Charting a Path to Carbon Neutral Agriculture

Mitigation Potential for Crop Based Strategies

June 2016

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1. Introduction

Over the past few years, the United Nations Framework Convention on Climate Change (UNFCCC) has paid increased attention to businesses as a source of resources and expertise to help address climate change. In particular, the Road to Paris, (launched November, 2014 at the World Climate Summit at the 19th Conference of the Parties to the UNFCCC (COP19) in Warsaw, Poland) has called upon businesses and others to help create a bottom-up public/private initiative to provide solutions that countries can adopt at COP 21 (December, 2015 in Paris, France). According to the IPCC (Smith et al., 2014), 24% of global anthropogenic GHG emissions are from deforestation and agricultural emissions from livestock, soil, and nutrient management. Reducing anthropogenic greenhouse gas (GHG) emissions in the AFOLU sector is essential in meeting the goal of mitigating emissions and minimizing climate change globally. With this study, *Charting a Path to Carbon Neutral Agriculture: Mitigation Potential for Crop Based Strategies*, ICF is assessing the potential of four Crop Based Strategies (CBS) to support achievement of the World Business Council for Sustainable Development's (WBCSD) *2050 Vision* goals of increasing crop yields, increasing carbon sequestration in soils, and improving use of plant materials (WBCSD, 2015b) as well as their goal of working toward carbon neutrality in harvesting biomass (WBCSD, 2015a).

1.1. Greenhouse Gas Emissions from Agriculture

Greenhouse gas emissions from agriculture made up 7.7 percent of all U.S. greenhouse gas (GHG) emissions in 2013 (EPA, 2015a). Exhibit 1 presents the historical GHG emissions from agricultural sources, from the 2014 U.S. Greenhouse Gas Inventory. These values exclude estimates associated with the production of products such as nitric acid and ammonia production. As indicator of the GHG associated with agriculture inputs, we present the emissions associated with nitric acid, and ammonia production as provided in Chapter 4 of the GHG Inventory, titled *Industrial Processes and Product Use*. The other agricultural emissions values are from Chapter 5, titled *Agriculture*. Nitrous oxide (N_2O) emissions from agricultural soil management made up the largest portion of agricultural emissions, followed by methane (CH_4) emissions from enteric fermentation (EPA, 2015a). According to the U.S. 2014 Climate Action Report (U.S. Department of State, 2014), nitrous oxide accounted for approximately 5 percent of the total U.S. GHG emissions in 2011, mainly coming from agricultural soil management and stationary fuel combustion (2014 Climate Action Report).

Exhibit 2 presents projected values for U.S. GHG emissions from agriculture as provided in the U.S. Climate Action Report. The Climate Action Report gives projected estimates for future GHG emissions that reflect national estimates and consider factors such as population growth, economic growth potential, historic rates of technology improvement, and normal weather patterns (U.S. Department of State, Climate Action Report, 2014). The projections are based on expected trends from technology deployment and adoption, demand-side efficiency gains, fuel switching, and U.S. policies and measures that will address GHG emissions (U.S. Department of

State, Climate Action Report, 2014). These projections provide indication of expected emissions under current policies and other factors; they do not take into account the vast impact that could be made by various actions undertaken by the private sector and the agricultural sector specifically, including those strategies discussed in this report.

Exhibit 1: U.S. GHG Emissions from Agricultural Sources (MMT CO_2-eq)[a]

Source	1990	2005	2009	2010	2011	2012	2013
Nitrous Oxide from Soil Management	224.0	243.6	264.1	264.3	265.8	266.0	263.7
Methane from Enteric Fermentation	164.2	168.9	172.7	171.1	168.7	166.3	164.5
Methane from Manure Management	37.2	56.3	59.7	60.9	61.4	63.7	61.4
Nitrous Oxide from Manure Management	13.8	16.4	17.0	17.1	17.3	17.3	17.3
Total Agricultural Emissions (Excluding ammonia and nitric production)	**448.7**	**494.5**	**523.3**	**524.8**	**522.1**	**523.0**	**515.7**
Nitrous Oxide from Nitric Acid Production	12.1	11.3	9.6	11.5	10.9	10.5	10.7
Carbon Dioxide from Ammonia Production	13	9.2	8.5	9.2	9.3	9.4	10.2

[a]Source: EPA (2015b, a).

Exhibit 2: Projected U.S. Greenhouse Gas Emissions: 2015-2030 (Tg CO_2-eq)[a]

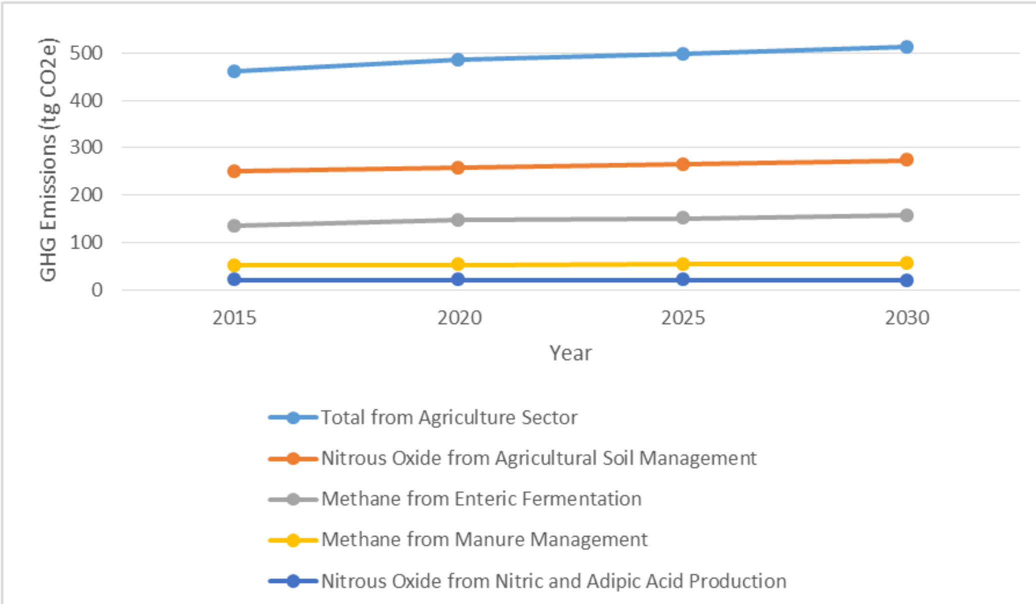
Source	2015	2020	2025	2030
Total from Agriculture	461	485	498	512
Nitrous Oxide (N2O) – Agricultural Soil Management	250	258	265	273
Methane (CH4) – Enteric Fermentation	135	147	151	157
Methane (CH4) – Manure Management	52	53	54	55
Nitrous Oxide (N2O) – Nitric and Adipic Acid Production	21	21	21	20

[a]Source: United States Climate Action Report 2014 (U.S. Department of State, 2014).

The values shown in the table above (Exhibit 2) are also displayed in the following graph (Exhibit 3). The top line in the graph below shows the total projected emissions from the agriculture sector, while the rest of the lines break down the agricultural total into its various sources (U.S. Department of State, 2014).[1]

[1] Projections of additional GHGs associated with the agricultural sector (e.g., ammonia production) are not available in the Climate Action Report, hence, the breakdown of sources in Exhibit 3 is not representative of all the GHGs associated with agriculture.

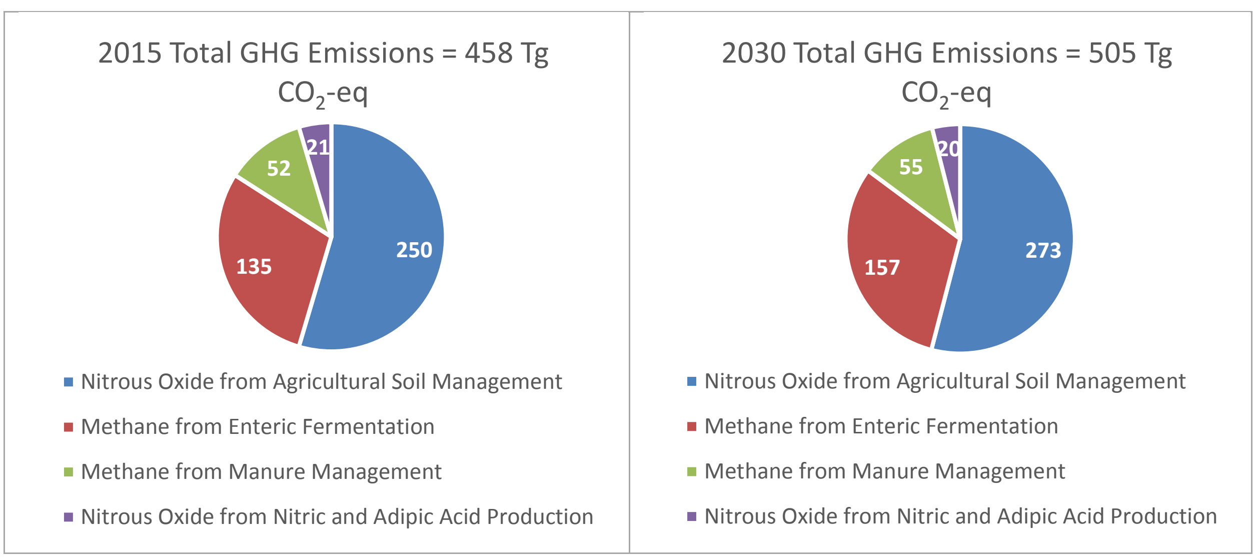
Exhibit 3: Projected U.S. Greenhouse Gas Emissions, Agricultural Sources



Source: United States Climate Action Report 2014 (U.S. Department of State, 2014).
Note: Adipic acid production is not related to fertilizer production, however, it's indicated as the Climate Action Report combined the estimates for nitric and adipic acid production.

The two pie charts below (Exhibit 4) show the projected breakdown of agricultural GHG emissions by specific sources, both in 2015 and 2030. Based on current management practices, agricultural sources of GHG emissions are expected to grow over the next 15 years, and nitrous oxide from agricultural soil management will remain the greatest source of GHG emissions from agriculture.

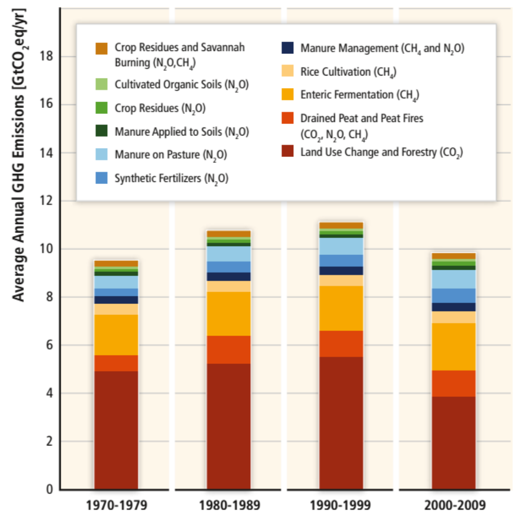
Exhibit 4: Projected U.S. Greenhouse Gas Emissions by Agricultural Source (Tg CO_2-eq)



Global Agriculture Emissions

According to the IPCC's Fifth Assessment Report (AR5), Agriculture, Forestry, and Other Land Use (AFOLU) activities can lead to non-CO_2 emissions primarily from agriculture, including methane from livestock and rice cultivation and nitrous oxide from manure storage, agricultural soils, and biomass burning (Smith et al., 2014). Exhibit 5, shows the breakdown of global GHG emissions from AFOLU, illustrating the relatively large contribution from enteric fermentation and other management practices (including fertilizers and manure management).

Exhibit 5: Global GHG Emissions from AFOLU



Source: Smith et al. (2014).

