeting the timing criterion indicate that the managers applied nitrogen in the fall for a crop planted in the spring (Ribaudo et al., 2011).

Step 3: Allocate applicable acres into the nitrogen management mitigation options. Data on the number of acres receiving applied nitrogen by region and commodity are combined with estimates of the percent of acres where nitrogen is not meeting the rate or timing criteria to estimate the applicable number of acres for each nitrogen management option included in the MACC. Figure 13 provides an illustration of the decision process for allocating acres by nutrient management mitigation option.

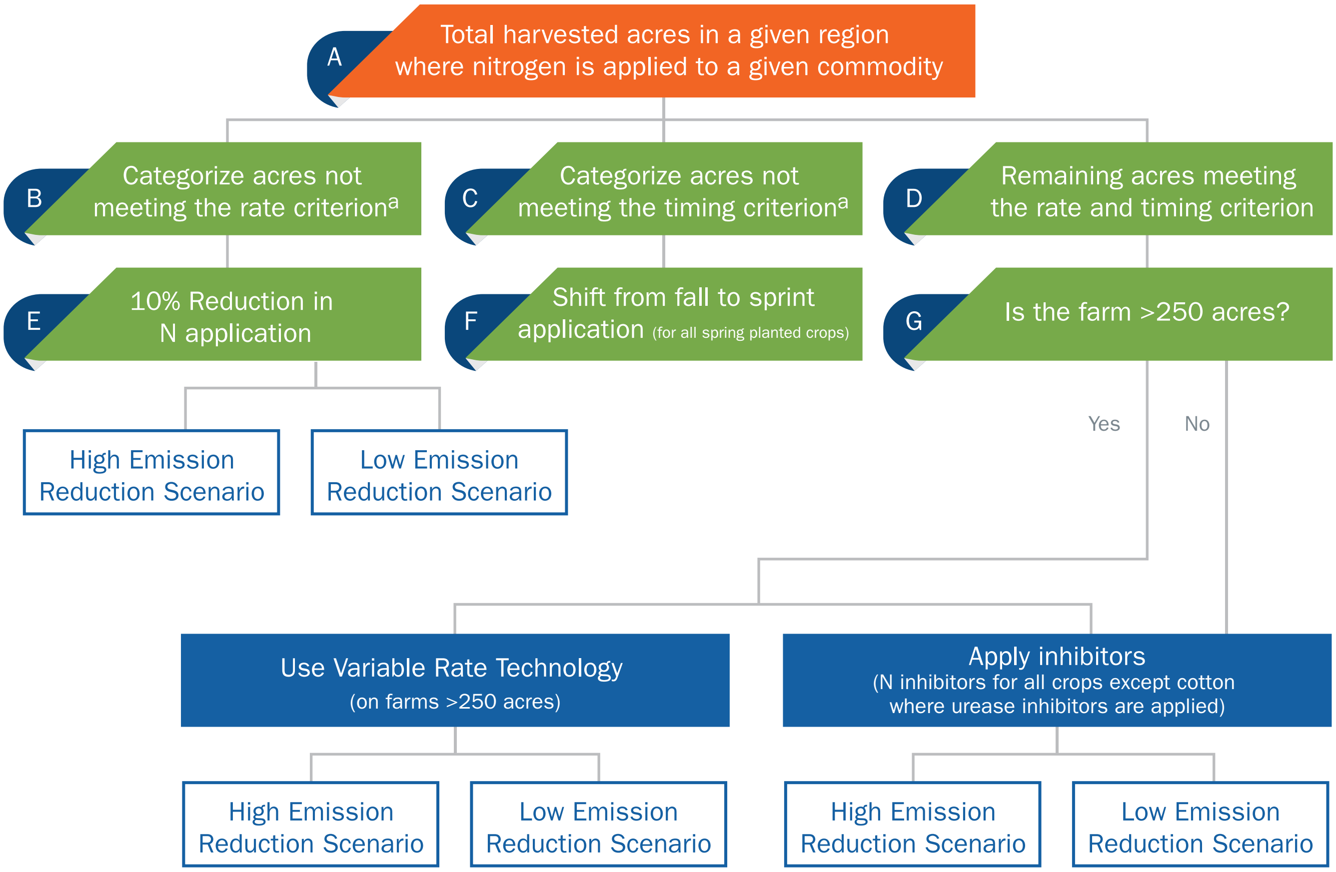
Starting with the quantity of harvested acres where nitrogen is applied (i.e., on farms with 100 or more harvested acres), this analysis applies the percent of acres not meeting the rate criteria (by crop) to the acres where nitrogen is applied by crop and region. The resulting acres are considered available for a 10 percent reduction in N application. The same process is followed to determine the number of acres not meeting the timing criteria. Acres not meeting the timing criteria are available for a switch from fall to spring N application. Due to data limitations, it was assumed that the acres not meeting the timing criteria are meeting the rate criteria and vice versa (i.e., the two are mutually exclusive).

Table 3: Percent of Acres Not Meeting Rate and Timing Criteria

Crop	Percent of Acres Not Meeting Rate Criteria	Percent of Acres Not Meeting Timing Criteria
Corn	35	34
Cotton	47	18
Sorghum	24	16
Soybeans	3	28
Wheat	34	11

Source: Ribaudo et al. (2011).

Figure 13 : Flow Diagram Illustrating the Process for Determining Nitrogen Management Option Applicability



[a] Source: Ribaudo et al. (2011).

Once the acres not meeting the rate or timing criteria are removed from the pool of acres where nitrogen is being applied, the remaining acres are divided into farms between 100 and 250 acres and farms with 250 acres or more. For the smaller farms, mitigation options are limited to using an inhibitor with nitrogen applications. For the larger farms, half are assumed to adopt an inhibitor and half are assumed to adopt variable rate technology (VRT). This allocation reflects the finding in ICF (2013) that the adoption of VRT is more cost effective for large farms than for small farms. A high and low emission reduction scenario is applied to the 10 percent reduction in N application, VRT, and nitrification inhibitor options to generate a range in results that capture the variation in published estimates of the emissions coefficients associated with these practices (see ICF (2013) for further details).

Table 4 shows which GHG mitigation options for nitrogen management are available to farms distinguished by crop produced and region of the country. For example, in Appalachia, acres of corn, soybeans, and cotton are available for a 10 percent reduction in nitrogen application but acres of wheat and sorghum are not. Emission reduction data associated with the adoption of VRT on soybean, cotton, and sorghum crops were not available at the time of this analysis. Consequently, only corn and wheat acres are considered applicable acres for adoption of this technology.

Table 4: Applicable Mitigation Options for Nitrogen Management by Crop and Region

USDA Region	Acres Not Meeting Rate and Timing Criteria										Acres Meeting Rate and Timing Criteria									
	Not Meeting Rate Specifications – 10% Reduction in N Application					Not Meeting Timing Specifications – Shift to Spring N Application					Inhibitor Application[a]					Variable Rate Technology (Farms ≥ 250 Acres)				
	Corn	Soybeans	Cotton	Wheat	Sorghum	Corn	Soybeans	Cotton	Wheat	Sorghum	Corn	Soybeans	Cotton	Wheat	Sorghum	Corn	Soybeans	Cotton	Wheat	Sorghum
Appalachia	●	●	●			●	●	●			●	●	●			●				
Delta	●	●	●			●	●	●			●	●	●			●				
Southeast	●	●		●		●	●		●		●	●		●		●			●	
S. Plains	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	
Pacific	●		●	●		●		●	●		●		●	●		●			●	
Mountain	●		●	●	●	●		●	●	●	●		●	●	●	●			●	
N. Plains	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	
Lake States	●	●		●		●	●		●		●	●		●		●			●	
Northeast	●	●				●	●				●	●				●				
Corn Belt	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●			●	

[a] Nitrification inhibitors: corn, soybeans, wheat, sorghum; urease inhibitors: cotton.

The GHG benefits of alternative nitrogen management options were evaluated for the majority of USDA regions and crop types.

Table 5 provides the associated applicable acres for each of the checked cells in Table 4. Total acres where nitrogen is applied are presented in the second column and represent the starting population of acres where a mitigation option could potentially be applied.

Table 5: Nutrient Management: Applicable Acres by Crop and Farm Size

Crop Type	Total Acres With N Applied	Mitigation Options				Total Potential Acres
		10% Reduction in N Application (acres)	Switch From Fall to Spring N Application (acres)	Inhibitor Application (acres)	Variable Rate Technology (acres)	
Corn	76,212,508	26,674,378	25,912,253	13,661,797	9,964,081	76,212,508
100 to 249	11,928,116	4,174,841	4,055,560	3,697,716	NA[a]	11,928,116
250 to 499	16,806,098	5,882,134	5,714,073	2,604,945	2,604,945	16,806,098
500 to 999	21,024,702	7,358,646	7,148,399	3,258,829	3,258,829	21,024,702
1,000 or more	26,453,592	9,258,757	8,994,221	4,100,307	4,100,307	26,453,592
Cotton	7,676,968	3,608,175	1,310,202	1,355,814	-	6,274,190
100 to 249	492,016	231,247	84,350	164,013	ND[b]	479,610
250 to 499	936,514	440,162	159,194	154,772	ND	754,128
500 to 999	1,824,952	857,727	310,216	301,599	ND	1,469,542
1,000 or more	4,423,486	2,079,038	756,442	735,429	ND	3,570,909
Sorghum	3,897,942	935,506	623,671	1,384,238	ND	2,943,414
100 to 249	716,184	171,884	114,589	429,711	ND	716,184
250 to 499	940,852	225,805	150,536	282,256	ND	658,597
500 to 999	1,021,878	245,251	163,500	306,563	ND	715,314
1,000 or more	1,219,027	292,567	195,044	365,708	ND	853,319
Soybeans	10,698,248	320,947	2,995,510	4,606,145	ND	7,922,602
100 to 249	2,652,897	79,587	742,811	1,830,499	ND	2,652,897
250 to 499	2,685,217	80,557	751,861	926,400	ND	1,758,817
500 to 999	2,926,071	87,782	819,300	1,009,494	ND	1,916,576
1,000 or more	2,434,064	73,022	681,538	839,752	ND	1,594,312
Wheat	38,727,189	13,167,244	4,259,991	11,700,094	9,599,860	38,727,189
100 to 249	3,818,607	1,298,326	420,047	2,100,234	NA	3,818,607
250 to 499	5,812,820	1,976,359	639,410	1,598,526	1,598,526	5,812,820
500 to 999	8,523,629	2,898,034	937,599	2,343,998	2,343,998	8,523,629
1,000 or more	20,572,133	6,994,525	2,262,935	5,657,337	5,657,337	20,572,133
Total	**137,212,855**	**44,706,250**	**35,101,625**	**32,708,087**	**19,563,941**	**132,079,904**

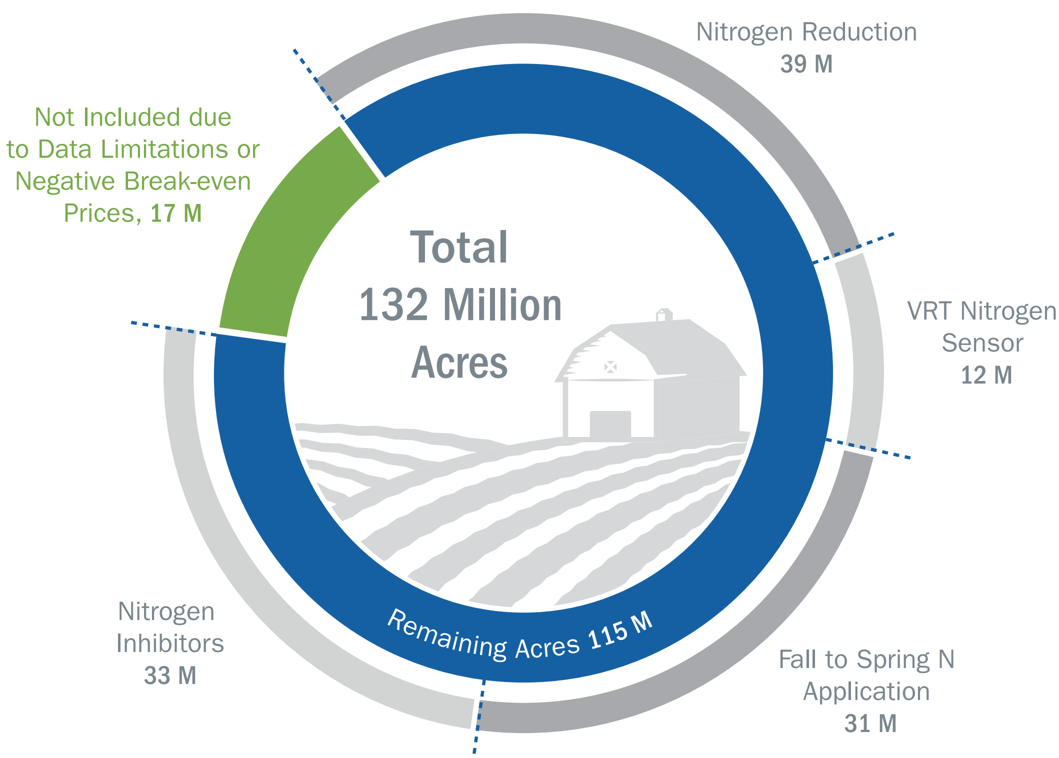
[a] NA = Not applicable. [b] ND= Not determined.

Finally, 17 million acres of cropland that receive N applications were considered not eligible for adoption of one of the GHG mitigation options due to data constraints. For some region-commodity combinations, there were insufficient data to assign an emission reduction coefficient to the adoption of a particular nitrogen mitigation practice. This analysis relied on DAYCENT output (see ICF [2013] for further discussion) to provide emission reduction potentials resulting from the adoption of the various nutrient management options by crop and region. Data are not available for all region-commodity-practice combinations (e.g., 10 percent reduction in N application for cotton in the Southern Plains). In other instances, the acres are ineligible for the adoption of a nitrogen mitigation practice due to a negative break-even price. A negative break-even price could mean that the associated mitigation option is already cost effective for the farm to adopt. In these cases, it is likely that farms are already using the practice. Alternatively, a negative break-even price could signal an issue with the underlying data. Figure 14 illustrates allocation of total acres with applied N to ineligible and eligible acres, and the allocation of eligible acres to the four nitrogen management practices considered in the MACC.