1.2. Purpose of This Study

The purpose of our study is to evaluate the mitigation potential for four alternative crop-based management strategies. We assessed the mitigation potential for the key life-cycle greenhouse gases (GHGs)—carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4)—in the United States. We summarize our findings of national mitigation potential based on projections of crop-based agricultural activities in 2020, 2030, 2040, and 2050.

The results of our findings will support the global dialogue on the most feasible methods for reducing emissions from crop production and also offsetting fossil fuel emissions by using biofuels in a financially viable manner that maintains or increases productivity for farmers.

ICF evaluated four CBSs for this study:

- CBS 1: Sustainable Nutrient Management (Reduce Direct and Indirect Emissions)
- CBS 2: Sustainable Tillage and Cover Crops (Reduce Direct and Indirect Emissions and Sequester Carbon)
- CBS 3: Produce Ethanol from Corn and Corn Stover to Offset Fossil Fuel Emissions in the Transportation Sector
- CBS 4: Optimize the Use of Excess Crop Residues (Offset Fossil Fuel Emissions)

Each of these CBSs is summarized below.

CBS 1: Sustainable Nutrient Management (Reduce Direct and Indirect Emissions)

Precision agriculture uses “big data” from a suite of farm-level information technologies—including Global Positioning System (GPS) maps, guidance systems, such as sprayer nozzles and boom controls, and application and site-specific monitoring and management, such as yield monitors and variable-rate application technologies (VRT)—to ensure accurate and precise farming. Use of precision agriculture is associated with reduced input use (including fertilizers and pesticides), resulting in both less on-farm GHG emissions and reduced upstream emissions (from reduced fertilizer and pesticide demand). Despite these benefits, adoption of precision agriculture has been mixed in the United States. According to a 2011 USDA ERS report (Schimmelpfennig and Ebel, 2011) based on 10-years of USDA ARMS survey data, yield monitors have been rapidly adopted by grain crop growers, whereas GPS maps and VRT technologies have suffered an adoption lag. Increased domestic adoption of precision agriculture will mitigate both direct and indirect GHG emissions. Similarly, increased domestic adoption of nitrification and urease inhibitors will also mitigate both direct and indirect GHG emissions by reducing nitrogen loss and decreasing quantity of applied fertilizers.

CBS 2: Sustainable Tillage and Cover Crops (Reduce Direct and Indirect Emissions and Sequester Carbon)

In addition to the mitigation options discussed above, the IPCC WG3, AR5 (Smith et al., 2014) cites reducing carbon losses from agricultural managed soils (i.e., by changing management practices) as another opportunity to reduce GHG emissions in the AFOLU sector. Tillage of soil increases the mineralization of soil organic carbon (SOC) to carbon dioxide (CO_2); a strong correlation exists between the intensity and the volume of soil disturbed and the amount of SOC lost as CO_2. With conventional tillage resulting in less than 15 percent of crop residue cover remaining, conservation tillage (reduced tillage or no-tillage) is a production method that can reduce carbon losses in agricultural managed soils. Cover-crop rotations (crops that are planted with the primary goal of managing soil quality) are another production method that can reduce CO_2 emissions, as are changing crop rotations. In addition, cover crops can be used in no-till systems to further improve the soil quality and further increase carbon sequestration, depending on the specific conditions. According to USDA ERS, in 2009, no-till accounted for 35 percent of U.S. cropland planted with the eight major commodity crops, where adoption varied substantially across crops. Increased adoption of reduced tillage practices will increase carbon sequestration and reduce GHG emissions associated with on-site fuel use from mobile sources and associated indirect emissions. ICF evaluated adoption of reduced tillage and use of cover crops.

CBS 3: Produce Ethanol from Corn and Corn Stover to Offset Fossil Fuel Emissions in the Transportation Sector

In the United States, the majority of biofuel (i.e., ethanol) is primarily produced from the starch in corn grain. Cellulosic ethanol, which is produced from cellulosic feedstocks (e.g., corn stover), further improves the energy balance of ethanol, and results in lower levels of life-cycle GHG emissions. Most corn producers in the United States have experienced increased yields over the last 10–15 years, which have resulted in higher levels of corn stover residing in fields. Residue management strategies, such as partial stover collection, reduce the problems of excess residue, maintain the minimum amount needed for soil health and productivity, and make corn and ethanol production more sustainable. This strategy focuses on the feasibility of commercially producing "hybrid ethanol" from both grain- and residue-derived sugars and the relative net GHG emissions compared to fossil fuels.

CBS 4: Optimize the Use of Excess Crop Residues (Offset Fossil Fuel Emissions)

In the United States, two additional options that appear promising for optimizing the use of excess crop residues are: (1) co-firing excess residue in coal fired power plants, and (2) processing excess residues into biochar for use as a soil amendment. Co-firing excess residue has the potential to offset a proportion of the coal needed to meet current (and future) energy demand, and biochar production has the potential to provide long-term sequestration of carbon (and provide energy from the combustion of the co-product syngas and bio-oil). The potential of both of these technologies depends to a great extent on the technological feasibility of these strategies. For example, the percent of residue that can be effectively co-fired without reducing the combustion efficiency of an Electric Generating Unit (EGU) or significantly increasing the ash yield; or the type of pyrolysis (e.g., high heat fast or low heat slow) can affect the resulting yield and characteristics of biochar.

Our study is based on readily available data, including publicly available data sets and published research findings. We did not conduct detailed modeling of agronomic impacts of alternative crop management strategies or economic modeling on impact of changes in prices with supply and demand of crops.

1.3. Organization of this Report

The remainder of this report is organized into six chapters:

Chapter 2: Methodology. This chapter presents the analytical frameworks used for conducting a life cycle analysis of the net change in implementing a crop based management strategy, estimating adoption potential, and for conducting a sensitivity analysis of the national abatement potential.

Chapter 3: CBS 1: Sustainable Nutrient Management. This chapter presents the technologies and associated emission reductions for application of nitrogen and urease inhibitors, variable rate technology, and use of swath control for fertilizer application.

Chapter 4: CBS 2: Sustainable Tillage and Cover Crops. This chapter presents the technologies and associated emission reductions for transitioning from conventional tillage (CT) to reduced till (RT) and no-till (NT), from reduced till (RT) RT to no-till (NT), and for the addition of winter cover crops.

Chapter 5: CBS 3: Produce Ethanol from Corn and Corn Stover to Offset Fossil Fuel Emissions in the Transportation Sector. This chapter presents the concepts for an integrated corn-corn stover ethanol plant. The emission reductions for producing ethanol are presented. Given the life-cycle analysis of net change in GHG emissions, the net change in downstream GHG emissions from ethanol use is included in the analysis.

Chapter 6: CBS 4: Optimize the Use of Excess Crop Residues (Offset Fossil Fuel Emissions). In this chapter, we evaluate two technologies: (i) pyrolysis of corn stover into biochar and the resulting field application of the biochar; and (ii) co-firing residue for electricity generation. The emission reductions for these two technologies are presented. Given the life-cycle analysis of net change in GHG emissions, the net change in downstream GHG emissions from fuel use is included in the analysis.

Chapter 7: Summary of Findings. In this final chapter, we summarize the mitigation potential across the CBSs 1 to 4.

1.4. References

EPA. 2015a. *Inventory of U.S. greenhouse gas emissions and sinks: 1990-2013: Chapter 5: Agriculture*. Washington, D.C.: Environmental Protection Agency. https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport/archive.html.

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2. Methodology

ICF conducted a life cycle assessment to estimate the change in greenhouse gas emissions associated with the adoption of alternative crop based management strategies. Our data sources are based on a review of the literature and publicly available data sets.[2] We cite them throughout each of the chapters that summarize our approach to evaluating each of the crop based management strategies. This section presents our framework for the life cycle assessment of GHGs, estimating adoption potential, and conducting the sensitivity analysis.

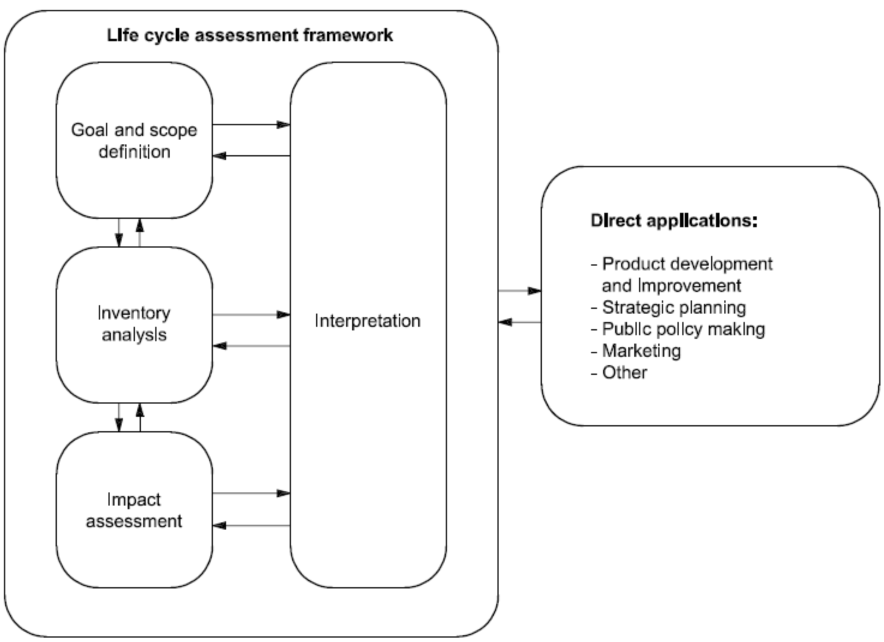
2.1. GHG Life Cycle Assessment (LCA) Framework

This section outlines the framework used to assess life-cycle GHG emission reductions from four of the CBSs (CBS 1 to 4). It explains the International Organization for Standardization (ISO) 14044 standard[3] for LCA and how ICF implemented it for this assessment.

LCA is an analytical technique designed to address "the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal" (ISO, 2006). ISO 14044 describes the process necessary for developing an LCA study.

Exhibit 6 presents the framework for conducting LCAs established by ISO 14044. The first phase, goal and scope, establishes the overall objective of the assessment and specifies how a study is designed, including the life-cycle boundaries and level of detail. The findings must be robust to the goal of the study.

Exhibit 6: ISO 14040 LCA Framework



Source: ISO (2006).

The second step, life cycle inventory analysis,

[2] We did not conduct detailed agronomic or economic modeling for our study.
[3] Environmental management – Life cycle assessment – Principles and framework

involves collecting information on the inputs, outputs, and flows between each of the processes across a product's life cycle.

The third step, impact assessment, assesses the impacts of the environmental burdens (for example, GHG emissions) across the life cycle. This typically involves characterizing individual emissions or releases and putting them on an equivalent basis with other emissions based on their contribution to environmental impacts such as global warming, air pollution, and human health impacts.

At the interpretation step, the results of the study are analyzed to draw findings and conclusions. Interpretation may involve identifying issues of concern or opportunities for reducing environmental impacts. Results can be validated at this stage by using sensitivity analysis, consistency checks, or uncertainty analysis.

This chapter explains steps in the ISO 14044 framework, including: the goal and scope of the analysis (Section 2.1.1) and development of a life-cycle inventory (Section 2.1.2). Interpretation and the application of these results are discussed in the individual CBS chapters.

2.1.1. Goal and Scope

An LCA is defined and structured around the goal and scope of the study. According to ISO 14044, the goal of an LCA should state the intended application of the study, the reasons for carrying out the study, and the intended audience. The breadth and depth of LCAs can vary, but a study must ensure that the level of detail and scope of the study sufficiently address the goal of the assessment.

The goal of this study is to analyze first-order, upper-bound GHG mitigation potential for different crop based-strategies for 2020, 2030, 2040, and 2050. ICF is carrying out this study to improve the understanding of the effectiveness of different strategies for reducing GHG emissions and to provide an upper-bound estimate of the mitigation potential for on-farm and life-cycle GHG emission reductions.