Tillage Management: Baseline Practices and Potential Adoption of New Practices

The MACC analysis includes three tillage management GHG mitigation options. These options are conversions from (1) conventional tillage to reduced tillage, (2) reduced tillage to long-term no-till, and (3) conventional tillage to long-term no-till. Baseline tillage management practices are established by applying region-commodity specific percentages of cropland managed under different tillage intensities to region-commodity specific data on harvested acreage in 2007 (USDA NASS, 2009). The tillage intensity percentages are derived from queries of data in recent ARMS (USDA ERS, 2014) on corn, cotton,

Figure 14: Total Eligible Acres for the MACC (in million acres)



sorghum, soybeans, and wheat. In the ARMS data, acres that have had no tillage in the previous 4 consecutive years are assumed to be managed with long-term no-till. Acres in conventional tillage are taken as presented, and all other tilled acres are assumed to be some form of reduced tillage.

Among the set of commodities covered in ARMS, any particular commodity is surveyed every few years and each survey focuses only on the major producing States for that commodity. As a result, the derived percentages for current tillage intensities (i.e., acres in permanent no-till, conventional tillage, and reduced tillage) are not comprehensive in that the ARMS data do not allow estimates of the tillage intensity percentages to be estimated for all crop-region combinations. Gaps in these percentages were filled using the following rules:

1. If data are available for a crop type and USDA region, data are used as summarized (see Table C-3).
2. If data are available for a crop type, but not for a particular region, the national average adoption rates for continuous no-till, reduced tillage, and conventional tillage for the crop type are used (see Table C-1).
3. If data are not available for a particular crop type (i.e., cotton), the average regional adoption rates for continuous no-till, reduced tillage, and conventional tillage for the USDA region are used (see Table C-2).

Applicable acres for reductions in tillage intensity mitigation options are derived from the harvested acres in the 2007 USDA Census of Agriculture and the tillage system percentages queried from the ARMS data. The number of acres by crop and region for adoption of reduced tillage practices is based on two steps:

Step 1: Exclude all farms smaller than 100 harvested acres. As with nutrient management, farms with less than 100 harvested acres are removed from the analysis because it is assumed that they are too small for the adoption of the GHG mitigation technologies considered in the

MACC to be economically feasible. Therefore, only acres on farms with 100 harvested acres or more are included in the analysis.

Step 2: Determine where baseline tillage management practices could be improved. Acres where long-term no-till is already occurring (i.e., acres that have not been tilled during the last 4 consecutive years) are removed from the analysis because they are already being managed with the tillage option that maximizes soil carbon. Acres currently in conventional tillage could transition to either reduced till or long-term no-till. This analysis assumes that half of all conventionally tilled acres are eligible to adopt reduced till and half are eligible to adopt long-term no-till. Finally, all acres currently managed with reduced till are assumed to be eligible to adopt long-term no-till. Table 6 summarizes the applicability of tillage management mitigation options by crop and region. Checkmarks indicate whether a mitigation option is applicable for the acres associated with a crop-region combination.

Table 6: Applicable Mitigation Options for Tillage Management by Crop and Region

USDA Region	Switch From Conventional Till to Reduced Till					Switch From Conventional Till to Continuous No-Till					Switch From Reduced Till to Continuous No-Till				
	Corn	Soybeans	Cotton	Wheat	Sorghum	Corn	Soybeans	Cotton	Wheat	Sorghum	Corn	Soybeans	Cotton	Wheat	Sorghum
Appalachia	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Delta	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Southeast	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Southern Plains	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Pacific	●		●	●	●	●		●	●	●	●		●	●	●
Mountain	●		●	●	●	●		●	●	●	●		●	●	●
Northern Plains	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
Lake States	●	●		●		●	●		●		●	●		●	
Northeast	●	●		●	●	●	●		●	●	●	●		●	●
Corn Belt	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●

The GHG benefits of reduced tillage options were evaluated for the majority of USDA regions and crop types.

Table 7 summarizes the potential number of applicable acres for the adoption of each tillage mitigation option by commodity and farm size.

Table 7: Tillage Management: Applicable Acres by Crop and Farm Size

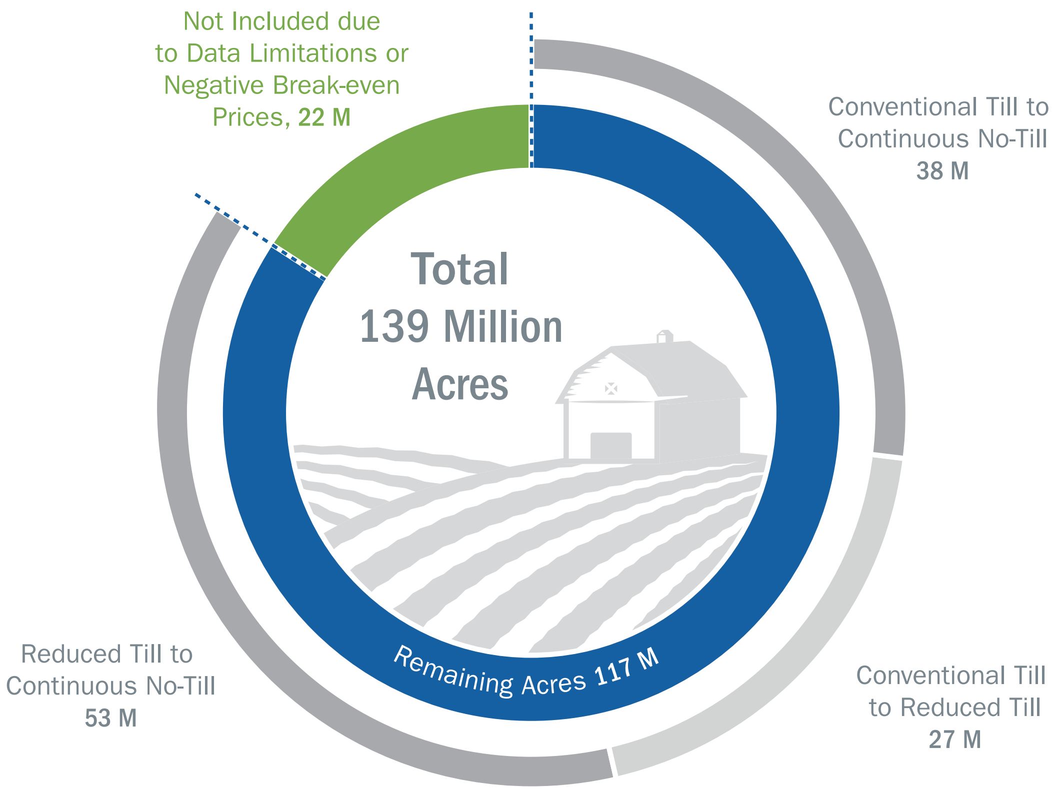
Crop/Farm Size (acres)	Mitigation Options			Total Applicable Acres
	Switch From Conventional Tillage to Reduced Tillage (acres)	Switch From Conventional Tillage to Continuous No-Till (acres)	Switch From Reduced Tillage to Continuous No-Till (acres)	
Corn	20,609,867	20,609,867	22,700,970	63,920,704
100 to 249	3,204,402	3,204,402	3,529,524	9,938,328
250 to 499	4,585,432	4,585,432	5,050,676	14,221,540
500 to 999	5,736,450	5,736,450	6,318,478	17,791,378
1,000 or more	7,083,583	7,083,583	7,802,292	21,969,458
Cotton	934,582	934,582	634,342	2,503,506
100 to 249	57,563	57,563	39,071	154,197
250 to 499	121,606	121,606	82,539	325,751
500 to 999	236,968	236,968	160,841	634,777
1,000 or more	518,445	518,445	351,891	1,388,781
Sorghum	1,209,667	1,209,667	1,738,089	4,157,423
100 to 249	222,257	222,257	319,346	763,860
250 to 499	291,979	291,979	419,525	1,003,483
500 to 999	317,124	317,124	455,654	1,089,902
1,000 or more	378,307	378,307	543,563	1,300,177
Soybeans	12,585,260	12,585,260	17,830,404	43,000,924
100 to 249	2,433,334	2,433,334	3,447,472	8,314,140
250 to 499	3,331,197	3,331,197	4,719,537	11,381,931
500 to 999	3,629,993	3,629,993	5,142,861	12,402,847
1,000 or more	3,190,736	3,190,736	4,520,535	10,902,007
Wheat	5,216,792	5,216,792	15,314,415	25,747,999
100 to 249	592,139	592,139	1,738,284	2,922,562
250 to 499	806,920	806,920	2,368,795	3,982,635
500 to 999	1,183,227	1,183,227	3,473,482	5,839,936
1,000 or more	2,634,505	2,634,505	7,733,854	13,002,864
Total	**40,556,168**	**40,556,168**	**58,218,220**	**139,330,556**

As with nitrogen management, some potentially applicable acres had to be omitted from the MACC analysis because of data constraints. First, this analysis relied on DAYCENT output (see ICF [2013] for further discussion) to provide emission reduction potentials resulting from the adoption of the various tillage intensity reduction options by crop and region. Emission reduction coefficients for changes in tillage intensity are not available for all crops and regions (e.g., switching from conventional till to no-till sorghum in the Pacific region). Second, for some region-crop combinations, the break-even prices associated with switching to a less GHG-intensive tillage system were negative (see ICF [2013]) (e.g., conventional tillage to reduced tillage for soybeans in the Southern Plains). Whether a given negative break-even price means that the option is already cost effective for farms to adopt, or that data are too limited to allow further analysis of the adoption decision, the associated acres were omitted from the MACC analysis. Figure 15 summarizes the number of potentially ineligible and eligible acres for adopting a reduced tillage system and, for the eligible acres, the number of acres that are eligible for each reduced tillage option.

Marginal Abatement Cost Curve for Crop Production Systems

Figure 16 shows the crop sector MACC for the adoption of GHG-mitigating nitrogen and tillage management practices for break-even prices between

Figure 15: Total Eligible Acres for Tillage Intensity Reduction Included in the MACC (million acres)



Mitigation potential was assessed for adoption of reduced tillage practices for approximately 117 million acres of cropland.

\$1 and \$100 per mt CO_2e. At the \$100 per mt CO_2e incentive level, U.S. farms supply GHG mitigation totaling about 40 Tg CO_2e. Of this, 4 Tg CO_2e is related to changes in nitrogen management and 36 Tg CO_2e is related to reducing tillage intensity. While reductions in tillage intensity have more mitigation potential than changes in nitrogen management, it is worth stressing that the mitigation benefits of reducing tillage intensity depend critically on the reduced tillage practices being adopted in the long term (views range between 20 years and permanently). That is, several years of soil carbon gains associated with reducing tillage intensity in a given field will be significantly reduced if at some point in the future that field is again subjected to more intense tillage (even if only occasionally).

Referring again to Figure 16, almost half of the 40 Tg CO_2e mitigation supplied by U.S. farms at \$100 per mt CO_2e can be achieved at \$30 per mt CO_2e. Above \$40 per mt CO_2e, the marginal cost of achieving additional mitigation through changes in nitrogen and tillage management practices increases quickly.

Table 8 presents a more detailed picture of the GHG mitigation that the crop production sector could supply at a CO_2 price of \$30 per mt CO_2e by identifying the top four sources of mitigation by region, mitigation option, and farm type. Among the regions, the Northern Plains supplies about 30 percent of all mitigation, with the Lake States at 28 percent, the Corn Belt at 20 percent, and the Delta at 8 percent. Given a CO_2 price of \$30 per mt CO_2e, these four regions account for 86 percent of the mitigation related to changes in nitrogen and tillage management. With respect to mitigation options, switching from reduced till to continuous no-till and switching from conventional till to continuous no-till account for 92 percent of the mitigation potential. With respect to farm type, changes in corn production systems account for 77 percent of total mitigation.

Figure 16: Marginal Abatement Cost Curve for Crop Production (Break-even Prices Less Than \$100 per mt CO_2e)

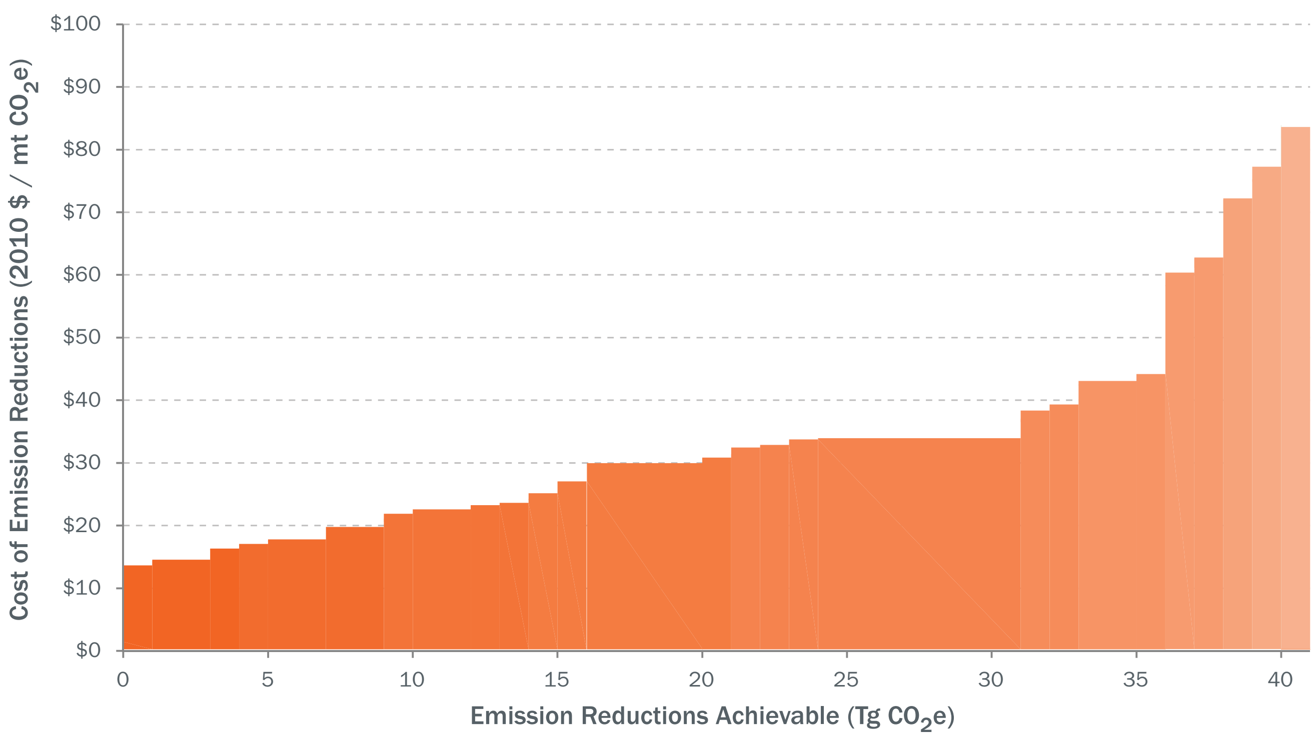


Table 8: Top Crop Production GHG Mitigation Sources at $30 per mt CO_2e by Region and Mitigation Option

Region	Share of Total Mitigation
Northern Plains	30%
Lake States	28%
Corn Belt	20%
Delta	8%

Mitigation Option	Share of Total Mitigation
Reduced Till to Continuous No-Till	56%
Conventional Till to Continuous No-Till	36%
Conventional Till to Reduced Till	3%
Nitrogen Reduction	3%

Farm Type	Share of Total Mitigation
Corn	77%
Wheat	13%
Soybeans	7%
Sorghum	3%

Note: Total mitigation potential is approximately 21 Tg CO_2e below $30 per mt CO_2e.

Land Retirement

This section describes the construction of the MACC associated with farms retiring land from crop production for the purpose of mitigating GHG emissions. The MACC incorporates the five farm-level mitigation options shown in the adjacent text box.

In constructing the MACC, each land retirement option is distinguished by USDA production region but not by farm size (ICF, 2013). This means that the farm-level economics of adopting the land retirement options vary by region but not by farm size. Additionally, within each region, State-level data allow identification of low- and high-cost versions of each mitigation option (see ICF [2013] for details). Low-cost versions tend to emphasize establishing grasses over trees and allow for non-native species. High-cost versions tend to emphasize establishing trees and/or allow only native vegetation. Across options, retired lands are assumed to be withdrawn from cultivation for at least 15 years. For four options, the primary GHG mitigation benefit is an increase in the quantity of carbon sequestered in soils and long-lived vegetation. For retiring organic soils, the main GHG benefit is the reduction in CO_2 emissions associated with the oxidation of organic soil carbon that occurs during field operations.

Mitigation Options for Land Retirement

- Retire Organic Soils
- Retire Marginal Cropland
- Restore Wetlands (Grass and Forested)
- Establish Windbreaks
- Plant Riparian Forest Buffers

Two key challenges in constructing the land retirement MACC are (1) determining the potential number of applicable acres for each land retirement option, and (2) allocating those acres across the 10 USDA production regions. Because farmers would retire virtually any acre now in commodity production if provided with a sufficient incentive, specifying a maximum number of cropland acres that could be retired and managed for GHG mitigation, either in aggregate or with respect to each mitigation option, is somewhat arbitrary. For the purposes of this analysis, the total amount of cropland that can be retired for all mitigation options is capped at 12.5 million acres. This acreage cap is based on recent experience with USDA's Conservation Reserve Program (CRP). The CRP, USDA's largest land retirement program, reached its peak enrollment of 36.8 million acres in 2007. Since 2007, enrollment has trended downward and, as of September 2015, stood at just over 24 million acres. Capping cropland retirements at 12.5 million acres for the purposes of constructing a MACC for GHG mitigation keeps the use of these options within the upper bounds of USDA's recent experience with land retirement programs.

Finally, past experience with USDA's land retirement programs has shown that farmers have a strong preference for offering economically marginal lands for enrollment. In general, this analysis assumes a continuation of this preference. Organic soils are the exception. These soils are typically very productive and profitable. On a per acre basis, however, CO_2 emissions associated with cultivating these soils are an order of magnitude higher than emissions from cultivating mineral soils. From a GHG mitigation perspective, it may be cost effective to target organic soils for retirement even though the per acre incentive will need to be significantly higher than the per acre incentive to retire mineral soils.

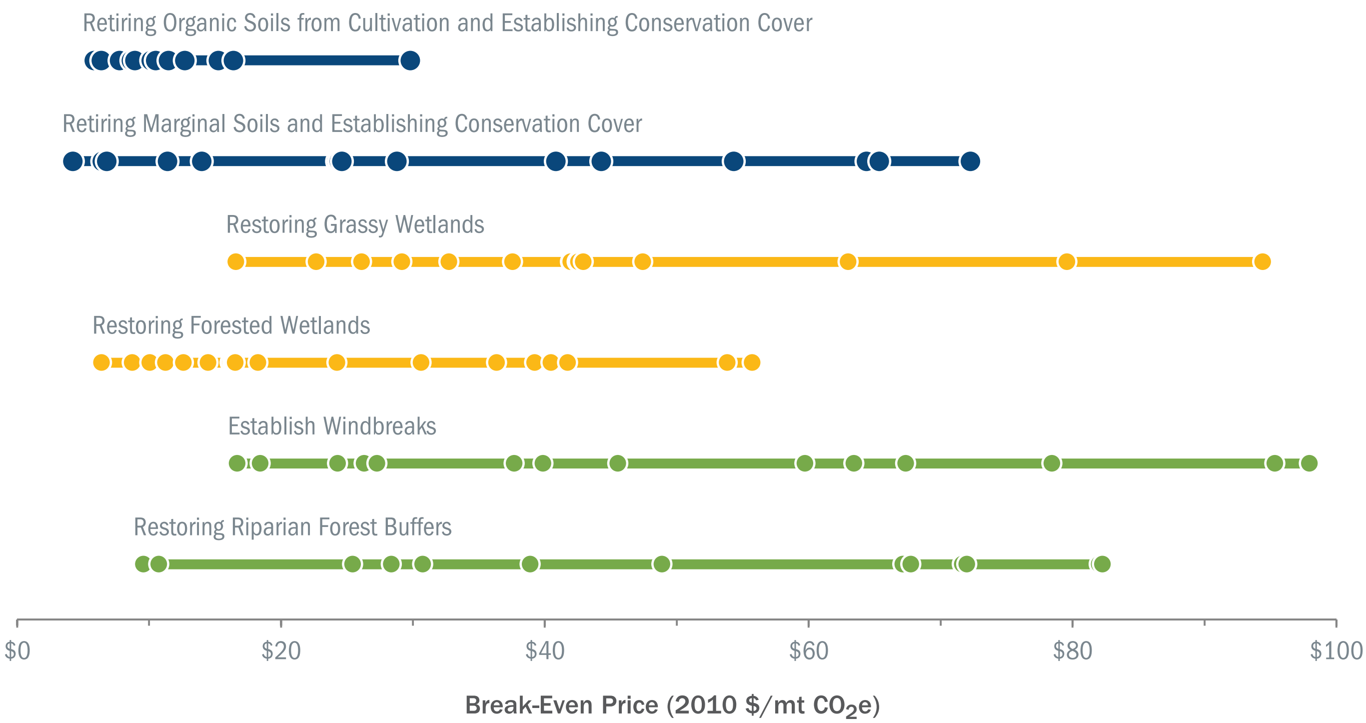
The CO_2 break-even prices used to construct the land retirement MACC are taken from ICF (2013) and readers can refer to that report for more details. Figure 17 shows a range of CO_2 break-even prices for each cropland retirement GHG mitigation option considered in the MACC. For a given mitigation option, each dot in the figure reflects the CO_2 break-even price for a specific representative farm distinguished by USDA production region and low-cost/high-cost adoption scenario. For a given farm and mitigation option, the CO_2 break-even price is the price per metric ton (mt) of CO_2 that when multiplied by the quantity of GHG mitigation that results from adoption, yields a dollar value that just equals that farm's adoption cost.

Land Management: Baseline Management Practices and Potential Adoption of New Practices

Figure 18 shows acres of cultivated organic soils as of 2010 according to the Inventory of *U.S. Greenhouse Gas Emissions and Sinks: 1990–2010* (EPA, 2012), acres in selected conservation practices on lands enrolled in USDA's CRP as of 2010,[6] and acres enrolled in USDA's Wetlands Reserve Program (WRP) as of 2012 (WRP, 2013). For all but organic soils, the lands referenced in the pie charts in Figure 18 reflect how farmers have responded to prior USDA incentives to shift land from commodity production into the land conservation options considered in the land retirement MACC. While prior incentives have generally not targeted GHG mitigation, this analysis assumes that farmers would respond to future incentives in much the same way that they have responded to past incentives—at least when viewed as dollars per acre. In developing the applicability of each land retirement mitigation option (except retiring organic soils), this assumption means that the regional distribution of the adoption of each option is consistent with the current regional pattern of adoption in the CRP and WRP.

At present, there are no USDA incentives that explicitly focus on retiring organic soils from cultivation. The pie chart illustrating the distribution

Figure 17: CO_2 Break-even Prices for Retiring Cropland by Mitigation Option

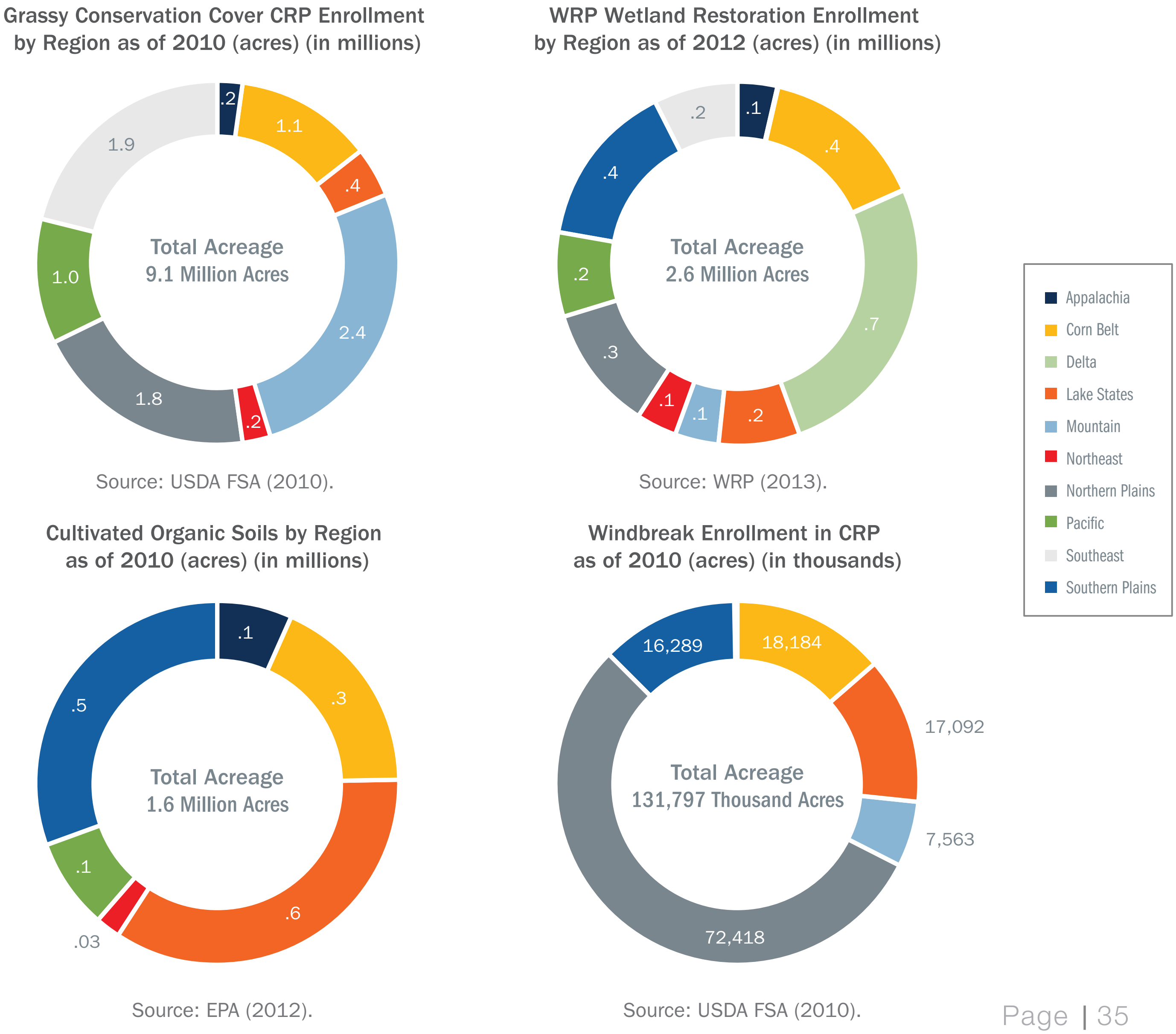


[6]CRP enrollment data for 2010 refers to USDA's fiscal year 2010 (i.e., October 2009 to September 2010).

of cultivated organic soils in Figure 18 shows a total of 1.6 million acres nationally that could potentially be retired. This is less than 1 percent of all U.S. cropland. For this study, all cultivated organic soils are assumed to be available for retirement.

For all other land retirement options, the data used to construct the pie charts in Figure 18 and to develop estimates of potential applicable acres were obtained from acreage and conservation practice data in the following key sources: recent enrollment data from CRP (USDA FSA, 2010) and WRP (WRP, 2013); data on the distribution of palustrine wetlands in the United States between emergent (grassy) and forested wetlands (USDA NRCS, 2013a); data on riparian acres in the *2004 National Water Quality Inventory: Report to Congress* (EPA, 2009); and data in the U.S. GHG Inventory for cultivated organic soils (EPA, 2012). Further details on the acres and associated regional percentages used to calculate the potential applicability of each land management option in the MACC analysis are provided in Appendix A: Data Sources Used for Land Retirement Applicable Acres Calculations.

Figure 18: Distribution of Selected Conservation Practices and Acreage of Cultivated Organic Soils, by USDA Farm Production Region



The baseline land management practices in 2007, 2010, and 2012 serve as the starting points for determining the potential applicability for each of the GHG-mitigating land retirement options considered in the MACC. The relationships between current enrollment and potential applicability are described in Table 9.