Based on this goal, ICF has defined the following key elements of the LCA scope:

- **Function of product system(s)** – The "product system" in this study encompasses the inputs, on-farm practices, and outputs from producing crops for food or fuel. For CBS 1, Precision Agriculture, and CBS 2, Conservation Tillage and Cover Crops, the product system's function is produce crops for food. In CBS 3, Produce Biofuel with Excess Grain and Agricultural Residue (Offset Fossil Fuel Emissions) , and CBS 4, Optimize the Use of Excess Crop Residues, the functions of the product systems are to produce biofuels (for CBS 3) and to produce biochar for use as soil amendment and produce energy using excess crop residues.
- **Functional unit –** The functional unit is a unit of measure that represents the function of the system; it is used as a common basis for expressing the life-cycle impacts for that system

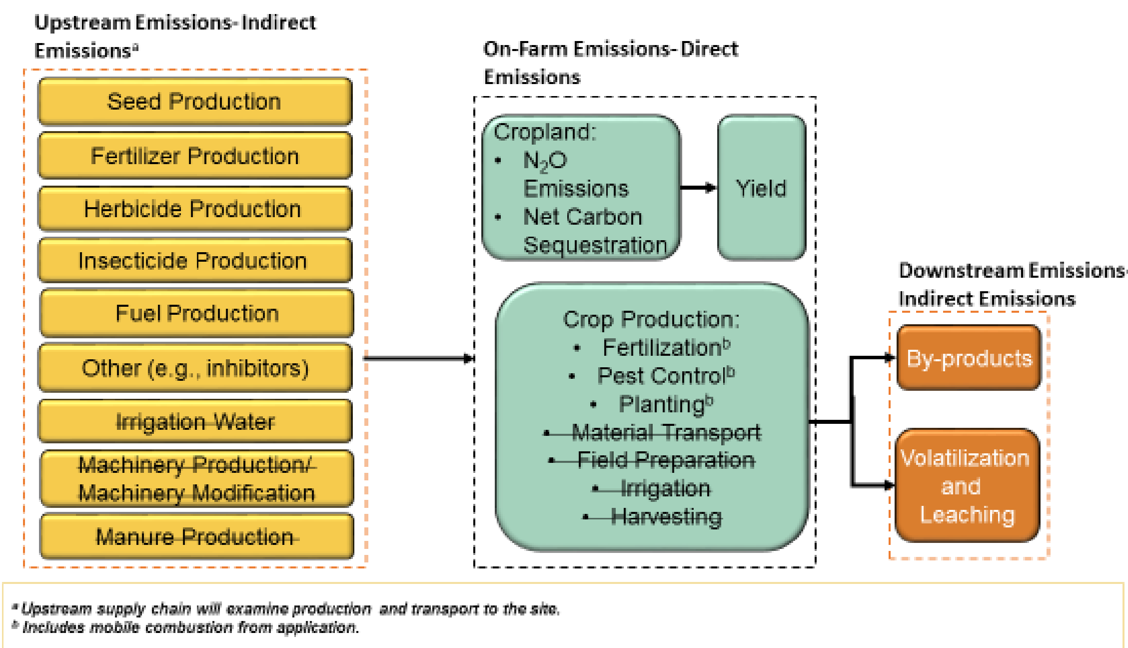
(e.g., in agricultural systems, the functional unit could be "kilograms crop produced," or "acre of land farmed"). The functional unit varies depending on the product system of each CBS. For CBS 1 and CBS 2, the functional unit is acres of cropland farmed (e.g., per acre of cropland). For CBS 3 and CBS 4, the functional unit is fuel or energy production (e.g., per liter of ethanol, megajoule of fuel, or kilowatt-hour of electricity).

- **System boundary –** The system boundary defines the inputs, outputs, flows, and processes that we modeled for estimating net change in life-cycle GHG emissions upon adoption of the CBSs. See below for more details on the system boundary.
- **Allocation procedures –** Allocation procedures define how GHG emissions from a process are allocated to different co-products in a study. ISO 14044 recommends avoiding allocation by expanding the system to include functions related to the co-products. However, ICF used this "system expansion" approach for electricity co-products from [ethanol] and biochar, which are sold to the grid and displace other forms of generation.
- **Impact categories and methodology –** ICF assessed the global warming potential using IPCC's Fourth Assessment Report (AR4) Global Warming Potentials (GWP) and expressed the results in units of metric tons of carbon dioxide-equivalents ($MTCO_2$-eq) per functional unit. We evaluated three greenhouse gases: carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4).
- **Data requirements –** The data requirements vary by CBS and are provided in each CBS chapter.
- **Assumptions** – The assumptions for each CBS's boundaries, data requirements, and other elements of the scope are provided in each CBS chapter.

The conceptual system boundaries of this study are shown in Exhibit 7 below. The life-cycle stages are split into three main categories: upstream (i.e., process and operations needed to produce the inputs and deliver them to the farm gate), on-farm (i.e., process, operations, and emissions sources on the farm), and downstream (e.g., transportation to market, waste management, end-processing or conversion of crops into other products such as biofuels, biochar, or electricity).

Since the goal of the study is to determine the GHG reduction potential of the CBSs, we are interested in the change in GHG emissions between current baseline practices and adoption of the CBSs. As a result, we compare two different systems—one with baseline practices, and one with the CBS applied—each with consistent life cycle boundaries to measure the change in emissions (or "Δ emissions"). Any emission sources that remain the same in the two systems—i.e., sources that are not affected by adoption of the CBS—do not result in a change in GHG emissions and are not considered. For example, we assumed that the end use of the crops will not be affected by adoption of CBS 2 and CBS 3 and exclude any later downstream stages from the analysis. The specific sources considered for each CBS are described in each CBS chapter below. For our study, changes in direct GHG emissions are those resulting on-site (e.g., cropland being managed for CBSs 1 and 2, ethanol and coal-fired plant for CBS 3 and 4). Changes in indirect GHG emissions are those resulting from production of inputs (e.g., fertilizer, herbicides, insecticides, seeds, inhibitors) and fuel (i.e., diesel) or volatilization or leaching of N_2O. For on-site crop production, the on-site source of GHGs from fertilization, pest control, and planting is combustion of fuels from equipment use.

Exhibit 7: Conceptual Diagram of System Boundaries Used in This Study



2.1.2. Life Cycle Inventory Analysis and Data Sources

This section presents the life-cycle GHG factors for production of upstream input products, fuels, and transportation processes. In particular, the factors for the following common products and processes are presented:

- Seeds
- Fertilizers
- Nitrification and urease inhibitors
- Pesticides
- Transportation
- Machinery
- Fuel production and combustion

- Regional electricity

Life cycle inventory data for on-farm practices and ethanol production, pyrolysis, and co-firing processes (for CBS 3 and CBS 4) are presented in the individual CBS chapters.

Seeds

We obtained emission factors for eight seed types: six of the seed factors were for cash crops and two were for cover crops. The emission factors represent GHG emission from "cradle" (i.e., raw inputs from nature) to delivery at the farm gate and are based on US life cycle inventory database (National Renewable Energy Laboratory, 2012). The emission factors for rapeseed seed, soybean seed, wheat seed, rye seed, clover seed, pea seed, and grass seed are based on 2010 data; the emission factors for barley are based on 2008 data and factors for corn are based on 2009 data (National Renewable Energy Laboratory, 2012).

Exhibit 8: Seed Emission Factors (kg of gas/unit of product)

Crop Type	Seed Type	Units	Emission Factor (kg of gas/unit of product)			
			CO_2	CH_4	N_2O	CO_2-eq
Cash Crop	Barley Seed	kg gas/kg seed	0.1428	0.0002	0.0008	0.4
	Corn Seed	kg gas/kg seed	0.7113	0.0008	0.0037	1.8
	Rapeseed Seed	kg gas/kg seed	0.7138	0.0009	0.0035	1.8
	Sorghum Seed [a]	kg gas/kg seed	0.7113	0.0008	0.0037	1.8
	Soybeans Seed	kg gas/kg seed	0.3272	0.0004	0.0002	0.4
	Wheat Seed	kg gas/kg seed	0.2018	0.0003	0.0012	0.6
Cover Crop	Clover Seed	kg gas/kg seed	1.2529	0.0016	0.0076	3.6
	Rye Seed	kg gas/kg seed	0.1262	0.0001	0.0006	0.3

Source: National Renewable Energy Laboratory (2012).
Emission factor boundaries are cradle to farm gate.
[a] For sorghum seed, we used the corn seed emission factor as a proxy due to lack of information on sorghum seed production GHG emissions.

Fertilizers

The top most common fertilizers in the United States were identified based on the 2010 USDA ARMS Survey (USDA ERS, 2015a). We used the emission factors for these fertilizers as provided in the Argonne National Laboratory's 2014 GREET model (Argonne National Laboratory, 2014). GREET did not contain emission factors for ammonium sulfate; these were taken from the ecoinvent 3 database; the emission factor is based on the average of several European ammonium sulfate production facilities (Weidema et al., 2013).

The emission factors included within GREET and ecoinvent represent cradle to production gate boundaries; to account for the transportation from the fertilizer production facility to the farm, ICF used the average distances traveled by different fertilizers from field crop production datasets in USDA's LCA Commons database (National Agricultural Library 2015, using estimates from GREET described in Wang 2009). These distances are indicated in Exhibit 9. The emission factors applied to these distance estimates are described in the "transportation" sub-section below. The resulting fertilizer emission factors are outlined in Exhibit 10.

Exhibit 9: Distance Traveled by Fertilizer Type and by Mode (miles)

Product	Ocean Freighter, Average Fuel Mix	Barge, Average Fuel Mix	Freight Rail, Diesel	Class 8 Truck	Class 6 Truck
Nitrogen Fertilizer	5668	646	1207	80.5	48.3
Phosphorous Fertilizer	6759	646	1207	80.5	48.3
Potassium Fertilizer	6276	646	1207	80.5	48.3
Lime	0	0	0	80.5	0

Source: National Agricultural Library (2015).

Exhibit 10: Fertilizer Emission Factors (kg gas/kg fertilizer)

Fertilizer Type	Emission Factor by Gas (kg gas/kg fertilizer)			
	CO_2	CH_4	N_2O	CO_2-eq
Ammonia (NH_3) [a]	2.6390	0.0076	0.0001	2.8
Urea (NH_2CONH_2) [a]	1.3027	0.0055	0.0000	1.5
Urea-Ammonium Nitrate Solution[a]	3.7089	0.0120	0.0099	7.0
Phosphate Fertilizer [a]	1.3223	0.0028	0.0000	1.4
Potassium Fertilizer (Potash) [a]	0.8150	0.0013	0.0000	0.9
Lime ($CaCO_3$) [a]	0.0236	0.0000	0.0000	0.02

Emission factor boundaries are cradle to farm gate.
[a] Argonne National Laboratory (2014).
[b] Weidema et al. (2013).

Within GREET, the emission factors for the nitrogen and phosphate fertilizers are based on weighted averages of related fertilizers based on their use in the United States for corn production (Johnson et al., 2013). The averaged fertilizers and their weighting are shown below in Exhibit 11.

Exhibit 11: Fertilizers and Their Weighting in GREET 2014

Fertilizer Type	Share of Total Use	Emission Factor by Gas (kg gas / kg fertilizer)			
		CO_2	CH_4	N_2O	CO_2-eq
Nitrogen Fertilizers (weighted average)	100%	2.4956	0.0079	0.0035	3.7
Ammonia (NH_3)	31%	See above			
Urea (NH_2CONH_2)	23%				
Ammonium Nitrate (NH_4NO_3)	4%				
Urea-Ammonium Nitrate Solution	32%				
Monoammonium Phosphate	4%				
Diammonium Phosphate	6%				
Phosphate Fertilizers (weighted average)	100%	1.3223	0.0028	0.0000	1.4
Monoammonium Phosphate	50%	See above			
Diammonium Phosphate	50%				

Source: Argonne National Laboratory (2014).