Starting with the assumption that the total amount of additional cropland that can be retired and managed with GHG mitigation land covers is 12.5 million acres, the potential applicable acres for each of the five GHG mitigation options considered are determined as follows:

1. Restoring Wetlands: In 2010, enrollment in the WRP totaled about 2.5 million acres. The distribution of these acres by region is shown in Figure 18. To establish the potential to restore additional wetland acres as a GHG mitigation option, this analysis assumes that the acres in the WRP could be doubled. It is assumed that the regional distribution of the additional acres would mirror the distribution in Figure 18. Based on 2007 National Resources Inventory (NRI) data for distribution of palustrine and estuarine wetlands (USDA NRCS, 2013a), it is assumed that about 70 percent of the newly restored wetlands would be forested and 30 percent would be grassy (emergent). Information on the distribution of existing wetland types is used as a proxy for the distribution of restored wetlands as data on how restored wetlands are allocated between forested and grassy systems are not readily available.

2. Retiring Organic Soils: As noted above, there are about 1.6 million acres of organic soils now under cultivation. While less than 1.0 percent of U.S. cropland, these soils have an average GHG mitigation value of between 11.5 and 14.3 mt CO_2e per acre per year. This makes retiring these soils from cultivation a very cost-effective, farm-level GHG mitigation option. This analysis assumes that all

Table 9: Data Sources for Baseline Acreage and Regional Distribution for Land Retirement Practices

Mitigation Option	Baseline Acreage and Distribution	Mitigation Potential
Establish Windbreaks	National Resources Inventory data for 2007 (acres of erodible cropland) (USDA NRCS, 2010), 2010 CRP Enrollment by Region for Field Windbreaks and Shelterbelts (acres) (Sampson and Kamp, 2005; USDA FSA, 2010)	2.2 million acres nationally, distributed regionally based on 2010 CRP acres in shelterbelts
Retire Organic Soils and Establish Conservation Cover	Acres of cultivated organic soils by region (EPA, 2012)	Retirement of all 1.6 million acres of organic soils in cultivation
Restore Wetlands	Acres enrolled in the WRP in 2012, by Region (WRP, 2013); distribution of emergent and forested wetlands (USDA NRCS, 2013a)	2.5 million acres nationally, distributed regionally based on WRP wetlands acres in 2012
Restore Riparian Forest Buffers	Riparian acres impaired by agricultural practices (2004 National Water Quality Inventory: Report to Congress [EPA, 2009]; USDA FSA [2010]; and USDA NRCS [2010])	Restoration of 0.89 million acres nationally
Retire Marginal Soils and Establish Conservation Cover	CRP Acres in Grass Plantings in 2010 (USDA FSA, 2010)	Retirement of 5.3 million acres nationally, distributed regionally based on enrollment in CRP

1.6 million acres of cultivated organic soils could be retired.

3. Restoring Riparian Forest Buffers: The 2004 National Water Quality Inventory: Report to Congress (EPA, 2009) assessed the overall water quality of 16 percent of all U.S. rivers and streams (measured in miles). This report found that 6 percent of the surveyed river and stream miles were associated with an agricultural use. Applying this percentage to all 3.5 million U.S. river and stream miles suggests that approximately 210,000 miles are associated with an agricultural use. Using a buffer of 35 feet on one bank and assuming restoration of the forest buffer on all agriculture-associated miles suggests a national technical potential for this practice of 890,909 acres. These acres are distributed regionally based on CRP enrollment for riparian forest buffer use as of 2010.

4. Establishing Shelterbelts/Windbreaks: Based on NRI data for 2007 (USDA NRCS, 2010), there are about 53.6 million acres of highly erodible [crop]land (HEL) and 45.6 million acres of non-HEL cropland on which soil erosion due to wind or water exceeds the applicable soil loss tolerance level. In an examination of NRI soil erosion data from the five surveys conducted over the period 1982–2003, Kertis and Livari (2006) find that wind accounts for about 44.4 percent of erosion due to wind or water. Applying the 44.4 percent value to the 99.2 million acres referred to above suggests that there are about 43.6 million acres of U.S. cropland that are subject to significant wind erosion. In a study of erodible land in the Big Sky States in the Western United States (i.e., Idaho, Montana, South Dakota, and Wyoming), Sampson and Kamp (2005) conclude that shifting about 5.0 percent of erosion-prone acres into conservation cover would be a reasonable GHG mitigation objective. Applying Sampson and Kamp's 5.0 percent value to 43.6 million acres implies a potential applicability of establishing additional shelterbelts of about 2.2 million acres nationally. These acres are distributed regionally based on the regional distribution of shelterbelts on CRP acres in 2010 (see Table A-3).

5. Retiring Marginal Cropland Soils and Establishing Conservation Cover (5.3 million acres): Subtracting the applicable acres described above for restoring wetlands, retiring organic soils from cultivation, establishing riparian forest buffers, and establishing shelterbelts from the land retirement cap of 12.5 million acres leaves 5.3 million acres. This acreage is assumed to be the potential applicability of shifting marginal cropland into grassy conservation covers. These acres are distributed regionally based on the distribution of acres in New Grass Plantings on CRP lands in 2010 (USDA FSA, 2010).

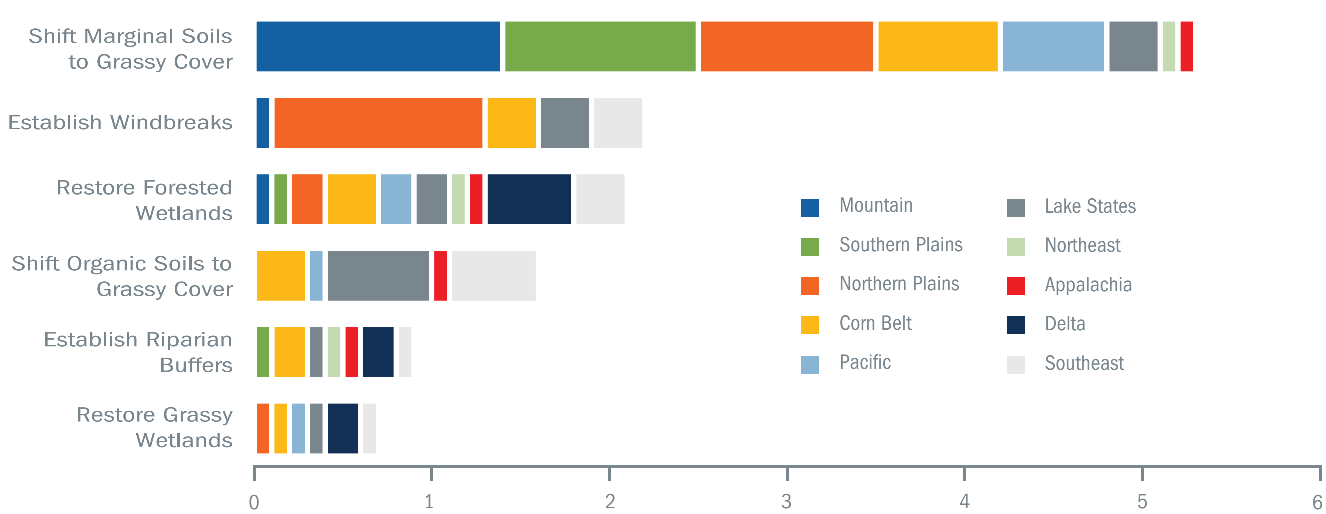
Figure 19 presents a national and regional picture of the applicable acres for all land retirement options considered in this chapter.

Marginal Abatement Cost Curve for Land Retirement

Figure 20 shows the MACC for the five GHG-mitigating land retirement options discussed in this chapter. As throughout this report, the region-option combinations shown on the MACC are limited to those with break-even prices between \$1 and \$100 mt CO_2e (see ICF, 2013). From both a policy and a farm perspective, cropland retirements are an economically attractive set of activities for achieving GHG mitigation in the farm sector. Focusing on \$10 per mt CO_2e, land retirement options collectively supply about 15 Tg CO_2e in GHG mitigation. Doubling the CO_2 price to \$20 per mt CO_2e increases the mitigation supplied to about 31 Tg CO_2e. Above \$30 per mt CO_2e, the marginal cost of achieving additional mitigation via land retirement rises quickly.

Table 10 presents a more detailed picture of the GHG mitigation that land retirement practices could supply at a CO_2 price of \$30 per mt CO_2e by identifying the top four sources of mitigation by region and by mitigation option. Among the regions, the Lake States and the Southeast regions each supply about a quarter of all mitigation, the Corn Belt supplies about 15 percent, and the Northern Plains region supplies 8 percent. Given a CO_2 price of \$30 per mt CO_2e, these four regions account for 71 percent of all GHG mitigation related to retiring croplands. With respect to mitigation options, retiring organic soils accounts for 67 percent of the mitigation potential, and restoring forested wetlands accounts for 20 percent.

Figure 19: Adoption Potential for Land Retirement Mitigation Options by Region[a]



[a] Does not include adoption that would otherwise occur under existing WRP or CRP enrollments.

Sources:
- Adoption potential for retirement of marginal soils for the establishment of grassy cover (USDA FSA, 2010)
- Adoption potential for retirement of marginal soils for the establishment of windbreaks (USDA FSA [2010] and Sampson and Kamp [2005])
- Adoption potential for retirement of marginal soils for the restoration of forested wetlands (WRP [2013] and USDA NRCS [2013a])
- Adoption potential for retirement of organic soils for the establishment of grassy cover (EPA, 2012)
- Adoption potential for retirement of marginal soils for the establishment of riparian buffers (EPA [2009] and USDA FSA [2010])
- Adoption potential for retirement of marginal soils for the restoration of grassy wetlands (WRP [2013] and USDA NRCS [2013a])

Figure 20: Marginal Abatement Cost Curve for Land Retirement Mitigation Options for Break-even Prices Below $100 per mt CO_2e

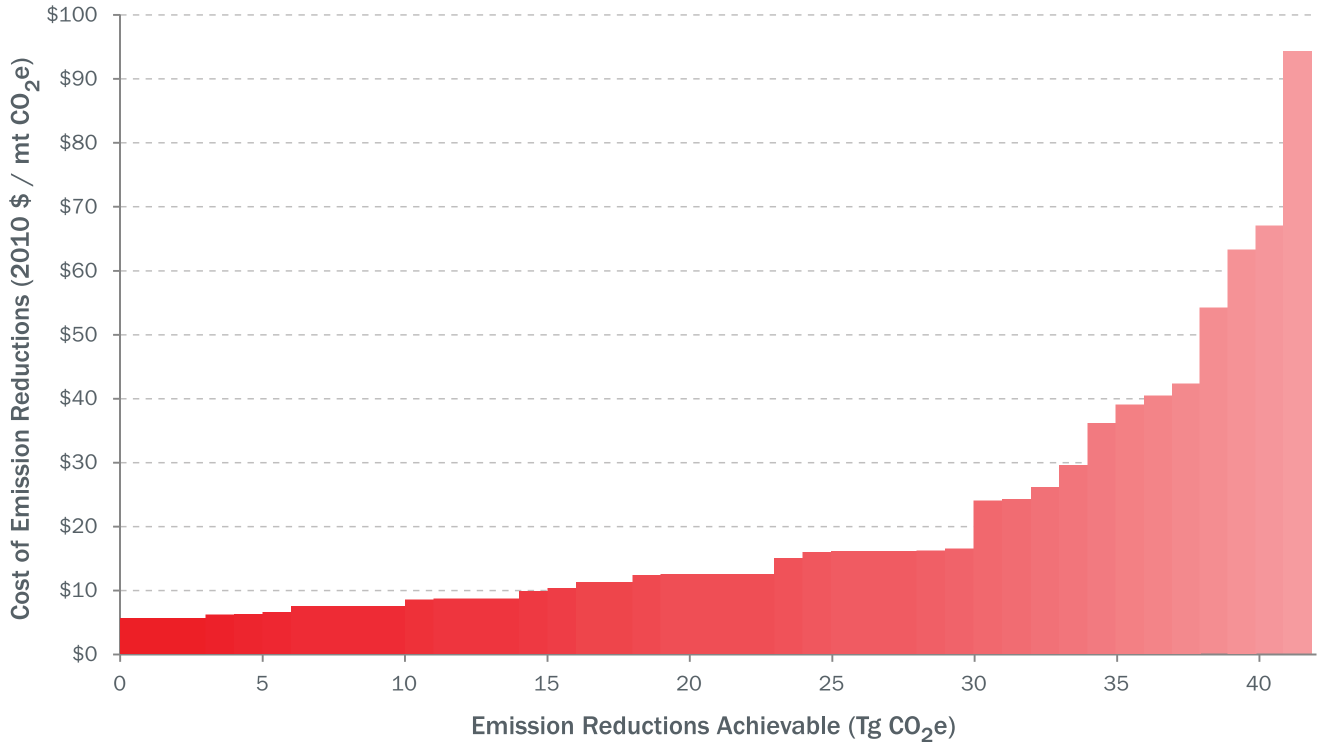


Table 10: Top Land Retirement GHG Mitigation Sources at $30 per mt CO_2e by Region and Mitigation Option

Region	Share of Total Mitigation
Lake States	25%
Southeast	23%
Corn Belt	15%
Northern Plains	8%

Mitigation Option	Share of Total Mitigation
Retire Organic Soils	67%
Restore Forested Wetlands	20%
Retire Marginal Soils	8%
Establish Windbreaks/Shelterbelts	3%

Legume Interseeding

There are about 529 million acres of non-Federal grazing land in the lower 48 States (USDA NRCS, 2013b). Included are lands classified as pasture and rangeland, and under the ownership or control of private parties, tribes, trusts, and State and local governments. From a technical perspective, there is general agreement that U.S. grazing lands could be managed to significantly increase the amount of carbon stored in their soils (Eagle et al., 2012; Follett et al., 2001). Often-cited practices that farms could adopt to increase soil carbon levels in grazing lands include management-intensive (or rotational) grazing, fertilizer applications, and irrigation.

From an economics perspective, the GHG mitigation potential of U.S. grazing lands is less clear. Grazing livestock is often a marginal economic use of land. Additionally, published estimates of carbon sequestration rates for the specific grazing land management practices, including those mentioned above, are generally in the range of 0.25 to 0.5 tons per acre per year (however, these estimates are based on few studies, and there is significant variation based on local conditions). In many areas, these conditions will hamper efforts to incentivize GHG-mitigating land management practices. Where grazing lands are characterized by low economic returns, farmers will be reluctant to incur additional production costs. Where adoption of specific management practices yields relatively small GHG benefits, buyers of mitigation units will offer relatively small incentives (at least when converted to a per acre basis).

Assessing the economic potential of U.S. grazing lands to sequester additional carbon is further hampered by limited data on (1) the farm-level costs of adopting specific GHG-mitigating practices, (2) the GHG mitigation that would result from adoption of specific practices, and (3) how these lands are currently managed. For example, the USDA 2007 Census of Agriculture (USDA NASS, 2009) documents the number of farms practicing management-intensive grazing, but provides no data on farms using other grazing land management practices. Furthermore, management-intensive grazing is really a set of diverse grazing systems that are highly tailored to local conditions. Hence, it is not possible to describe a representative system with associated representative adoption costs and resulting GHG mitigation.

In its assessment of farm-level, GHG-mitigating technologies and practices, ICF (2013) identified one GHG mitigation option for grazing lands. The option is frost interseeding of legumes in pastures and rangelands. Published data are available for this option on adoption costs and expected GHG mitigation. Based on these data, ICF (2013) estimated the farm-level CO_2 break-even prices for this practice as shown in Table 11. On a per acre basis, the carbon sequestration potential ranges from 0.07 to 1.26 mt CO_2e per year (ICF, 2013). At a carbon sequestration value of 0.07 mt per acre, break-even prices universally exceed $100 per mt CO_2e. Consequently, the values presented in Table 11 are all based on the "high" potential mitigation of 1.26 mt CO_2e per acre.

Table 11: Regional Emission Reductions Resulting From Frost Interseeding of Legumes for Break-even Prices of Less Than $100 per mt CO_2e

Region	Grazing Land Type	Break-even Price (2010 $/mt CO_2e)	Regional Emission Reductions (mt CO_2e)	Cumulative Emission Reductions (mt CO_2e)
Corn Belt	Rangeland	$15	1,356	1,356
Mountain	Rangeland	$15	2,925,666	2,927,022
Northern Plains	Rangeland	$15	1,118,955	4,045,977
Pacific	Rangeland	$15	515,512	4,561,489
Southern Plains	Rangeland	$15	1,731,597	6,293,086
Pacific	Pastureland	$38	278,355	6,571,441
Southern Plains	Pastureland	$38	1,642,568	8,214,009
Mountain	Pastureland	$38	575,764	8,789,773
Northern Plains	Pastureland	$38	508,963	9,298,736
Appalachia	Pastureland	$38	1,042,464	10,341,200
Corn Belt	Pastureland	$38	1,299,724	11,640,924
Lake States	Pastureland	$38	561,355	12,202,279
Northeast	Pastureland	$38	383,892	12,586,171

Grazing Lands Management: Baseline Management Practices and Potential Adoption of New Practices

Based on NRI data, estimates of the acres of non-Federal pastureland and rangeland in each USDA production region are shown in Table 12. Distinguishing grazing lands as rangeland[7] or pasture[8] is necessary because they represent two distinct management regimes. Rangeland, primarily found west of the 100th meridian, is less productive and generally receives little active management. In the MACC analysis, the CO_2 break-even price for adopting frost interseeding of legumes on rangeland is estimated using the cost of machinery, seed, and labor. Pasture is concentrated east of the 100th meridian and typically is subject to more management treatments than rangeland. The estimated break-even price for adopting frost interseeding of legumes on pasture includes the cost of herbicide, potash, phosphorus, lime, soil tests, machinery, seed, and labor costs.

Similar to the assumption made with respect to acres available for land retirement, the MACC analysis assumes that there are 10 million acres

[7]Rangeland is principally composed of native grasses, grass-like plants, forbs, or shrubs suitable for grazing and browsing, and introduced forage species managed in an extensive manner (USDA NRCS, 2013b).

[8]Pasture land is used for the production of introduced forage plants for livestock grazing. Pasture 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 (USDA NRCS, 2013b).

available for the adoption of frost interseeding of legumes. Additionally, it is assumed that these acres are evenly split between pastureland and rangeland. Because frost conditions are rare in the Delta and Southeast regions, this management practice was not considered a GHG mitigation option in these regions. Using the distribution of pastureland and rangeland acres provided in the 2010 NRI (USDA NRCS, 2010), the 10 million acres are distributed by USDA production region as shown in Figure 21. For reference purposes, 5 million acres is equal to about 5 percent of all pastureland and 1 percent of all rangeland.

Marginal Abatement Cost Curve for Legume Interseeding

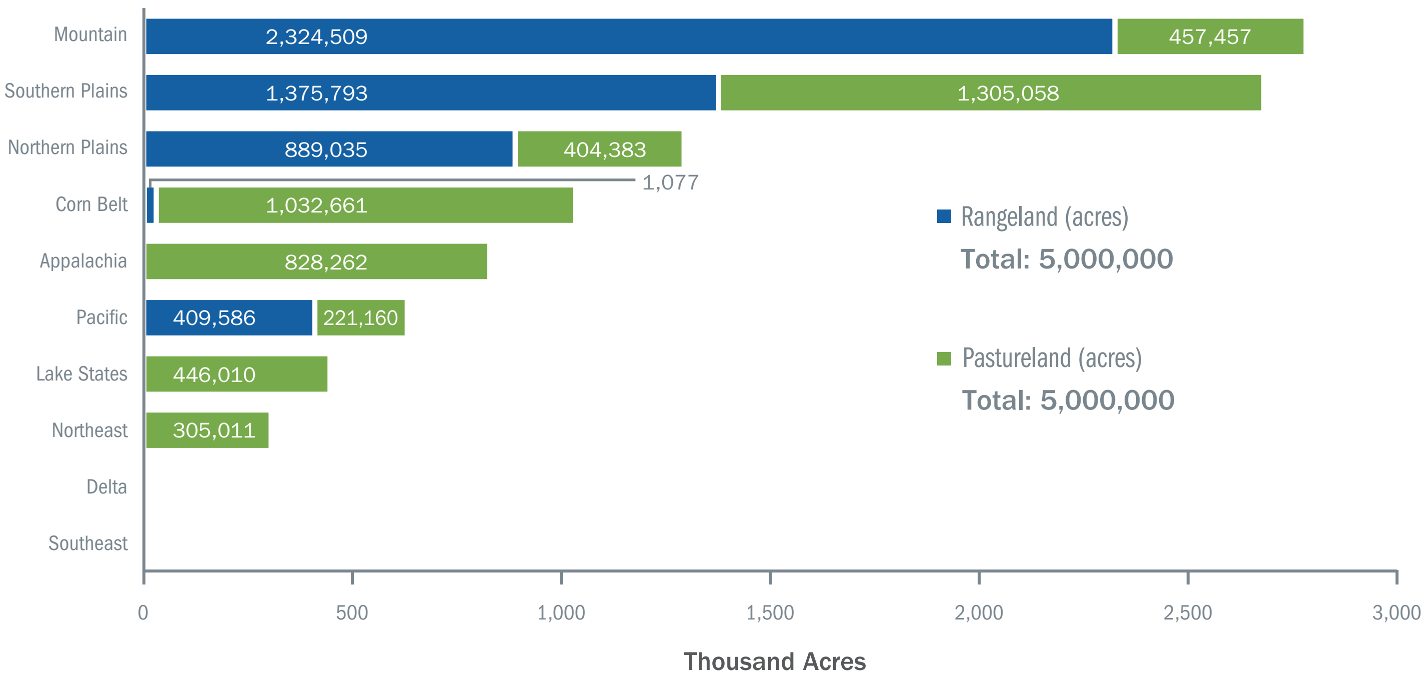
The MACC for frost interseeding of legumes is not shown explicitly here because it consists of two bars: one at \$15 per mt CO_2e and one at \$38 per mt CO_2e. At \$38 per mt CO_2e, the total GHG mitigation potential is 12.6 Tg CO_2e; at \$15 per mt CO_2e, the mitigation potential is 6.3 Tg CO_2e. The fourth column in Table 11 presents total mitigation by region.

Table 12: Total Non-Federal Grazing Land in the United States

Region	Rangeland (acres)	Pastureland (acres)
Appalachia	-	16,228,200
Corn Belt	87,200	20,233,000
Delta	301,200	11,204,700
Lake States	-	8,738,700
Mountain	188,206,900	8,963,000
Northeast	-	5,976,100
Northern Plains	71,981,900	7,923,100
Pacific	33,162,700	4,333,200
Southeast	2,744,900	10,831,500
Southern Plains	111,392,900	25,570,100
Subtotal	**407,877,700**	**120,001,600**
	Total Grazing Land	**527,879,300**

Source: USDA NRCS (2010), Table 2.

Figure 21: Applicable Acres of Rangeland and Pastureland for Legume Interseeding



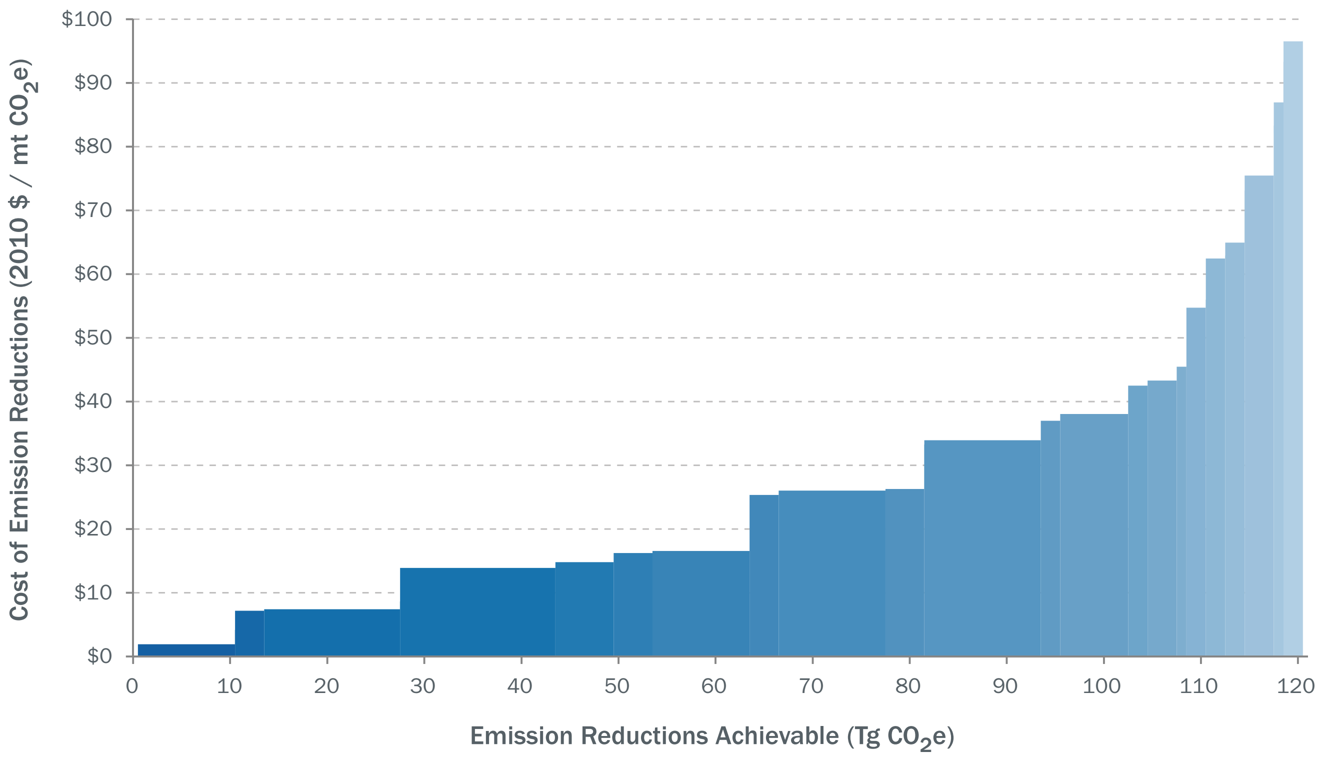
Summary and Conclusions

This report analyzes the potential of the U.S. farm sector to mitigate GHG emissions using a MACC framework. The approach combines farm-level information on specific technologies and practices that various types of farms could adopt to reduce their GHG footprint (including adoption costs and the GHG mitigation that would result from adoption) with regional and national descriptions of how manure, nitrogen, tillage, land use, and grazing lands are currently managed. Prior sections present MACCs for livestock production systems, crop production systems, land use management, and grasslands management, respectively. Figure 22 combines the information in these MACCs into a single MACC reflecting the GHG mitigation potential of U.S. agriculture as a whole. As in the previous sections, the MACC shown in Figure 22 considers CO_2 prices between $1 and $100 per mt CO_2e. At the $100 price, total mitigation supplied by U.S. agriculture is about 120 Tg CO_2e.

Key National Results

Figure 22 indicates that the GHG mitigation potential from U.S. agriculture increases relatively gradually up to a CO_2 price of between $30 and $40 per mt CO_2e. At the $40 price, U.S. farms supply mitigation totaling a little over 100 Tg CO_2e, or about 83 percent of the mitigation potential at $100 per mt CO_2e. Above $40 per mt CO_2e and 100 Tg CO_2e, the MACC turns sharply upwards.