Nitrification and Urease Inhibitors

In the literature, nitrification and urease inhibitors they have been excluded from other similar analyses due to the gap in data. These papers include the United Soybean Board's "Life Cycle Impact of Soybean Production and Soy Industrial Products" and "Cradle-to-farm Gate Analysis of Milk Carbon Footprint: A Descriptive Review" found in the Italian Journal of Animal Science (Pirlo, 2012; United Soybean Board, 2010). However, for our study we assumed that GHG emissions from the production and transportation of nitrification and urease inhibitors were equivalent a herbicide, Chlorpyrifos. This assumption results in a LCA emission factor that is higher than the factor for a fertilizer on a per-kg of product basis.

Pesticides

We obtained LCA emission factors for herbicides and insecticides for the most common herbicides and insecticides used according to the 2010 USDA ARMS Survey (USDA ERS, 2015a). ICF obtained the inventory data for these herbicides from the US life cycle inventory database; data are from 2010 (National Renewable Energy Laboratory, 2012). ICF also obtained insecticide data from the ecoinvent database; data are from 2010 (Weidema et al., 2013). Due to a lack of specific life-cycle inventory data, ICF found proxy compounds to be substituted for several herbicides. The proxy compounds are indicated in Exhibit 12. The LCA emission factors have a cradle to farm gate boundary.

Exhibit 12: Emission Factors for Active Ingredients

Pesticide Name	Units	Emission Factor by Gas (kg of gas/unit of process)			
		CO_2	CH_4	N_2O	CO_2-eq
Herbicide					
Acetochlor [a, b]	kg gas / kg herbicide	22.91	0.04	0.0004	24.1
Alachor [a]	kg gas / kg herbicide	10.03	0.03	0.0020	11.35
Amides [c, d]	kg gas / kg herbicide	10.44	0.02	0.0002	11.1
Atrazine [a, b]	kg gas / kg herbicide	15.75	0.03	0.0003	16.5
Bentazon [a, e]	kg gas / kg herbicide	10.68	0.03	0.00	12.03
Bromoxynil [f, g]	kg gas / kg herbicide	11.66	0.02	0.00	12.35
Chlorpyrifos [a, h]	kg gas / kg herbicide	8.05	0.02	0.00	9.06
Clomazone [g, i]	kg gas / kg herbicide	9.89	0.03	0.00	11.13
Cyanazine [a, b]	kg gas / kg herbicide	16.66	0.03	0.0003	17.5
Dicamba [g]	kg gas / kg herbicide	8.17	0.02	0.02	15.3
Dinitroalinine [c]	kg gas / kg herbicide	5.63	0.02	0.0046	7.5
Metolachlor [a, b]	kg gas / kg herbicide	22.72	0.04	0.0004	23.9
Oxime [a, j]	kg gas / kg herbicide	2.14	0.01	0.0000	2.5
Pendimethalin [g]	kg gas / kg herbicide	3.72	0.01	0.01	5.92
Phenoxy [c]	kg gas / kg herbicide	7.08	0.02	0.0001	7.7
Phosphinic acid [c,h]	kg gas / kg herbicide	8.05	0.02	0.0015	9.1
S-Metolachlor [g]	kg gas / kg herbicide	7.12	0.02	0.00	8.33
Sulfonyl Urea [c]	kg gas / kg herbicide	10.68	0.03	0.0017	12.1
Sulfosate [a,h]	kg gas / kg herbicide	8.05	0.02	0.00	9.03
Triallate [g, k]	kg gas / kg herbicide	4.65	0.01	0.00	4.91
Triazine [c]	kg gas / kg herbicide	9.34	0.07	0.0002	11.2
Trifluralin [f,g]	kg gas / kg herbicide	5.63	0.02	0.00	7.47
Insecticide					
Insecticides [a, b]	kg gas / kg insecticide	22.53	0.04	0.0004	23.7
2, 4- D [c]	kg gas / kg insecticide	7.08	0.02	0.0001	7.6
Bifenthrin [a,l]	kg gas / kg insecticide	17.46	0.05	0.00	18.7
Carbofuran [a, b, m]	kg gas / kg insecticide	22.53	0.04	0.00	23.7
Glufosinate [a, h]	kg gas / kg insecticide	8.05	0.02	0.00	9.03
Glyphosate [c]	kg gas / kg insecticide	11.66	0.02	0.0003	12.4
Lambda- Cyhalothrin [a,l]	kg gas / kg insecticide	17.46	0.05	0.00	18.7
Organophosphate [c]	kg gas / kg insecticide	8.05	0.02	0.0015	9.1
Pyretroid [c]	kg gas / kg insecticide	17.46	0.05	0.0003	18.7

Emission factor boundaries are cradle to farm gate.
[a] NREL (2012).
[b] National Agricultural Library (2015).
[c] Argonne National Laboratory (2014).
[d] Use Napropamide as a proxy.
[e] Use [Sulfonyl]urea-compounds as a proxy.
[f] Use Nitrile-compound as a proxy.
[g] Ecoinvent.
[h] Use Organophosphorus-compound as a proxy.
[i] Use Unspecified Pesticides as a proxy.
[j] Use Cyclohexane as a proxy.
[k] Use Dithiocarbamate-compound as a proxy.
[l] Use Pyretroid as a proxy.
[m] Use Insecticides as a proxy.

The GREET emission factors for herbicides and insecticide are cradle to production gate. ICF supplemented these emission factors with transportation distances from the field crop production datasets in USDA's LCA Commons database; distances are presented in Exhibit 13; emission factors for the different transportation modes are presented in the next section in Exhibit 14.

Exhibit 13: Distance Traveled by Mode

	Distance Traveled (miles)				
	Ocean Freighter, Average Fuel Mix	**Barge, Average Fuel Mix**	**Freight Rail, Diesel**	**Class 8 Truck**	**Class 6 Truck**
Pesticides	6437	644	1207	80.5	48.3

Source: National Agricultural Library (2015).

Transportation

ICF identified six different modes of transportation for the analysis. The emission factors for five of the modes of transportation (transoceanic ship, barge, diesel freight train, class 8 truck and class 6 truck) are based on US life cycle inventory developed by NREL (National Renewable Energy Laboratory, 2012). The emission factors are cradle to gate and exclude GHG emissions from the production of transportation equipment and infrastructure. The datasets for transoceanic ship, barge, and diesel freight train are from 2008 and the trucks datasets are from 2007. These emission factors are used to estimate GHG emissions from the transportation of fertilizer, herbicide, and insecticide inputs from their production facilities to the farm.

Exhibit 14: Transportation Emission Factors by Mode

Transportation Mode	Units	Emission Factor by Gas			
		CO_2	CH_4	N_2O	CO_2-eq
Transoceanic ship	kg gas / metric ton-km	0.0178	0.0000	0.0000	0.02
Inland waterways, barge	kg gas / metric ton-km	0.0322	0.0000	0.0000	0.03
Freight train	kg gas / metric ton-km	0.0379	0.0000	0.0000	0.04
Class 8 Truck	kg gas / metric ton-km	0.1321	0.0001	0.0000	0.14
Class 6 Truck	kg gas / metric ton-km	0.1753	0.0001	0.0000	0.18

Emission factor boundaries are well to wheel; i.e., they include all GHG emissions from the production of raw fuel inputs, processing, refining, distribution, and final combustion.
Source: NREL (2012).

The transportation emission factors, in the case of fertilizers and pesticides were applied to transportation distances outlined in the field crop production datasets from the USDA LCA Commons database (National Agricultural Library, 2015) and the amount of each product delivered to the farm. For example, if 2 metric tons of fertilizer were transported 50 km by a class 8 truck, the GHG emissions would be calculated by multiplying 2 metric tons by 50 km by 0.18 kgCO_2-eq/metric ton-km with a result of 18 kg CO_2-eq.

Machinery

On-farm machinery emission factors are based on the diesel used by machinery type per acre. ICF derived diesel consumption for each equipment type by crop type and tillage practice based on the University of Tennessee's analysis "Field Crop Budgets for 2015" (University of Tennessee, 2015). Exhibit 15 provides illustrative example for the diesel consumption per acre by process for corn and tillage practice. The upstream emissions from diesel production were used to develop the machinery emission factors (Argonne National Laboratory, 2014).

Exhibit 15: Diesel Consumption by Equipment Type per Acre for Corn, Conventional Tillage

Process	Power Unit	Fuel (gallons/acre)
Chisel	Tractor, 215 hp, Chisel Plow	0.87
Disk	Tractor, 215 hp, Tandem Disk	0.70
Prepare Seedbed	Tractor, 215 hp, Do-All	0.73
Plant	Tractor, 215 hp, Planter	0.60
Fertilize	Tractor, 215 hp, Fertilizer Spreader	0.64
Weed Control	SP Boom Sprayer	0.11
Harvest	Combine, Grain Head	2.6
Haul	Tractor, 215 hp, Grain Cart	0.39
Haul	Semi Tractor/Trailer	0.9

Source: University of Tennessee (2015).

To quantify the life cycle emissions associated with spreading seed by crop plane over one acre, ICF assumed that an AT-602 Air Tractor was used to seed one acre (Air Tractor, 2015; Allamakee SWCD, 2012). The AT-602 consumes approximately 5 gallons of avgas per acre. ICF calculated the combustion and upstream emissions associated with the allotted amount of fuel (Argonne National Laboratory, 2014). Exhibit 16 presents illustrative example of the emission factors for conventional tillage of corn based on the diesel consumed for the on farm machinery.

Exhibit 16: Machinery Emission Factors (Corn, Conventional Tillage)

Process	Power Unit	Units	Emission Factor by Gas (kilogram of gas/unit of process)			
			CO_2	CH_4	N_2O	CO_2-eq
Chisel	Tractor, 215 hp	kg gas / acre	10.18	0.02	0.00	10.61
Disk	Tractor, 215 hp	kg gas / acre	8.17	0.01	0.00	8.52
Prepare Seedbed	Tractor, 215 hp	kg gas / acre	8.54	0.01	0.00	8.91
Plant	Tractor, 215 hp	kg gas / acre	6.96	0.01	0.00	7.25
Fertilize	Tractor, 215 hp	kg gas / acre	7.42	0.01	0.00	7.74
Weed Control	Tractor, 215 hp	kg gas / acre	1.31	0.00	0.00	1.36
Harvest	Tractor, 215 hp	kg gas / acre	30.11	0.05	0.00	31.40
Haul	SP Boom Sprayer	kg gas / acre	4.53	0.01	0.00	4.72
Haul	Combine	kg gas / acre	10.50	0.02	0.00	10.95
Seeding	Crop Dusting Plane [a]	kg gas / acre	34.56	0.0029	0.0006	34.85

Source: University of Tennessee (2015), Argonne National Laboratory (2014).
Emission factor boundaries are well to wheel.
[a] Air Tractor (2015) based on use of gasoline as a proxy for avgas.

Fuel Production and Combustion

ICF used fuel production and combustion data for five liquid fuels from GREET 2014. For end-use combustion, ICF assumed natural gas and residual oil combustion in a stationary reciprocating engine, diesel fuel use in a farming tractor, gasoline use in a farming tractor, and LPG use in a commercial boiler (Argonne National Laboratory, 2014). These factors were suitable for the end uses they were applied to in this analysis.

ICF used coal production emission factors for lignite and bituminous coal from NREL's US life cycle inventory database. The emission factors represent cradle to plant gate and do not include the combustion of the coal (National Renewable Energy Laboratory, 2012). Exhibit 17 presents the emission factors for liquid fuels. Exhibit 18 presents the emission factors for coal production.