Figure 22: Marginal Abatement Cost Curve for GHG Mitigation in U.S. Agriculture

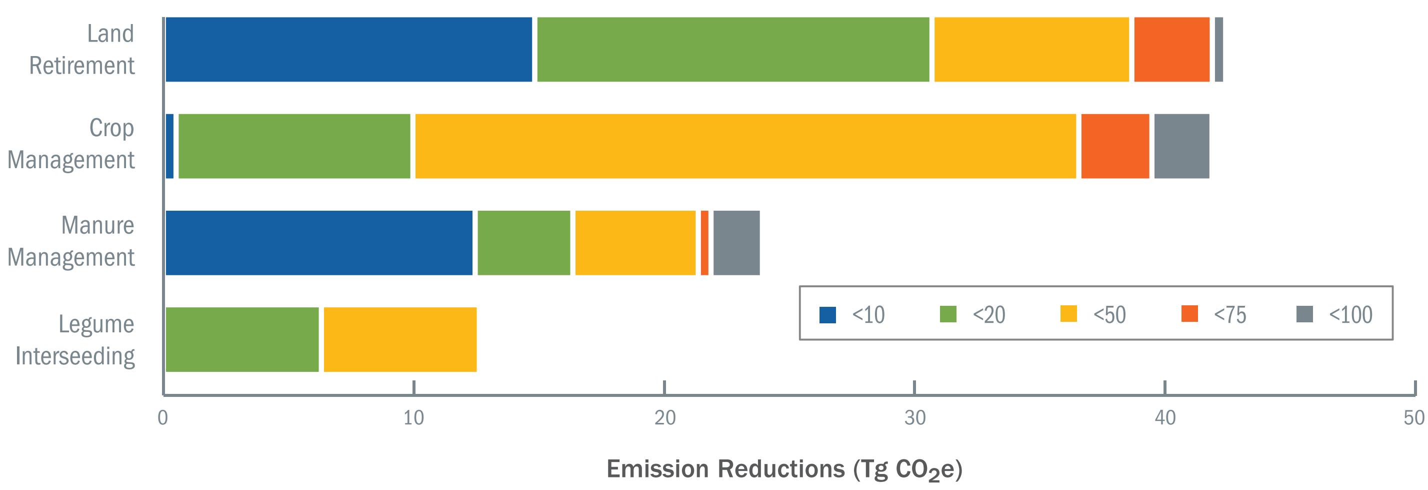


Low-end estimates of the social cost of carbon dioxide (SC-CO_2)[9] fall in the range of $30 to $40 per mt CO_2 (Interagency Working Group on Social Cost of Carbon, 2015). The MACC then suggests that incentivizing farms to mitigate GHG emissions may be cost effective up to the low-end estimates of the SC-CO_2. Above 100 Tg CO_2e, however, achieving additional mitigation in agriculture will likely not compare well with mitigation options in other sectors.

Figure 22 also shows that at a CO_2 price of $20 per mt CO_2e, U.S. farms supply mitigation of about 63 Tg CO_2e. The implied total cost would be about $1.26 billion. A number of USDA conservation programs have annual budgets in excess of $1.0 billion (e.g., the Conservation Reserve Program, the Environmental Quality Incentives Program, and the Agricultural Conservation Easements Program). Existing USDA conservation programs do not explicitly pay for GHG mitigation but actions taken under these programs currently produce an estimated 54 Tg CO_2e in GHG mitigation annually (U.S. Department of State, 2016). Figure 22 suggests that a targeted effort to incentivize farmers to adopt GHG-mitigating practices and technologies, budgeted at about $1 billion annually, could double the mitigation associated with the current suite of USDA's conservation programs.

Figure 23 reorganizes the information in the MACC for U.S. agriculture into a side-by-side comparison of the mitigation potential of cropland, livestock, land-use, and grassland management systems by CO_2 price level. This arrangement reveals that at an incentive level of $10 per mt CO_2e, farm-level adaptations are largely limited to changes in land use and manure management. At this price, actions taken on U.S. farms in these two areas mitigate about 27 Tg CO_2e. Doubling the incentive level to $20 per mt CO_2e more than doubles the mitigation supplied by the farm sector (to 63 Tg CO_2e) and provides sufficient incentive to achieve some farm-level mitigation response in all four areas shown in Figure 23.

Figure 23: Potential Mitigation by Agricultural Source Area and CO_2 Price Level ($ / mt CO_2e)



[9] The SC-CO_2 refers to the modeled impacts of CO_2 emissions on society, such as health, environmental, and economic impacts.

Key Results by Region, Practice/Technology, Commodity, and Farm Size

As can be seen in Figure 23, at an incentive level of $100 per mt CO_2e, the GHG mitigation that results from farm-level changes in manure management practices and technologies is about 24 Tg CO_2e. More than half of this mitigation, however, is achievable at an incentive level of $10 per Tg CO_2e. This suggests that incentivizing changes in manure management practices, specifically on confined dairy and swine operations, would be a particularly cost-effective area to achieve additional GHG mitigation in the agricultural sector.

The section on Animal Production Systems breaks down the mitigation potential of manure management systems at the incentive level of $30 per mt CO_2e by region, technology or practice, and farm size. At $30 per mt CO_2e, total mitigation from changes in manure management practices is about 20 Tg CO_2e. Among the regions, the Corn Belt and Pacific regions each supply about 25 percent, while Appalachia and the Mountain States each supply 14 percent (i.e., these four regions account for 78 percent of all mitigation supplied by livestock operations). Viewed by mitigation option, complete mix and two covered lagoon anaerobic digester options account for more than 70 percent of total mitigation. Given the capital, maintenance, and operations costs of digester systems, it is not surprising that large confined animal operations (i.e., swine operations with more than 5,000 head and dairy operations with more than 2,500 head) account for more than 70 percent of all mitigation.

Returning to Figure 23 and focusing on cropland systems, at an incentive of $100 per mt CO_2e, the total mitigation potential from changes to tillage and nitrogen management practices and technologies is about 40 Tg CO_2e. This is about 67 percent higher than the mitigation potential associated with this incentive level for changes in livestock systems. At lower CO_2 prices, however, mitigation from crop systems is not as cost-effective as that associated with changes in manure management. For example, at $10 per mt CO_2e farms supply almost no mitigation related to changes in tillage and nitrogen management, and at $20 per mt CO_2e, they supply about 7.5 Tg CO_2e. At a price of $30 per mt CO_2e, however, crop producers supply mitigation totaling 19 Tg CO_2e. This is equivalent to the mitigation supplied at $30 per mt CO_2e from livestock systems and about half of the mitigation potential from cropping systems at $100 per mt CO_2e.

The section on Crop Production Systems disaggregates the mitigation potential of crop production systems at a $30 per mt CO_2e incentive by region, technology or practice, and commodity. Among the regions, the Lakes States and the Northern Plains account for 58 percent of the mitigation supplied, and the Corn Belt accounts for about 20 percent. Among technologies and practices, reductions in tillage intensity account for 97 percent of all mitigation, and changes in nitrogen management account for 3 percent. Among commodities, changes in tillage and nitrogen practices related to corn production account for 77 percent of the mitigation supplied, while wheat and soybean systems (collectively) account for 23 percent.

Figure 23 indicates that land-use changes in the form of cropland retirements are the most cost-effective set of activities to incentivize if the objective is to achieve additional GHG mitigation in the U.S. farm sector. At the lower incentive levels of $10 and $20 per mt CO_2e, U.S. farms supply mitigation totaling 15 and 30 Tg CO_2e, respectively. These values are about half of all mitigation supplied by the farm sector at these CO_2 prices. The MACC for land-use change (i.e., Figure 20) shows that the marginal cost of additional GHG abatement from cropland retirements turns sharply upward at $30 per mt CO_2e. At this incentive level, GHG mitigation from cropland retirements is 34 Tg CO_2e. From a policy or program perspective, this may reflect the upper bound of the potential to incentivize additional GHG mitigation through cropland retirements.

The section on Land Retirement disaggregates the 34 Tg CO_2e in mitigation that farms supply at an incentive level of $30 per mt CO_2e by region and land retirement practice. Viewed by region, the Lake States and Southeast regions each supply about 25 percent, with the Corn Belt at about 15 percent, the Northern Plains at 8 percent, and both the Delta and Pacific regions at 7 percent. Among the practices, retiring organic soils, restoring forested wetlands, and retiring marginal soils account for 67 percent, 20 percent, and 8 percent, respectively, of all mitigation potential across all land retirement practices.

Finally, Figure 23 shows a total mitigation potential of 12.5 Tg CO_2e for for grassland management (i.e., legume interseeding). About half of this total is supplied from rangelands at an incentive level of $15 per mt CO_2e, and half from pasture lands at $38 per mt CO_2e (see Table 11 in Chapter 5). Among the four areas shown in Figure 23, the mitigation potential for grassland management. is the least informed by the literature. In reviewing existing studies on grassland GHG mitigation options, ICF (2013) identified one practice—frost interseeding of legumes—for which both adoption costs and resulting GHG mitigation are available. Additionally, at the sector level, there is virtually no data related to the current distribution of existing grassland management practices. While the mitigation potential shown in Figure 23 reflects the assumption that frost interseeding of legumes would be suitable for a relative small area of grasslands, 1 percent of rangelands, and 5 percent of pasture lands, much more work is needed to appreciate the economic potential of grassland management to mitigate GHG emissions.

Limitations

As with previous studies that have assessed the GHG mitigation potential of U.S. agriculture, the analysis presented here had to make a number of accommodations to address limitations imposed by the availability of time, data, and other resources. The most significant limitation was the scarcity of data related to how various manure management, tillage, and nitrogen management technologies and practices are currently distributed across U.S. crop and livestock operations. Assessing the potential effectiveness of incentivizing farms to mitigate GHG emissions by changing specific technologies and practices requires a baseline reflecting the technologies and practices now in place on farms across the national and regional landscapes. In developing the MACCs presented in this report, this study constructed proxy distributions for various manure management, tillage, and nitrogen management technologies and practices but in each case had to tailor the approach to available data, published studies, and other publically available sources. For example, the baseline distribution for manure management practices was constructed from livestock population data by region and farm size in the 2007 U.S. Agricultural Census, and queries of recent ARMS data on manure management practices on dairy and swine operations. While the ARMS data are the most comprehensive data available on manure management practices by region and farm size, the data are often constrained by small sample sizes and the need to aggregate the wide array of practices and technologies actually used on farms into a relatively small number of more general categories.

Data, time, and resources constraints also necessitated that this study adopt four assumptions that should be explicitly acknowledged. In each instance, the assumption likely resulted in the MACCs underestimating the mitigation that could be supplied by farms across the range of CO_2 prices considered.

First, the literature on GHG mitigation and agriculture identifies numerous farm-level actions that this analysis omits. Examples in livestock systems include options to reduce emissions from enteric fermentation (e.g., by changing feed mixes or incorporating feed additives like monensin) and managing manure on beef feedlots and poultry operations. Examples in crop production systems include substituting manure for synthetic fertilizer, switching to slow-release nitrogen products, and incorporating biochar in cropland soils. The criteria for including a mitigation option in this analysis were (1) the option could be clearly defined, (2) there were citable sources to document the farm-level adoption costs, and (3) there were citable sources to document the GHG mitigation that would result from adoption. For omitted options, one or more of these criteria were not met.

A second important limitation of the MACC analysis is that it focuses solely on GHG mitigation related costs and benefits. For a number of the technologies and practices considered, it is likely that in addition to GHG mitigation benefits, adoption by a farm would also result in co-production of other marketable and/or environmental goods. In manure management, for example, installation of an anaerobic digester can result in the production of electricity or natural gas for sale to utilities or other off-farm buyers. Similarly, establishing riparian forest buffers would likely result in water quality improvements and could increase the value of access to the farm for hunting. To the extent that the value of such market and environmental co-products can be captured by a farm, the break-even prices used in the MACC analysis to trigger adoption of a technology or practice will likely be overstated. At the same time, the value of co-products to a farm will typically depend on local conditions, and thus are difficult to generalize to regional or national levels. By focusing on just the GHG-related costs and benefits, the MACC analysis informs the GHG incentive levels that, in and of themselves, will make adoption of the technologies and practices considered economically rational from the farm perspective.

A third limitation of the MACC analysis is that within the categories of nitrogen management and manure management, the MACC framework explicitly limits each "representative farm" to adopting one GHG-mitigating technology or practice. A crop producer, for example, can reduce nitrogen application rates or switch from fall to spring application but it cannot do both. Similarly, a confined dairy operation with an anaerobic lagoon system can install a solids separator or an impermeable cover but not both. Conceptually, the adoption of multiple GHG-mitigating manure or nutrient management practices and technologies by a farm will likely result in additional mitigation. To be included in the MACC analysis, however, it would be necessary to know the marginal mitigation that would result from adopting a second technology or practice, given that another technology or practice is already in place. At present, the scientific literature does not allow this to be done.

Finally, the MACC analysis does not consider farm-level GHG mitigation options associated with afforesting agricultural lands, improving energy efficiency, or installing renewable energy systems (e.g., solar panels or wind mills). These are all areas where significant potential exists to achieve additional mitigation in the farm sector. The focus of this study, however, was on working agricultural systems and what farmers could do within these systems to mitigate GHG emissions. A complete assessment of the mitigation potential of the U.S. farm sector would include the opportunities in working lands management, afforestation, energy efficiency, and renewable energy.

References

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

EPA. 2004. *AgSTAR Handbook: A Manual for Developing Biogas Systems at Commercial Farms in the U.S.* Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/sites/production/files/2014-12/documents/agstar-handbook.pdf.

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. 2010. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2008*. 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.

Follett, R.F., J.M. Kimble, and R. Lal. 2001. *The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect.* Boca Raton, FL: Lewis Publishers.

ICF. 2013. *Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production Within the United States.* Washington, DC: ICF International, Prepared for USDA Climate Change Program Office.

Interagency Working Group on the Social Cost of Carbon. 2015. *Technical Support Document: Technical Update of the Social Cost of Carbon.* Regulatory Impact Analysis Under Executive Order 12866: United States Government. https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf.

Kertis, C.A., and T.A. Livari. 2006. Soil Erosion on Cropland in the United States: Status and Trends for 1982–2003. Proceedings of the 8th Federal Interagency Sedimentation Conference, April 2–6, 2006, Reno, NV.

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.

Sampson, R.N., and M. Kamp. 2005. Forest and Agroforestry Opportunities for Carbon Sequestration in the Big Sky: The Big Sky Carbon Sequestration Partnership.

U.S. Department of State. 2016. *Second Biennial Report of the United States: Under the United Nations Framework Convention on Climate Change.* https://unfccc.int/files/national_reports/biennial_reports_and_iar/submitted_biennial_reports/application/pdf/2016_second_biennial_report_of_the_united_states_.pdf

USDA ERS. 2011a. *U.S. Crop and Livestock Management Practices by Farm Size and Production Region based on the ARMS, 2004-2009.* Washington, DC: U.S. Department of Agriculture, Economic Research Service in response to request from the Climate Change Program Office.