Exhibit 17: Liquid Fuel Production and Combustion Emission Factors[a]

Fuel	Units	Production of Fuel (kg of gas/unit of process)			Combustion of Fuel (kg of gas/ unit of process)			Total (kg of gas/ unit of process)		
		CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
Natural Gas	kg gas/ ft^3	0.0122	0.0003	0.0000	0.0558	0.0004	0.0000	0.0680	0.0007	0.0000
Residual Oil	kg gas/ gallon	1.427	0.0185	0.0000	11.79	0.0006	0.0001	13.22	0.0191	0.0001
Diesel Fuel	kg gas/ gallon	1.748	0.0181	0.0000	9.923	0.0001	0.0001	11.67	0.0181	0.0002
Gasoline	kg gas/ gallon	2.172	0.0160	0.0004	6.919	0.0006	0.0001	9.091	0.0166	0.0006
LPG	kg gas/ gallon	1.339	0.0120	0.0000	5.780	0.0001	0.0004	7.119	0.0121	0.0004

[a] Source: Argonne National Laboratory (2014).
Emission boundaries are well to final combustion.

Exhibit 18: Coal Production Emission Factors

Coal Type	Units	Emissions from Production of Coal			
		CO_2	CH_4	N_2O	CO_2-eq
Lignite	kg gas / kg coal	0.0954	0.00108	0.000	0.12
Bituminous	kg gas / kg coal	0.0624	0.00345	0.000	0.15

Source: National Renewable Energy Laboratory (2012).

Regional Electricity

ICF developed regional electricity emission factors specific to the grid mix of each of the USDA regions based on state electricity grid mix data from EPA's eGRID 2010 (EPA, 2015). ICF developed life-cycle GHG emission factors for electricity produced by each type of generation using GREET, and multiplied these factors by the state grid mix from eGRID. ICF then calculated the average GHG emissions intensity across the states within each of the 10 USDA regions. This analysis assumed 6.5% losses due to transmission and distribution (Argonne National Laboratory, 2014). Exhibit 19 presents the emission factors developed for each USDA region.

Exhibit 19: USDA Regional Upstream Emission Factors

USDA Region	Units	Electricity Upstream			
		CO_2	CH_4	N_2O	CO_2-eq
Pacific	grams gas / kilowatt-hour	227	0.496	0.005	241
Mountain	grams gas / kilowatt-hour	691	1.124	0.011	722
Northern Plains	grams gas / kilowatt-hour	671	0.996	0.011	699
Southern Plains	grams gas / kilowatt-hour	673	1.225	0.011	707
Lake States	grams gas / kilowatt-hour	676	1.055	0.012	706
Corn Belt	grams gas / kilowatt-hour	821	1.229	0.013	856
Delta States	grams gas / kilowatt-hour	569	1.061	0.010	598
Northeast	grams gas / kilowatt-hour	468	0.880	0.009	493
Appalachian	grams gas / kilowatt-hour	762	1.162	0.013	795
Southeast	grams gas / kilowatt-hour	580	1.002	0.010	608

Source: Adapted from EPA (2015) and Argonne National Laboratory (2014).
All emission factors represent GHG emissions from cradle to wall socket.

2.2. Adoption Potential

The adoption potential represents the maximum potential for acres of cropland or quantity of agricultural residues to undergo changes in crop based management strategies. We used data on current management practices as provided in the USDA ARMS data base and made assumptions on the projected changes in practices. We used results from the August 2015 version of the Monsanto Model as the basis for acres in production in 2020, 2030, 2040, and 2050. Exhibit 20 summarizes the underlying data that we used to determine current management practices and the key assumptions for estimating acres of cropland that transition to an alternative practice or availability of agricultural residues or excess grain for alternative uses (e.g., biofuel, biochar, or electricity production).

Exhibit 20: Key Data Sources and Assumptions for Estimating Adoption Potential

Key Data Sources for Current Management/Production Practices	Key Assumptions for Projected Change in Practices
CBS 1.1: Application of Inhibitors	
• USDA ARMS Farm Financial and Crop Production Practices Data	• Acres that are not using inhibitors transition to using them

Key Data Sources for Current Management/Production Practices	Key Assumptions for Projected Change in Practices
– percent of planted acres using inhibitors by crop type	• 50% of the corn and wheat acreage transition to use of nitrification inhibitors and the other 50% transition to urease inhibitors • All sorghum, soybeans, and rapeseed acreage that are not using inhibitors adopt nitrification inhibitors • All barley acreage not using inhibitor adopt urease inhibitors
CBS 1.2: Expand the Use of Precision Agriculture (Reduce Direct and Indirect Emissions), Domestically	
• USDA ARMS Farm Financial and Crop Production Practices Data – percent of planted acres using precision agriculture by crop type	• 50% of the cropland acres not using precision agriculture transition to use of variable rate technology • 50% of the cropland acres not using precision agriculture transition to use of swath control
CBS 2.1: Sustainable Tillage	
• USDA ARMS Farm Financial and Crop Production Practices Data – percent of planted acres using conventional tillage, reduced tillage and no till by crop type	• 50% of the cropland acres in conventional tillage transition to no till practices and 50% transition to reduced till practices • 100% of the cropland acres in reduced till transition to no till
CBS 2.2 Winter Cover Crops	
• USDA NASS – acres of cover crops	• Approximately 2% of corn and soybean cropland plant cover crop and approximately 1 % of winter wheat plant cover crops • Acres of corn, soybean and winter wheat that are not using cover crops transition to planting cover crops
CBS 3: Produce Biofuel with Excess Grain and Agricultural Residue (Offset Fossil Fuel Emissions), Domestically	
• Monsanto Model – corn acres, corn yields • Wang et al., (2014) – corn stover collection rate	• Production of integrated corn-corn stover ethanol at retrofitted plants is constrained according to the available nameplate capacity of existing corn grain ethanol plants that could be retrofitted

Key Data Sources for Current Management/Production Practices	Key Assumptions for Projected Change in Practices
• GREET1_2014 Model – life-cycle integrated ethanol process	• Production of integrated corn-corn stover ethanol at new plants is constrained according to both the amount of excess corn grain and remaining corn stover available (i.e., the amount of corn stover left over after meeting the increased ethanol capacity post retrofit) • Excess corn grain is processed at the new integrated corn-corn stover ethanol plants, and no additional corn grain is diverted from the market—i.e., the increase in integrated ethanol capacity from new plants is based on new corn and left-over corn stover
CBS 4.1: Pyrolysis of Corn Stover into Liquid Fuels and Biochar, Including Field Application of the Biochar Co-Product	
• Monsanto Model – corn acres • Wang et al. (2014)– corn stover collection rate • Wang et al. (2014)– life-cycle corn stover pyrolysis process	• 50% of the corn stover is processed (e.g., converted to biochar, syngas, and bio-oil) via fast pyrolysis and 50% is converted via slow pyrolysis • 100% of the biochar is applied to fields (0% is combusted for energy/electricity)
CBS 4.2: Co-Firing Corn Stover for Electricity Generation	
• Monsanto Model – corn acres • Wang et al. (2014)– corn stover collection rate • EIA – coal mining and coal plant information	• 50% of the corn stover is combusted assuming a maximum of 10% co-firing and 50% is combusted assuming a maximum of 20% co-firing

2.3. Sensitivity Analysis

ICF conducted a sensitivity analysis on the impact of key input parameters on the resulting national mitigation potential. For each of the key input parameters, ICF generated the national mitigation potential based on the lower and upper bound for the parameter. We present the key parameters, their lower and upper bound and the resulting range for the mitigation potential in the relevant chapters of this report.

2.4. References

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Appendix 2.A: Common Data for Estimating Mitigation Potential

This appendix presents several sets of data that we used to evaluate the adoption potential and mitigation potential, for several CBSs. In particular, this appendix presents the following data sets:

- 2.A-1: Direct and Indirect N_2O Emissions
- 2.A-2: Fertilizer Application Rates
- 2.A-3: Herbicide Application Rates
- 2.A-4: Pesticide Application Rates
- 2.A-5: Global Warming Potentials (GWPs)

2.A-1: Direct and Indirect N_2O Emissions

Direct N_2O emissions result from the processes of nitrification and denitrification. We used the emission factors as provided in USDA report entitled *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory* (Eve et al., 2014). These emission factors are based on process-based simulation models and are available for corn, sorghum, soybeans, and wheat for three soil types (course, medium, and fine) in 20 Land Resource Regions (LRRs). Based on a visual review of the USDA report entitled*, Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin,* ICF estimated the LRR composition of each USDA region and calculated a weighted average emission factors for corn, sorghum, soybeans, and wheat. For barley and rapeseed, ICF used the IPCC Tier I emission factor (i.e., 0.01 kg N2O-N per kg N). These emission factors are presented in Exhibit 2.A-2 below.

Indirect N_2O emissions result from two sources: i) volatilization of N as NH_3 and oxides of N (NO_x) and the deposition of these gases and their products NH_4^+ and NO_3^- onto soils and the surface of lakes and other waters; and ii) leaching and runoff of N from fertilizers . ICF used the ratio of indirect to direct N_2O emissions a provided in the USDA 1990-2008 inventory, using data from the year 2008. As a reference point, the ratio of the indirect and direct emissions using the default values as provided for the IPCC Tier I emission factors is 0.325[4] (IPCC, 2006). Consequently, the US- based estimates are less than the global default values.

Relatively high uncertainty exists for the estimate of indirect N_2O emissions. As indicated in the U.S. EPA, at the 95% confidence interval the range for estimate is -46% to 160% of the 2013 emissions (EPA, 2015a). Similarly, the estimate of reductions of indirect N_2O emissions could be of this magnitude.

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[4] Default for direct emissions is 0.01 kg N_2O-N per kg N, for indirect emissions from volatilization is .001 kg N_2O-N per kg N, and for leaching and runoff is 0.00225 kg N_2O-N per kg N. Ratio is (0.001 + 0.00225)/0.01 = 0.0325 (IPCC, 2006).

Exhibit 2.A-2: Nitrous Oxide Emissions for 2008 from Differently Cropped Soils (Tg CO_2-eq)

Source of Emissions	Barley	Corn	Rapeseed	Sorghum	Soybeans	Wheat	Non Major Crops
Direct		**54**		1.5	21.8	6.3	19.5
Volatilization		1.3			1.1	0.3	2.5
Leaching & Runoff		9		0.4	5.9	1.6	3.8
Total Indirect		10.3		0.4	7	1.9	6.3
Ratio of Indirect to Direct	0.27[a]	0.19	0.27[a]	0.27	0.32	0.30	0.32

Source: USDA (2011).
[a] For barley and rapeseed, assumed average value of 0.27.

Exhibit 2.A-3: Weighted Average Base Emission Rate by USDA Region (kg N_2O acre^{-1})

Soil Type/ Crop Type	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Course										
Barley	0.01	0.00	0.00	0.00	0.09	0.03	0.01	0.04	0.00	0.00
Corn	0.30	0.50	0.14	0.45	0.04	0.52	0.20	0.07	0.24	0.06
Rapeseed	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Sorghum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Soybeans	0.36	0.40	0.47	0.30	0.00	0.21	0.11	0.00	0.23	0.00
Wheat	0.01	0.03	0.00	0.06	0.31	0.00	0.20	0.28	0.02	0.27
Medium										
Barley	0.01	0.00	0.00	0.00	0.09	0.03	0.01	0.04	0.00	0.00
Corn	0.45	0.75	0.23	0.67	0.05	0.75	0.29	0.08	0.41	0.10
Rapeseed	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Sorghum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
Soybeans	0.55	0.57	0.77	0.43	0.00	0.30	0.13	0.00	0.42	0.01
Wheat	0.01	0.03	0.00	0.08	0.39	0.00	0.27	0.41	0.03	0.39
Fine										
Barley	0.01	0.00	0.00	0.00	0.09	0.03	0.01	0.04	0.00	0.01
Corn	0.60	0.92	0.31	0.79	0.09	0.99	0.46	0.13	0.57	0.16

Soil Type/ Crop Type	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Rapeseed	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Sorghum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
Soybeans	0.63	0.65	0.89	0.48	0.00	0.36	0.17	0.00	0.47	0.01
Wheat	0.03	0.04	0.01	0.10	0.53	0.00	0.35	0.55	0.07	0.56

Source: For corn, sorghum, soybeans, and wheat, ICF developed estimate factors in term of kg N_2O-N per acre for each USDA region by weighing the USDA estimates by LRR by the relative LRR area in each USDA region. For barley and rapeseed, ICF used the IPCC Tier I emission factor (i.e., 0.01 kg N_2O-N per kg N) and the regional average N application rate as provided in Section 2.A-3 to derive emissions of N_2O per acre.