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

USDA ERS. 2014. *Summary of U.S. ARMS Data on Tillage Practices by Crop Type and Region.* Washington, DC: U.S. Department of Agriculture, Economic Research Service in response to request from the Climate Change Program Office.

USDA FSA. 2010. *Conservation Reserve Program: Annual Summary and Enrollment Statistics.* Washington, DC: U.S. Department of Agriculture, Farm Service Agency.

USDA NASS. 2009. *2007 Census of Agriculture:* United States: Summary and State Data. Volume 1, Geographic Area Series, Part 51. Report Number AC-07-A-51. Washington, DC: U.S. Department of Agriculture, National Agricultural Statistics Service. https://www.agcensus.usda.gov/Publications/2007/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf.

USDA NRCS. 2010. *2007 National Resources Inventory: Soil Erosion on Cropland.* Washington, DC: U.S. Department of Agriculture, Natural Resources Conservation Service. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_012269.pdf.

USDA NRCS. 2013a. *2007 National Resources Inventory: Wetlands.* Washington, DC: U.S. Department of Agriculture, Natural Resouces Conservation Service. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1117255.pdf.

USDA NRCS. 2013b. *Summary Report: 2010 National Resources Inventory.* Washington, DC, and Ames, IA: U.S. Department of Agriculture, Natural Resouces Conservation Service, and Iowa State University, Center for Survey Statistics and Methodology. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1167354.pdf.

WRP. 2013. *Wetlands Reserve Program (WRP): 2008 Farm Bill Report (FY 2009 Through FY 2012).* Washington, DC: U.S. Department of Agriculture, Natural Resources Conservation Service, Wetlands Reserve Program. www.nrcs.usda.gov/Internet/NRCS_RCA/reports/fb08_cp_wrp.html.

Appendix A: Data Sources Used for Land Retirement Applicable Acres Calculations

This appendix details the data sources, methods, and assumptions used to estimate the acres currently in (i.e., the baseline) and the acres that could be added to (i.e., the potentially applicable acres) each of the five land retirement options considered in this report.

Retire Organic Soils and Establish Conservation Cover

All cultivated organic soils identified in EPA (2012) are assumed to be available for retirement and conversion to grassy conservation cover for the purpose of reducing emissions of CO_2 related to the oxidation of organic soil carbon during field operations. The regional distribution of cultivated organic soils is shown in Table A-1.

Table A-1: Cultivated Organic Soils by Region as of 2010

USDA Region	Distribution by Region (acres)
Appalachia	107,796
Corn Belt	280,491
Delta	-
Lake States	570,681
Mountain	-
Northeast	35,699
Northern Plains	-
Pacific	124,196
Southeast	477,884
Southern Plains	-
Total	1,596,746

Source: EPA (2012).

Restore Riparian Forest Buffers

Applicable acres for restoring riparian forest buffers were based on State-level CRP data on acres in riparian forest in 2010, as well as data in the *2004 National Water Quality Inventory: Report to Congress* (EPA, 2009) and the 2007 National Resources Inventory (USDA NRCS, 2010). The *2004 National Water Quality Inventory: Report to Congress* (EPA, 2009) assessed the overall water quality of 16 percent of all rivers and streams in the United States (measured in miles). The report found that 6 percent of these rivers and streams are associated with an agricultural use. Applying this percentage to all 3.5 million miles of domestic rivers and streams implies that approximately 210,000 miles are associated with an agricultural use. Using a buffer of 35 feet on one bank, and assuming establishment of a forest buffer on all 210,000 miles suggests a technical potential for this practice to be applied on approximately 890,909 acres. As shown in Table A-2, the proportional distribution (percentage) of currently enrolled riparian buffers in each State is calculated by dividing the area of enrolled buffers in each State as of 2010 by the total area enrolled in riparian buffers throughout the country (870,297 acres). These percentages are multiplied by the potential applicability for riparian forest buffers (890,909 acres) in order to distribute the area according to baseline practices. For example, for Alabama applicability, 890,909 acres is multiplied by 3.87 percent (Alabama's enrollment in CRP as of 2010, as a portion of total U.S. enrollment for riparian buffers), which is equal to 34,478 additional acres of riparian buffers in Alabama.

Table A-2: Fiscal Year 2010 CRP Enrollment in Riparian Buffers and Total Applicable Acres for Riparian Forest Buffers

State	USDA Region	Riparian Buffers (acres)	Distribution by State	Applicable Acres per State[a]
Alabama	Southeast	33,660	3.87%	34,457
Arizona	Mountain	0	0%	-
Arkansas	Delta	61,036	7.01%	62,482
California	Pacific	12,669	1.46%	12,969
Colorado	Mountain	817	0.09%	836
Connecticut	Northeast	36	0.00%	37
Delaware	Northeast	114	0.01%	117
Florida	Southeast	64	0.01%	66
Georgia	Southeast	1,449	0.17%	1,483
Idaho	Mountain	7,168	0.82%	7,338
Illinois	Corn Belt	110,721	12.72%	113,343
Indiana	Corn Belt	5,843	0.67%	5,981
Iowa	Corn Belt	65,497	7.53%	67,048
Kansas	Northern Plains	3,932	0.45%	4,025
Kentucky	Appalachia	25,069	2.88%	25,663
Louisiana	Delta	5,401	0.62%	5,529
Maine	Northeast	160	0.02%	164
Maryland	Northeast	16,635	1.91%	17,029
Massachusetts	Northeast	5	0.00%	5
Michigan	Lake States	3,468	0.40%	3,550
Minnesota	Lake States	47,575	5.47%	48,702
Mississippi	Delta	165,202	18.98%	169,115
Missouri	Corn Belt	29,302	3.37%	29,996
Montana	Mountain	2,326	0.27%	2,381
Nebraska	Northern Plains	3,230	0.37%	3,306
New Hampshire	Mountain	15	0.00%	15
New Jersey	Northeast	230	0.03%	235
New Mexico	Northeast	5,280	0.61%	5,405
New York	Mountain	13,492	1.55%	13,812
North Carolina	Northeast	31,514	3.62%	32,260
North Dakota	Appalachia	557	0.06%	570
Ohio	Northern Plains	7,069	0.81%	7,236
Oklahoma	Corn Belt	1,519	0.17%	1,555
Oregon	Southern Plains	35,805	4.11%	36,653
Pennsylvania	Northeast	24,777	2.85%	25,364
South Carolina	Southeast	26,864	3.09%	27,500
South Dakota	Northern Plains	5,586	0.64%	5,718

State	USDA Region	Riparian Buffers (acres)	Distribution by State	Applicable Acres per State[a]
Tennessee	Appalachia	6,399	0.74%	6,551
Texas	Southern Plains	33,275	3.82%	34,063
Utah	Mountain	209	0.02%	214
Vermont	Northeast	2,359	0.27%	2,415
Virginia	Appalachia	23,977	2.76%	24,545
Washington	Pacific	23,051	2.65%	23,597
West Virginia	Appalachia	4,429	0.51%	4,534
Wisconsin	Lake States	16,552	1.90%	16,944
Wyoming	Mountain	5,959	0.68%	6,100
	Total	**870,297**	**100%**	**890,909**

[a] Based on total adoption potential of 890,909 acres and distributed based on 2010 CRP enrollment by State.

Source: USDA FSA (2010).

Establish Windbreaks

Regional CRP data on acres in field windbreaks and shelterbelts in 2010 were used to calculate regional percentages of the total acres enrolled. These percentages were then applied to the 2.2 million acres of U.S. cropland determined to be potentially applicable for establishing new windbreaks and shelterbelts. For example, as seen in Table A-3, 72,418 acres in the Northern Plains region are enrolled as CRP field windbreaks and shelterbelts. These acres represent 54.95 percent of total CRP acres in windbreaks and shelterbelts. Multiplying 2.2 million by 0.5495 yields an estimate of 1,208,826 acres of current cropland that could be shifted to windbreaks in the Northern Plains region.

Table A-3: CRP Enrollment per Region for Field Windbreaks and Shelterbelts, 2010, and Associated New Applicable Acres for Windbreaks

USDA Region	Current Enrollment (acres)	Distribution by Region[a]	Cultivated Land To Be Retired for Windbreaks (acres)[b]
Appalachia	85	0.06%	1,419
Corn Belt	18,184	13.80%	303,533
Delta	-	0.00%	-
Lake States	17,092	12.97%	285,305
Mountain	7,563	5.74%	126,244
Northeast	23	0.02%	384
Northern Plains	72,418	54.95%	1,208,826
Pacific	12	0.01%	200
Southeast	16,289	12.36%	271,901
Southern Plains	131	0.10%	2,187
Total	**131,797**	**100.00%**	**2,200,000**

[a]Percentage allocated to each region per 2010 CRP enrollment (USDA FSA, 2010).

[b]Total adoption potential based on the national estimate (2.2 million acres) provided by Sampson and Kamp (2005).

Sources: USDA FSA (2010) and Sampson and Kamp (2005).

Restore Wetlands

In this analysis, it is assumed that enrollment in the WRP could be doubled, from 2.65 million acres to 5.3 million acres. Based on data for palustrine wetlands as of 2007, it is also assumed that 70 percent of the additional restored wetlands would be forested and 30 percent would be grassy (USDA NRCS, 2013a). The restored wetland acres would be distributed as indicated in Table A-4.

Retire Marginal Soils and Establish Conservation Cover

By assumption, the MACC analysis limits the total quantity of cropland that can be retired for GHG mitigation purposes to 12.5 million acres (see the introduction to section on Land Retirement). After the areas of land shifting into the four land uses described above (i.e., organic soil retirement, riparian forest buffers, windbreaks, and wetlands restoration) are subtracted from the 12.5 million acres, the remaining 5.3 million acres are assumed to be cropland available for establishing conservation cover. These acres are allocated to the USDA production regions based on the each region's share of acres in New Grass Plantings on CRP lands in 2010 (USDA FSA, 2010). For example, of the 9.07 million acres of new grass plantings in the CRP, 12.35 percent are in the Corn Belt. Multiplying 5.3 million acres by 0.1235 yields 655,973 acres of cropland that are available for shifting to conservation cover in the Corn Belt. Distribution among the Farm Production Regions is shown in Table A-5.

Table A-4: WRP Enrollment From 2009 to 2012 and Potential Applicability for Restoring Forested and Grassy Wetlands

WRP Wetland Restoration by Region	WRP Wetlands (acres)[a]	Distribution by Region	Cultivated Land To Be Retired for Restoring Forested Wetlands (acres)[b]	Cultivated Land To Be Retired for Restoring Grassy Wetlands (acres)[b]
Appalachia	123,481	4.66%	86,436	37,044
Corn Belt	372,551	14.06%	260,786	111,765
Delta	680,040	25.66%	476,028	204,012
Lake States	222,471	8.40%	155,729	66,741
Mountain	88,256	3.33%	61,779	26,477
Northeast	111,339	4.20%	77,937	33,402
Northern Plains	303,058	11.44%	212,141	90,917
Pacific	218,870	8.26%	153,209	65,661
Southeast	368,587	13.91%	258,011	110,576
Southern Plains	161,243	6.08%	112,870	48,373
Total	**2,649,895**	**100.00%**	**1,854,927**	**794,969**

[a] Total acreage enrolled in WRP between 2009 and 2012 and active (as of 2013) is the basis for the total acreage potential by USDA Farm Production Region (WRP, 2013).

[b] The distribution between forested and grassy wetlands is calculated based on the 2007 NRI acreage estimates for palustrine wetlands, categorized as either palustrine emergent (grassy) or palustrine forested (Table 5, p. 20, in USDA NRCS, 2013). The 2007 NRI indicates about 72.5 percent forested and 27.5 percent emerging, which has been rounded to 70 percent and 30 percent here, respectively.

Sources: WRP (2013) and USDA NRCS (2013a).

Table A-5: Acres of Grassy Conservation Cover and Applicable Acres for Retiring Marginal Soils

USDA Region	Current Grassy Conservation Cover Enrollment (acres)	Distribution by Region	Retire Marginal Soils and Establish Conservation Cover (acres)[a]
Appalachia	181,556	2.00%	106,349
Corn Belt	1,119,863	12.35%	655,973
Delta	14,144	0.16%	8,285
Lake States	429,577	4.74%	251,630
Mountain	2,379,689	26.24%	1,393,931
Northeast	182,850	2.02%	107,107
Northern Plains	1,770,274	19.52%	1,036,959
Pacific	1,047,922	11.55%	613,833
Southeast	6,976	0.08%	4,086
Southern Plains	1,936,273	21.35%	1,134,194
Total	**9,069,124**	**100.00%**	**5,312,345**

[a] Based on total adoption potential of 5,312,345 acres and distributed based on 2010 CRP enrollment by State.

Source: USDA FSA (2010).

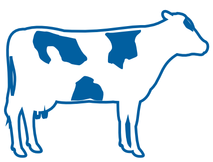
Appendix B: USDA Agricultural Resource Management Survey (ARMS) Data: U.S. Livestock Management Practices by Farm Size and Production Region, 2004–2009[10]

The data contained in Appendix B tables were derived from queries of data in the ARMS database. The queries were performed by ARMS specialists at USDA's Economic Research Service. The queries were coordinated by John Horowitz, with assistance from Robert Ebel, Nigel Key, and Kohei Ueda.

Tables B-1 and B-2 report GHG-relevant farming practices for manure handling systems for dairy and hog operations, by farm size and production region. All numbers are derived from ARMS. Several options were available for defining farm size. For dairy, the number of milk cows was used to measure farm size. For hogs, hundredweight gain was used. To define the categories for farm size, boundaries were selected that yielded roughly equal sample sizes and minimized non-disclosable cells. Cells are non-disclosable if there are too few observations resulting in data that could be linked to a specific operation. To improve statistical significance and minimize the number of non-disclosable cells, USDA regions that share similar production characteristics were aggregated.