ICF estimated the distribution of course, medium, and fine soils based on a visual analysis of the USDA Natural Resources Conservation Service digital general soil map of the United States (commonly referred to as the STATSGO data base (i.e., State Soil Geographic dataset)).[5] In estimating adoption potential by USDA region, ICF distributed the cropland acres by the resulting distributions in Exhibit 2.A-3.

Exhibit 2.A-4: Distribution of Soil Types of USDA Region

Soil Type	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Fine	5%	5%	20%	25%	10%	0%	10%	10%	5%	25%
Medium	10%	25%	40%	15%	35%	10%	45&	30%	5%	35%
Coarse	85%	70%	40%	60%	55%	90%	45%	60%	90%	40%

Source: USDA NRCS (n.d.)

2.A-2: Fertilizer Application Rates

ICF obtained fertilizer data by state from USDA and the Canola Council. To estimate the fertilizer application rates per USDA Region, we averaged the application rates for the states within the USDA Production Region.

[5] A visual map is available online at: http://ldas.gsfc.nasa.gov/nldas/images/NLDAS_STATSGO_soiltexture.gif.

Exhibit 2.A-5: Fertilizer Application Rates (lbs of N/acre)

Crop Type	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Corn	154.10	156.81	178.50	121.11	130.71	83.25	139.84	130.70	178.53	131.36
Barley	71.06	0.00	0.00	66.06	75.09	46.92	73.66	71.54	0.00	0.00
Rapeseed / Canola[a]	154.10	156.81	178.50	121.11	130.71	83.25	139.84	130.70	178.53	131.36
Sorghum	0.00	0.00	0.00	0.00	45.52	0.00	66.16	0.00	0.00	76.29
Soybeans	20.27	18.37	21.14	12.92	0.00	0.00	11.51	0.00	0.00	0.00
Wheat	0.00	98.99	0.00	95.55	58.87	0.00	58.96	69.75	0.00	53.35

Source: USDA NASS. (2015), except as noted.
[a] Canola Council. (2015b).

ICF modeled three types of nitrogen fertilizers: anhydrous ammonia, urea, and liquid nitrogen. We selected these three types because, although many forms of nitrogen fertilizer are used throughout the United States, there is approximately an even distribution of the use of these (with additional variation among different crop types, though that is not modeled here).

Exhibit 2.A-6: Nitrogen Content for Nitrogen Fertilizers

Product Inputs	N Content[a]
Anhydrous Ammonia	82%
Urea	45%
Liquid N	30%

2.A-3: Herbicide Application Rates

For modeling the change in herbicide application rates due to changes in tillage practices, ICF developed a national average application rates for applied active ingredients. We used each of these active ingredients in our life-cycle GHG analysis to estimate the change in life-cycle GHG emissions due to changes in tillage practices and the resulting change in herbicide application. We used the following four step process:

1) **Identified the top six active ingredients applied.** Using data provided in USDA NASS Quick Stats 2.0 data set, we identified the top active ingredients based on the percent of planted acres that apply the active ingredient. For Barley, we included seven active

ingredients to capture any active ingredient that was applied for over 20% of planted acres.

2) **Identified application rate per active ingredient.** We obtained the average application rate as provided in the USDA NASS Quick Stats 2.0 data set.

3) **Estimated average application rate.** The NASS data provides the average application rate for acres where the herbicide is applied. Recognizing that a landowner could apply more than one active ingredient, we estimated the total application of the active ingredient across all planted acres and calculated a national average application rate across all planted acres (i.e., estimated an average representative acre as a weighted average (i.e., Sum of [Percent of Areas Planted] x [Avg Rate]).

4) **Identified the percent of acres that apply an herbicide**. Using data from USDA ARMS Survey we obtained estimate of acres that apply an herbicide. This number provides an indication of how representative the application of herbicides is across planted acres. As indicated, herbicides are applied on well over 80% of planted acres. The actual average application rate for acres where the herbicide is applied will be higher than the national average across all planted acres (i.e., more aligned with the average rater rather than the weighted average).

Exhibit 2.A-7 presents our findings.

Exhibit 2.A-7: Herbicide Active Ingredients by Crop Type

Most Used Active Ingredients by Crop Type	Treated (Percent of Area Planted)[a]	Avg. Rate for Year (lbs/acre) [a]	Contribution to Representative Acre (lbs/acre)[c]
Barley			
Pinoxaden	42%	0.05	0.02
Glyphosate Iso. Salt	35%	1.16	0.41
Bromoxynil Octanoate	32%	0.22	0.07
Mcpa, 2-Ethylhexyl	32%	0.34	0.11
Fluroxypyr 1-Mhe	25%	0.09	0.02
Thifensulfuron	20%	0.01	0.002
Tribenuron-Methyl	20%	0.01	0.002
National Average	82%[b]		0.63
Corn			
Atrazine	55%	1.02	0.56
Glyphosate Isopropylamine Salt	38%	0.89	0.34
Acetochlor	29%	1.26	0.36
Mesotrione	27%	0.12	0.03
S-Metolachlor	27%	1.11	0.30
Glyphosate Potassium Salt	24%	1.16	0.28
National Average	95%[b]		1.87

Most Used Active Ingredients by Crop Type	Treated (Percent of Area Planted)[a]	Avg. Rate for Year (lbs/acre) [a]	Contribution to Representative Acre (lbs/acre)[c]
Rapeseed			
Glyphosate	35%	0.16	0.16
Glufosinate	35%	0.23	0.23
National Average	82%		0.39
Sorghum			
Atrazine	64%	1.32	0.84
Glyphosate Iso. Salt	47%	1.28	0.60
S-Metolachlor	37%	1.18	0.44
2,4-D, 2-Ehe	20%	0.65	0.13
Dimethenamid-P	17%	0.72	0.12
Dicamba, Dimet. Salt	15%	0.30	0.05
National Average	84%[b]		2.18
Soybeans			
Glyphosate Pot. Salt	59%	1.63	0.96
Glyphosate Iso. Salt	30%	1.33	0.40
2,4-D, 2-Ehe	11%	0.52	0.06
Chlorimuron-Ethyl	11%	0.02	0.00
Flumioxazin	11%	0.08	0.01
Clethodim	9%	0.08	0.01
National Average	96%[b]		1.44
Wheat			
Glyphosate Pot. Salt	45%	0.85	0.38
Fluroxypyr 1-Mhe	31%	0.09	0.03
Fenoxaprop-P-Ethyl	29%	0.06	0.02
Clodinafop-Propargil	28%	0.04	0.01
Glyphosate Iso. Salt	26%	0.56	0.15
Mcpa, 2-Ethylhexyl	26%	0.24	0.06
National Average	87%[b]		0.65

[a] USDA NASS (2015).
[b] USDA ERS (2015b).
[c] Calculated as weighted average.

2.A-4: Insecticide Application Rates

For insecticide application rates, we used the same four step process that was used to identify active ingredients for herbicides and the resulting weighted average rates. Exhibit 2.A-8 presents the average application rates applied across planted acres. We used these quantities to evaluate net change in production related GHGs for insecticide inputs due to changes in management practices.

Exhibit 2.A-8: Insecticide Active Ingredients by Crop Type

Most Used Active Ingredients by Crop Type	Treated (Percent of Area Planted)[a]	Avg. Rate for Year (lbs/acre) [a]	Contribution to Representative Acre (lbs/acre)[c]
Barley			
Lambda-Cyhalothrin	4%	0.02	0.0008
Chlorpyrifos	1%	0.26	0.0026
National Average	1%[b]		0.0034
Corn			
Bifenthrin	4%	0.06	0.0024
Cyfluthrin	2%	2.00	0.0400
Lambda-Cyhalothrin	2%	2.00	0.0400
Tefluthrin	2%	0.12	0.0024
Beta-Cyfluthrin	1%	0.01	0.0001
Permethrin	1%	0.09	0.0009
National Average	9%[b]		0.0824
Rapeseed[d]			
Lambda-Cyhalothrin	4%	0.02	0.0008
Chlorpyrifos	1%	0.26	0.0026
National Average	1%[b]		0.0034
Sorghum			
Beta-Cyfluthrin	2%	0.01	0.0002
Lambda-Cyhalothrin	1%	0.03	0.0003
Zeta-Cypermethrin	1%	0.03	0.0003
National Average	6%[b]		0.0008
Soybeans			
Chlorpyrifos	6%	0.45	0.0270
Lambda-Cyhalothrin	6%	0.03	0.0018
Bifenthrin	3%	0.08	0.0024
Acephate	1%	0.96	0.0096
Cyfluthrin	1%	0.06	0.0006
Dimethoate	1%	0.46	0.0046
National Average	18%[b]		0.0466
Wheat			
Chlorpyrifos	2%	0.18	0.0036
National Average	5%[b]		0.0036

[a] USDA NASS (2015).
[b] USDA ERS (2015b).
[c] Calculated as weighted average.
[d] Assumed same active ingredients and application rates as those used for barley.

2.A-5. Global Warming Potentials (GWPs)

In developing the results of this study, ICF assessed the global warming potential (GWP) using the GWP values as defined in the IPCC's AR4. ICF used these values to express the results in units of metric tons CO_2-eq ($MTCO_2$-eq) per functional unit.

Exhibit 2.A-9: GWP for Key GHGs

GHG	GWP
CO_2	1
CH_4	25
N_2O	298

Source: IPCC , (2007).

2.A-6. References

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3. CBS 1: Sustainable Nutrient Management

CBS 2 Sustainable Nutrient Management

- CBS 1.1 Application of Inhibitors
- CBS 1.2 Precision Agriculture: Variable Rate Technology for Fertilizer Application and Swath Control

Fertilizer use results in upstream (from production of these inputs), on farm and down-stream GHG emissions. CBS 1 analyzes three key options for sustainable nutrient management that reduce fertilizer use and the corresponding GHG emissions. First, we present the application of nitrification and urease inhibitors. Inhibitors function by slowing the process through which fertilizers are broken down into byproducts that can be volatilized and/or are "lost" to the plant. As such, inhibitors have been shown to reduce input needs and emissions. The second and third sections discuss two strategies for precision agriculture. Precision agriculture (also referred to as precision farming, site specific crop management, and satellite farming) is characterized by the use of field-specific data (gathered during operations) that calibrate the application of inputs and optimize fuel and input use (Schimmelpfennig and Ebel, 2011). Precision agriculture techniques use GPS and GIS technologies to map inputs to specific characteristics of small units of cropland, and use this site-specific data to recommend or track varied input levels on a field. Variable rate technology, a technique that uses site-specific information on crop health and fertilizer needs to apply the optimal amount of inputs across a field is discussed first. ICF selected GreenSeeker™ as a representative and common variable rate technology option. Swath control, a technology that uses sensors to ensure that inputs are only applied in one layer across a field, removing the risk of over-application from overlap of sprayers or fatigued tractor drivers, is discussed second.

ICF focused on application of inhibitors, variable rate technology, and swath control because they are relatively common and well-studied in the United States. Each of these three practices has unique boundaries which are discussed separately below.

Nitrogen Use Efficiency

Nitrogen Use Efficiency (NUE) is defined as the ratio between the uptake of fertilizer nitrogen by crops and the total amount of nitrogen applied to the crops. This value measures how much of the nitrogen applied in fertilizer is actually used to benefit crop growth and health.

The benefits of nitrification inhibitors in reducing N_2O emissions are well established. In 2001, IPCC Working Group III stated that use of nitrification inhibitors and other improved nitrogen-use management practices could potentially cut emissions by 30% globally (Moomaw et al., 2001). More recently, the IPCC Fourth Assessment Report (Smith et al., 2007) found that improving nitrogen use efficiency (NUE) can reduce both direct N_2O emissions from crop management and indirect GHG emissions from the manufacturing of nitrogen-based fertilizer, and they pointed to NI as a practice that can improve nitrogen use efficiency. The decrease in greenhouse gas emissions from use of inhibitors is also well documented in the scientific literature.

3.1. Application of Inhibitors

3.1.1. Types of Nitrification and Urease Inhibitors

The Association of American Plant Food Control Officials (AAPFCO) defines enhanced efficiency fertilizers (EEFs) as "fertilizer products with characteristics that allow increased plant uptake and reduce the potential of nutrient losses to the environment when compared to an appropriate reference product" (Hatfield and Venterea, 2014). Nitrification and urease inhibitors are important types of EEFs that increase nitrogen-use efficiency and decrease GHG emissions. Trenkel (2010) provides the AAPFCO's definitions of nitrification inhibitors and urease inhibitors specifically:

Key Considerations in Applying Inhibitors

- Inhibitors reduce nitrogen loss allowing crops access to a larger percentage of applied fertilizer. This efficiency can increase crop yield and/or decrease the amount of fertilizer needed to achieve the same yield.
- Resulting changes in yield depend on baseline nutrient use efficiency and yield.
- Timing of application and soil moisture impact inhibitor effectiveness.

- **Nitrification inhibitor (NI):** A substance that inhibits the biological oxidation of ammoniacal-N to nitrate-N; and
- **Urease inhibitor (UI):** A substance that inhibits hydrolytic action on urea by the enzyme urease (Trenkel, 2010).

Nitrification inhibitors function by slowing the nitrification process that occurs after nitrogen-based fertilizer is applied to crops. NIs keep nitrogen fertilizer in its ammonium form longer, which increases nitrogen-use efficiency. Similarly, urease inhibitors slow the rate at which urea is hydrolyzed, which greatly reduces the losses of ammonia to the air and improves the efficiency of any urea-containing fertilizer (Trenkel, 2010).

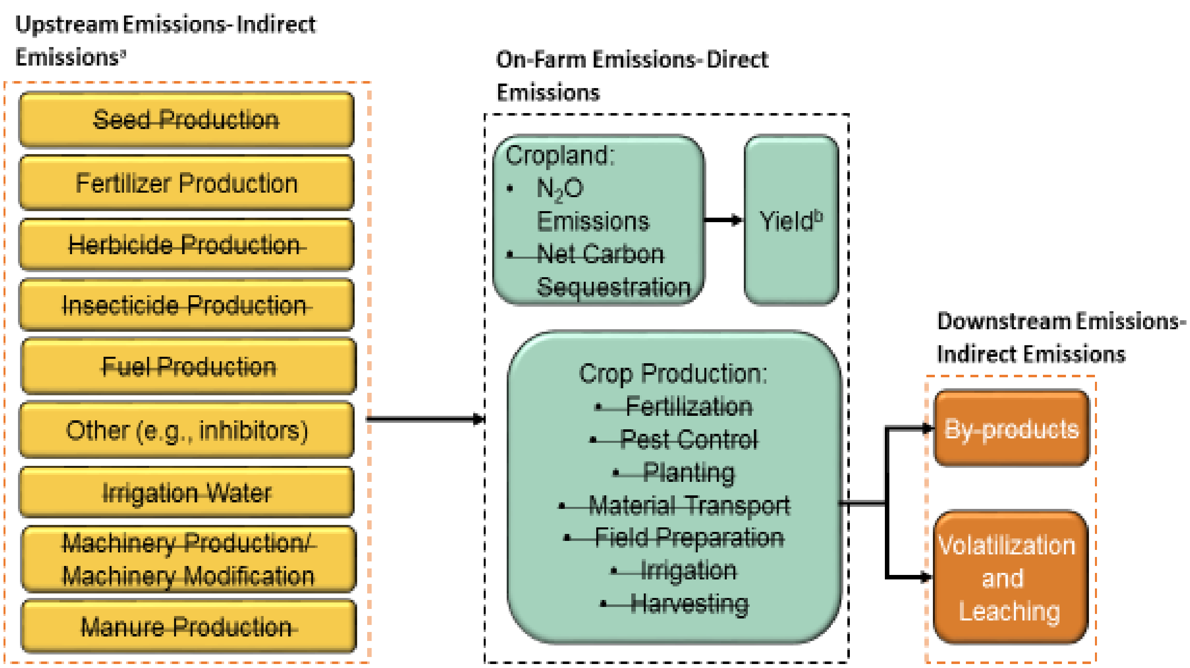
In analyzing available nitrification and urease inhibitors, ICF modeled one common example of each inhibitor type for estimating the mitigation potential. For nitrification inhibitors, ICF focused on N-Serve, an inhibitor from DowChemical that uses the active ingredient nitrapyrin[6] (Franzen, 2011). As of 2010, N-Serve was labelled for use with corn, sorghum, and wheat, and it can be used with any ammonium fertilizer (Trenkel, 2010). For urease inhibitors, ICF modeled Agrotain, a series of urease inhibitors from Agrotain International that all use the active ingredient NBPT[7] (Franzen, 2011). Some of Agrotain's products (such as Agrotain Plus and Super U) also include

[6] More precisely, nitrapyrin is 2-chloro-6-[trichloromethyl] pyridine.
[7] NBPT, a common urease inhibitor, is n-butyl thiophosphoric traimide.

DCD, a nitrification inhibitor[8] (Trenkel, 2010). NBPT, Agrotain's main ingredient, is typically used on corn and wheat, but Agrotain Plus (containing DCD) can also be used on barley (Trenkel, 2010). Agrotain and other UIs can be used with any form of urea and are commonly paired with urea or urea ammonium nitrate (UAN). Where possible, inputs to the calculations for estimating mitigation potential were differentiated for data specific to N-Serve (or NIs in general) and Agrotain (or UIs in general).

When developing estimates of the mitigation potential, ICF aggregated some information on nitrification and urease inhibitors when the literature and data did not differentiate between them or did not provide valid estimates for both types of inhibitors. We evaluated the mitigation potential on a per-acre basis by crop type and USDA Farm Production Region. ICF estimated the net GHG emissions associated with the processes in Exhibit 21 below.

Exhibit 21: LCA Accounting Boundaries for Use of Inhibitors



[a] Upstream supply chain will examine production and transport to the site.
[b] Yield data of crops not modeled for GHG emissions calculations, but are included in the MACC analysis for changes in revenue.

While the benefits of using inhibitors are well established, farmers do face crop management challenges in achieving the maximum possible GHG reduction from inhibitors. For example, the effectiveness of nitrapyrin (N-Serve's active ingredient) and other nitrification inhibitors is

[8] As sufficient data was not available to differentiate, ICF assumed uniform use of across all types of Agrotain urease inhibitors.

extremely dependent on timing of fertilizer and inhibitor application, soil moisture and temperature conditions, leading to variability in emission reductions across seasons and years (Hatfield and Venterea, 2014; Schwab and Murdock, 2010; Thapa et al., 2015).

ICF modeled inhibitor application based on crop type. N-Serve is used mostly with corn, sorghum, and wheat, while Agrotain is primarily used with corn, barley, and wheat (Trenkel, 2010). Exhibit 22 indicates assumed application of nitrification and urease inhibitors by crop type.

Exhibit 22: Assumed Inhibitor Types Applied to Specific Crop Types[a]

Inhibitor	Barley	Corn	Rapeseed[b]	Sorghum	Soybean	Wheat
Nitrification Inhibitor (N-Serve, containing nitrapyrin)	0%	50%	50%	100%	50%	50%
Urease inhibitor (Agrotain, containing NBPT)	100%	50%	50%	0%	50%	50%

Source: [a] Trenkel (2010).
[b] Assumed a 50/50 split for rapeseed and soybean.

Due to the improved nitrogen use efficiency resulting from use of inhibitors, farms using inhibitors can reduce their amount of applied fertilizer without any loss in yield (Trenkel, 2010). Trenkel referenced a Dow AgroSciences experiment in Iowa where N-Serve was applied with 15 fewer pounds of N per acre than usual, resulting in an increase in yield (Trenkel, 2010). In this study, the pounds of N decreased from 160 to 145, a 9% reduction in fertilizer use (Trenkel, 2010). Therefore, ICF modeled a scenario with a 9% reduction in fertilizer needs. Given the application rates mentioned in Chapter 2, we then estimated the change in fertilizer use in pounds of nitrogen per acre and the resulting net change in GHGs from reduced fertilizer production and use.

3.1.2. Emission Reductions

N_2O emission reductions associated with inhibitor use are based on values from Halvorson et al., (Halvorson et al., 2014) who studied impacts of both NIs and UIs on corn in Colorado from 2002 to 2012. The findings from Halvorson et al. (2014) are consistent with other studies and meta-analyses. We would have preferred to cite a meta-analysis as the source of our emission reduction values, rather than individual results; however, all the meta-analyses cited mostly international studies as their sources and we preferred to use US-based research. Emission reductions for NIs, modeled for nitrapyrin (N-Serve's active ingredient), range from 22 percent to 35 percent reduction in N_2O released to the atmosphere, compared with conventional fertilizer application (Halvorson, 2014). Emission reductions for UIs (Agrotain, specifically) range from 41 to 61 percent compared to use of conventional fertilizer. We assumed these Colorado corn values for all other crops and regions, except for wheat. We used a wheat-specific emission reduction value of 50 percent from Thapa's 2015 results on wheat in Minnesota (Thapa et al., 2015). We used lower and upper bounds of these emission reductions to define two emission reduction scenarios. We were unable to find comprehensive emission reductions that varied by region. Exhibit 23 presents the emission reduction bounds for nitrification and urease inhibitors.

Exhibit 23: Emission Reduction of N_2O from Use of Inhibitor

Crop Type	Nitrification Inhibitor		Urease Inhibitor	
	Lower Bound	Higher Bound	Lower Bound	Higher Bound
Barley	22%	35%	41%	61%
Corn[a]	22%	35%	41%	61%
Rapeseed	22%	35%	41%	61%
Sorghum	22%	35%	41%	61%
Soybeans	22%	35%	41%	61%
Wheat[b]	22%	50%	41%	61%

Source:
[a] Corn emission reduction values for nitrification and urease inhibitors are from Halvorson (2014). These values are assumed for all crop types (except the higher bound of NIs on wheat).
[b] Higher bound of emission reductions of nitrification inhibitors on wheat is from Thapa et al. (2015).

As mentioned in Chapter 2: Summary of Methodology, N_2O emissions per acre are as provided by USDA in the report entitled *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory* (Eve et al., 2014). Direct N_2O emission reductions are the product of the N_2O emissions per acre and the percent reduction indicated in Exhibit 23. In Exhibit 23, the indirect N_2O emissions emission reductions are the product of the indirect N_2O emissions per acre (expressed as a ratio of the direct N_2O emissions) and the percent reduction.