Definition of Dairy and Hog Farm Sizes

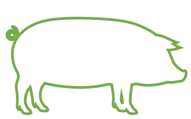
Dairies, 2005



For dairies, the number of milk cows for classifying farms by size are:

- Small: 99 or fewer milk cows
- Medium: 100–499 milk cows
- Large: 500 or more milk cows

Hogs, 2004



Because there are several types of hog farms, each specializing in raising animals in different life-cycle phases, hundredweight (cwt) gain was used to measure farm size. Hundredweight gain equals hundredweight of hogs sold or removed under contract less hundredweight of hogs purchased or placed under contract, plus hundredweight of inventory change during 2004. A finished hog weighs approximately 250 lbs or 2.5 cwt at slaughter.

- Small: 2,499 or less hundredweight gain (approx. 1,000 head of finished hogs)
- Medium: 2,500–12,499 hundredweight gain (approx. 10,000 head)
- Large: 12,500 (approx. 10,000 head) or more hundredweight gain

[10] The USDA Economic Research Service compiled this information in response to a request from the Office of the Chief Economist, Climate Change Program Office, in March 2011.

Table B-1: Percent of Dairy Farms Using Specific Types of Manure Storage Facilities, 2005

USDA Production Region	Open Storage	Covered Storage	Holding Pond	Single-Stage Lagoon	Two-Stage Lagoon	Open Manure Pit	Covered Manure Pit	Open Slurry or Manure Tank	Covered Slurry or Manure Tank
All	22	4*	8	8	3	29	5	3	2*
Small	23	4*	4*	3	1*	26	3	2*	1*
Medium	21	4	14*	16	4	36	10	8	4*
Large	22	5	23	21	20	28	5	5	A
Corn Belt	26	9*	7	9	#	32	7*	#	D
Small	29	11*	#	6*	#	27	6*	D	D
Medium	23*	7*	14*	14	#	41	8*	#	0
Large	D	d	33	15	18	33	10	15	0
Northeast and Lake States	17	3*	3*	3	0	30	4	3	#
Small	19*	#	D	#	0	26	2*	1*	D
Medium	12	3*	8*	10	#	42	11*	11	#
Large	7*	8*	13*	22*	9*	54	13	#	0
N. Plains and S. Plains	20	0	18*	31	23*	12*	0	D	D
Small	D	0	d	0	D	0	0	0	0
Medium	14*	0	#	37	21*	A	0	0	0
Large	21	0	27	24	31	21	0	D	D
App., South east, Delta	20	4*	a	14*	7*	30	5*	6*	0
Small	23	#	10*	11*	4*	28	5*	5*	0
Medium	15*	#	A	20*	#	34*	#	#	0
Large	21*	#	17	18*	49	18*	0	d	0
Mountain and Pacific	46	2*	29	24	14	22	8	4*	8
Small	62	0	33	20*	#	27*	#	D	13*
Medium	44	3*	28	28	14*	22	13*	5*	8*
Large	30	3*	27	22	23	15	2*	3*	d

Source: Economic Research Service calculations are from USDA ARMS. Coordinated by John Horowitz, with assistance from Robert Ebel, Nigel Key, and Kohei Ueda. Coefficient of Variation (CV) = (Standard Error/Estimate) x 100. '*' indicates that CV is greater than 25 and less than or equal to 50.' #' indicates not disclosed because the CV is greater than 50 and less than or equal to 75. 'a' indicates not disclosed because CV is above 75. 'd' indicates not disclosed for legal reasons.

Table B- 2: Percent of Hog Farms Using Specific Types of Manure Storage Facilities, 2004

USDA Production Region	Holding Pond	Single-Stage Lagoon	Two-Stage Lagoon	Manure Pit Under Building	Other Manure Pits	Slurry or Manure Tank (Open)	Slurry or Manure Tank (Closed)
All	5	13	4	35	8	2*	#
Small	2	5	#	14*	8	2*	d
Medium	6*	19	8*	66	11	1*	d
Large	14*	31*	7	60	5*	6*	a
Corn Belt	5*	9	4*	51	12	5*	#
Small	1*	4*	#	25	13	#	d
Medium	6*	15*	5*	69	14	#	d
Large	15*	11	6*	85	#	11*	d
Northeast and Lake States	A	#	#	50*	11*	1*	0
Small	A	D	d	a	A	D	0
Medium	D	#	d	93	12*	#	0
Large	D	#	#	92	d	d	0
N. Plains and S. Plains	5*	*	#	21	6*	d	d
Small	#	10*	d	10*	7*	0	0
Medium	d	30	#	48	#	0	0
Large	a	62*	#	#	d	d	d
App., Southeast, Delta	15	57	10	4*	d	#	d
Small	12*	19*	#	7*	d	#	d
Medium	14*	70	*	a	d	d	0
Large	18*	75	*	a	0	0	0
Mountain and Pacific	0	0	d	d	0	0	d
Small	0	0	d	0	0	0	d
Medium	d	d	d	d	d	d	d
Large	NA	NA	NA	NA	NA	NA	NA

Source: Economic Research Service calculations are from USDA ARMS. Coordinated by John Horowitz, with assistance from Robert Ebel, Nigel Key, and Kohei Ueda. Coefficient of Variation (CV) = (Standard Error/Estimate) x 100. '*' indicates that CV is greater than 25 and less than or equal to 50.' #' indicates not disclosed because the CV is greater than 50 and less than or equal to 75. 'a' indicates not disclosed because CV is above 75. 'd' indicates not disclosed for legal reasons. 'NA' indicates that the estimate is not available.

Appendix C: USDA Agricultural Resource Management Survey (ARMS) Data: U.S. Crop Management Practices by Farm Size and Production Region, 2009–2012[11]

The data contained in Appendix C tables were derived from queries of data in the ARMS database. The queries were coordinated by Roger Claassen at the USDA Economic Research Service at the request of the USDA Climate Change Program Office.

The following tables provide crop acreage and tillage shares by crop, USDA Farm Production Region, and both crop and region. The data are from the ARMS Production Practices and Costs Report for wheat in 2009, corn in 2010, barley and sorghum in 2011, and soybeans in 2012. These field-level surveys provide data on no-till for up to four consecutive years on the surveyed field.

No-till in survey year: For spring-planted crops, a field is considered to be in no-till if it had zero tillage operations and the survey respondent reported using no-till or did not plant a crop the previous fall. For winter wheat, a field is considered to be in no-till if it has zero tillage operations prior to planting wheat and reports using no-till or does not plant a crop in the following spring/summer. This definition includes some fields that are not tilled but have less than 30 percent crop residue at planting. Exclusion of fields with less than 30 percent residue coverage would reduce estimated no-till by approximately 3 million acres over all crops and years (4 percent of acres represented by the survey).

No-till history: Survey respondents report whether no-till was used in each season of the 3 years prior to the survey year.

Tables C-1 through C-3 show total acreage covered for each crop-specific survey, the share of acres that were (1) no-till in the survey year (NT); (2) no-till continuously for 4 years (CNT); (3) no-till for 1–3 years prior to the survey year (Alt Till); and (4) tilled in all 4 years (Till). Therefore, these estimates are based on a subsample that only contains observations where tillage practices can be identified for all 4 years (197 million acres; 93 percent of acres represented by the survey).

Because the ARMS Production Practices and Costs Survey is crop-specific and the survey sample is based on a subset of States that represent 90–95 percent of production for the survey crop, regional results will not be representative of all crops or all States within the region. Table C-4 shows States that were included in each of the seven surveys used.

Table C-1: Tillage Adoption Rates by Crop

Year	Crop	Total Acres Represented in Survey	NT Share	4-Year Tillage Category		
				CNT	Alt Till	Till
2009	Wheat, Durum	2,107,614	79.8%	62.3%	28.0%	9.7%
2009	Wheat, Spring	12,424,513	44.4%	33.7%	23.1%	43.3%
2009	Wheat, Winter	33,327,702	35.7%	17.8%	45.1%	37.1%
2010	Corn	75,426,148	24.7%	17.4%	29.1%	53.5%
2011	Barley	2,044,097	34.6%	26.7%	30.5%	42.9%
2011	Sorghum	4,465,529	53.5%	35.4%	25.7%	38.9%
2012	Soybeans	67,288,419	38.1%	23.5%	31.3%	45.2%

[11] The USDA Economic Research Service compiled this information in response to a request from the Office of the Chief Economist, Climate Change Program Office, in January 2014.

Table C-2: Tillage Adoption Rates by Farm Production Region

Farm Production Region	Total Acres Represented in Survey	NT Share	4-Year Tillage Category		
			CNT	Alt Till	Till
Appalachian	6,304,363	66.7%	47.0%	35.6%	17.4%
Corn Belt	67,925,792	31.3%	18.5%	31.3%	50.2%
Delta States	5,686,788	13.2%	6.8%	16.1%	77.1%
Lake States	25,631,863	14.0%	8.1%	28.8%	63.1%
Mountain	10,928,755	50.0%	33.1%	48.4%	18.5%
Northeast	2,208,822	42.3%	28.2%	45.7%	26.1%
Northern Plains	60,407,504	43.8%	29.9%	33.4%	36.7%
Pacific	3,036,179	22.6%	9.6%	69.2%	21.2%
Southeast	266,180	35.5%	22.4%	41.8%	35.8%
Southern Plains	14,687,777	20.4%	12.2%	19.2%	68.7%

Table C-3: Tillage Adoption Rates by Crop and Farm Production Region

Crop	Farm Production Region	Total Acres Represented in Survey	NT Share	4-Year Tillage Category		
				CNT	Alt Till	Till
Wheat, Durum	Mountain	526,367	76.2%	53.8%	35.7%	10.6%
	Northern Plains	1,581,246	81.0%	65.2%	25.5%	9.4%
	Lake States	1,475,607	3.0%	N/A	11.6%	87.7%
Wheat, Spring	Mountain	2,684,207	59.3%	46.1%	34.5%	19.4%
	Northern Plains	7,611,477	49.1%	37.8%	19.7%	42.5%
	Pacific	653,221	21.8%	8.7%	42.0%	49.3%
Wheat, Winter	Corn Belt	2,456,858	61.4%	16.4%	61.1%	22.5%
	Lake States	627,805	65.4%	19.0%	57.9%	23.1%
	Mountain	5,123,349	45.9%	29.6%	60.1%	10.3%
	Northern Plains	12,035,504	37.4%	17.5%	51.1%	31.4%
	Pacific	2,179,113	23.9%	10.0%	79.5%	10.4%
	Southeast	10,905,073	23.8%	14.5%	20.1%	65.3%
Corn	Appalachian	2,054,557	52.9%	41.6%	34.2%	24.2%
	Corn Belt	35,366,920	17.8%	13.6%	25.6%	60.8%
	Lake States	13,075,096	12.3%	8.8%	28.6%	62.6%
	Mountain	1,171,768	49.4%	N/A	55.7%	29.2%
	Northeast	2,151,492	42.3%	28.1%	45.8%	26.1%
	Northern Plains	19,188,931	41.0%	28.1%	33.0%	39.0%
	Southeast	266,180	35.5%	22.4%	41.8%	35.8%
	Southern Plains	2,151,204	8.5%	N/A	19.0%	78.4%

Crop	Farm Production Region	Total Acres Represented in Survey	NT Share	4-Year Tillage Category		
				CNT	Alt Till	Till
Barley	Appalachian	79,426	56.5%	49.2%	40.3%	N/A
	Lake States	97,760	2.5%	0.0%	28.4%	71.6%
	Mountain	1,240,709	36.0%	27.6%	27.7%	44.7%
	Northeast	57,330	43.0%	32.6%	40.2%	N/A
	Northern Plains	365,028	44.9%	35.2%	27.9%	36.9%
	Pacific	203,844	11.7%	8.2%	46.0%	45.8%
Sorghum	Mountain	182,355	50.1%	32.4%	55.5%	12.1%
	Northern Plains	2,651,675	78.5%	51.8%	31.4%	16.7%
	Southern Plains	1,631,500	13.3%	8.9%	13.1%	78.0%
Soybeans	Appalachian	4,170,380	73.7%	49.6%	36.2%	14.2%
	Corn Belt	30,102,014	44.8%	24.5%	35.6%	39.9%
	Delta States	5,686,788	13.2%	6.8%	16.1%	77.1%
	Lake States	10,355,594	14.7%	7.9%	29.7%	62.5%
	Northern Plains	16,973,644	40.1%	30.5%	28.6%	40.9%

N/A indicates that the estimates are not available because there are too few observations to report or the coefficient of variation is greater than 50 percent.

Table C-4: Surveyed States

State	Wheat, Durum 2009	Wheat, Spring 2009	Wheat, Winter 2009	Corn 2010	Barley 2011	Sorghum 2011	Soybeans 2012
Arizona	-	-	-	-	Y	-	-
Arkansas	-	-	-	-	-	-	Y
California	-	-	-	-	Y	-	-
Colorado	-	Y	Y	Y	Y	Y	-
Georgia	-	-	-	Y	-	-	-
Idaho	Y	Y	Y	-	Y	-	-
Illinois	-	-	Y	Y	-	-	Y
Indiana	-	-	-	Y	-	-	Y
Iowa	-	-	-	Y	-	-	Y
Kansas	-	-	Y	Y	-	Y	Y
Kentucky	-	-	-	Y	-	-	Y
Louisiana	-	-	-	-	-	-	Y
Michigan	-	-	Y	Y	-	-	Y
Minnesota	-	Y	Y	Y	Y	-	Y
Mississippi	-	-	-	-	-	-	Y
Missouri	-	-	Y	Y	-	-	Y
Montana	Y	Y	Y	-	Y	-	-
Nebraska	-	-	Y	Y	-	Y	Y
New York	-	-	-	Y	-	-	-
North Carolina	-	-	-	Y	-	-	Y
North Dakota	Y	Y	Y	Y	Y	-	Y
Ohio	-	-	Y	Y	-	-	Y
Oklahoma	-	-	Y	-	-	Y	-
Oregon	-	Y	Y	-	Y	-	-
Pennsylvania	-	-	-	Y	Y	-	-
South Dakota	Y	Y	Y	Y	-	Y	Y
Tennessee	-	-	-	-	-	-	Y
Texas	-	-	Y	Y	-	Y	-
Virginia	-	-	-	-	Y	-	Y
Washington	-	Y	Y	-	Y	-	-
Wisconsin	-	-	-	Y	Y	-	Y
Wyoming	-	-	-	-	Y	-	-

'Y' indicates stat included in survey.

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