We assumed that there is no net change in use of mobile equipment, hence, the net change in GHGs from use of mobile equipment is zero. A LCA value for the production of inhibitors is not available. Consequently, we used the LCA factor for herbicide Chlorpyrifos as substitute for an inhibitor. We assumed an inhibitor application rate of 0.4047 kg/acre (or 1 kg/ha) based on a recommended rate for a nitrification inhibitor (Trenkel, 2010). The LCA GHG emissions from nitrification inhibitors are well below the GHG emission savings from fertilizer production, hence, this assumption has minor impact on the resulting mitigation potential.

3.1.3. Adoption Potential

We based the adoption potential on the acreage that are applying fertilizer and are not using nitrification inhibitors. Exhibit 24 indicates the percent of acres that are using inhibitors as reported in 2010 in the ARMS Survey. As indicated, the ARMS survey only indicated the use of inhibitors on corn crops in eight states. We've also indicated the percent of acres that apply fertilizer. Rapeseed is not included as ARMS does not have data on rapeseed, hence we used the values for barley. The acres of cropland where inhibitors can be applied are limited to acres in states where nitrogen is applied and acres that are not using inhibitors.

Exhibit 24: Use of Nitrification Inhibitors and Fertilizer by State (percent of planted acres)

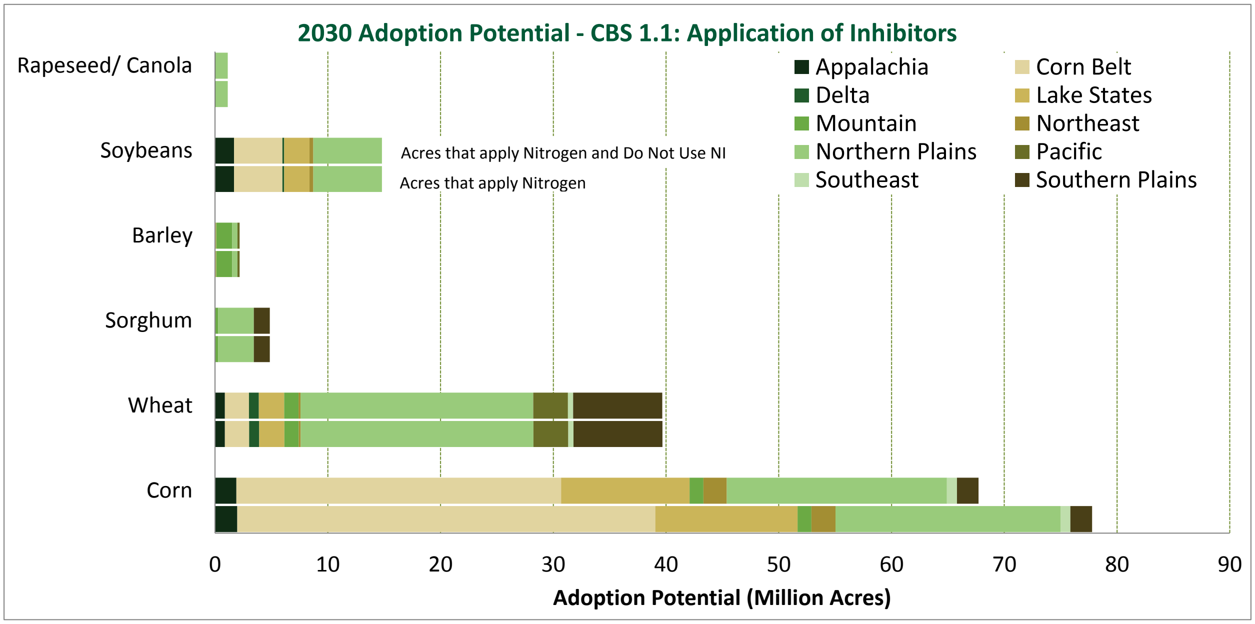
State	Nitrification Inhibitor Use for Corn	Application of Nitrogen Fertilizer					
		Barley	Corn	Rapeseed	Sorghum	Soybeans	Wheat
Alabama			90%				98%
Alaska							
Arizona			98%		61%		
Arkansas						NA	92%
California		100%					67%
Colorado			98%		61%		
Connecticut	3%		94%			37%	81%
Delaware	3%						100%
Florida	0%		90%				98%
Georgia			90%				98%
Hawaii							
Idaho		96%					98%
Illinois	22%		98%			11%	99%
Indiana	22%		99%			16%	
Iowa	22%		95%			7%	
Kansas	2%		99%		97%	21%	93%
Kentucky	6%		96%			28%	80%
Louisiana						4%	92%
Maine	3%		94%			37%	81%
Maryland	3%					24%	
Massachusetts	3%		94%			37%	81%
Michigan	9%		99%			28%	96%
Minnesota	9%	96%	87%			16%	91%
Mississippi						6%	100%
Missouri	22%		99%		100%	13%	90%
Montana		93%					
Nebraska	2%		99%		99%	32%	84%

State	Nitrification Inhibitor Use for Corn	Application of Nitrogen Fertilizer					
		Barley	Corn	Rapeseed	Sorghum	Soybeans	Wheat
Nevada							
New Hampshire	3%		94%			37%	81%
New Jersey	3%		94%			37%	81%
New Mexico							
New York	3%		86%				
North Carolina			94%			39%	88%
North Dakota	2%	100%	100%			42%	99%
Ohio	22%		100%			19%	99%
Oklahoma					69%		95%
Oregon							97%
Pennsylvania	3%		94%			37%	81%
Rhode Island	3%						
South Carolina			100%				
South Dakota	2%		98%		84%	31%	83%
Tennessee						42%	
Texas			99%		64%		47%
Utah			98%		61%		
Vermont	3%		94%			37%	81%
Virginia						32%	
Washington		100%					100%
West Virginia						32%	
Wisconsin	9%		93%			34%	
Wyoming		96%	90%				98%

Source: USDA ERS (2015b).

Exhibit 25 presents the resulting adoption potential by acres of cropland. The lower bar represents the acres of cropland that apply nitrogen, the upper bar represents acres that the ARMS data indicates are not applying inhibitors, and, hence represent the acres for which application of inhibitors could be adopted. ARMS data only indicated use of inhibitors on corn cropland, hence, the adoption potential for the other crop types is equivalent to those acres that apply nitrogen.

Exhibit 25: Adoption Potential for Application of Inhibitors



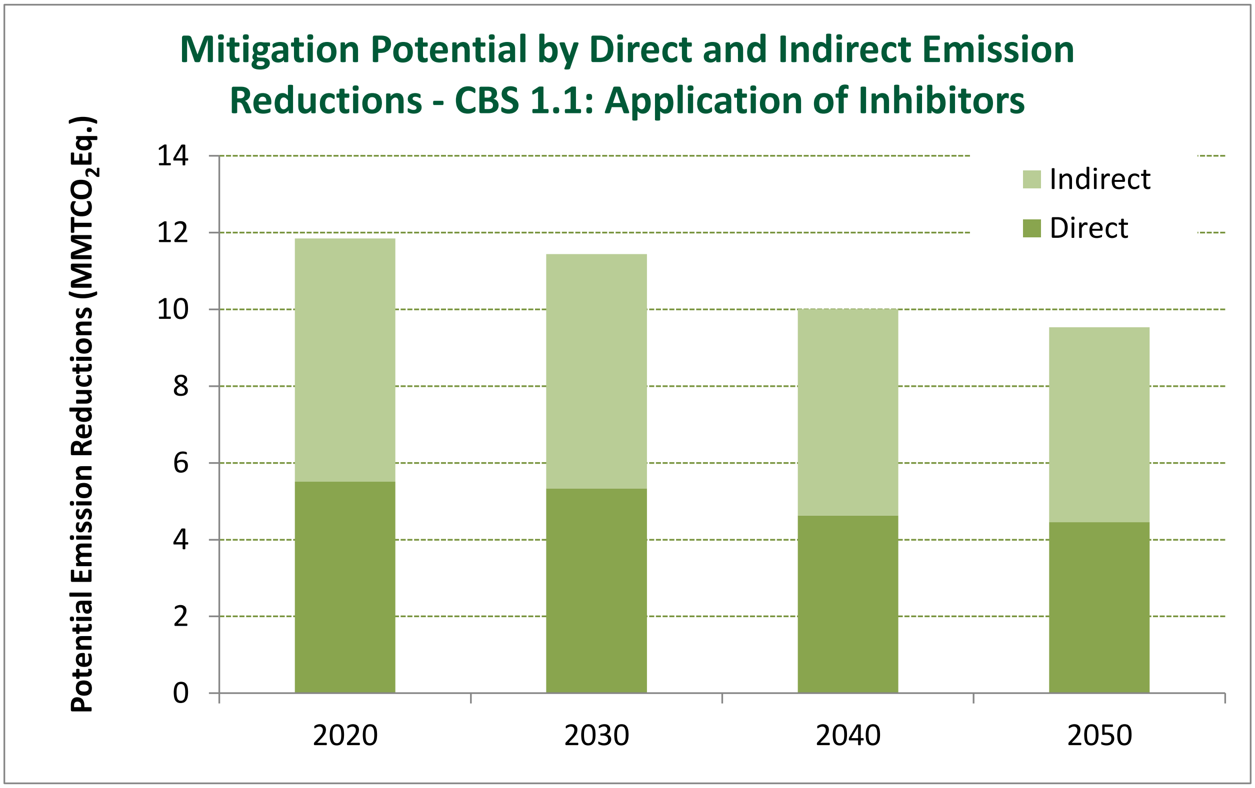
3.1.4. Mitigation Potential for 2020, 2030, 2040, and 2050

Key assumptions for estimating the mitigation potential include:

- Use of two emission reduction scenarios for modeling a lower and upper bound for nitrification and urease inhibitors;
- Use of best available crop and region emission reduction and yield data applied to all crops and all regions, where crop- or region-specific data was not available;
- No LCA factor is available for production of inhibitor, hence, used a value for herbicide Chlorpyrifos as a substitute for inhibitor; and
- Application of inhibitors is approximately 1 pound/acre, which is insignificant in comparison to the application of fertilizer and the resulting LCA.

Exhibit 26 presents the mitigation potential summarized by year and by direct versus indirect emission reductions. As indicated, direct and indirect emissions are comparable. Emission reductions decline over time as acreage decreases due to increases in yield.

Exhibit 26: Mitigation Potential for Use of CBS 1.1 Application of Inhibitors



The key findings include:

- Data indicates that inhibitors are currently used only on corn crops, hence, all acres that use fertilizer for other crops can adopt inhibitor;
- The use of fertilizer on soybeans is relatively high in some states; if fertilizer use is over-estimated, emission reduction potential for soybeans will be overestimated;
- As yield increases over time as indicated in the Monsanto Model, acreage declines, consequently, the mitigation potential decreases over time as acreage declines;
- Indirect emission savings from reduction in fertilizer use are on par with direct N_2O savings;
- Limited data exists on effectiveness of inhibitors for specific inhibitor types, crop types, regions, and inhibitor types across fertilizer types;
- Consensus exists on GHG emission reductions from inhibitors, but uncertainty in the scale of emission reductions; and
- Limited data sources that give comprehensive results (including emission reduction, fertilizer changes, and yield changes), consequently, the values of input variables come from more than one study.

3.1.5. Sensitivity Analysis and Risk Factors

3.1.5.1. Sensitivity Analysis

Exhibit 27 indicates the upper and lower bounds for selected input variables.

Exhibit 27: Lower and Upper Bounds for Selected Input Variables for CBS on Applying Inhibitors

Variable	Units	Value Used for Base Case	Lower Bound	Upper Bound
Nitrification Inhibitors – Emission Reduction Lower Bound	Percent	22%	22%[a]	35%[b]
Nitrification Inhibitors – Emission Reduction Upper Bound	Percent	35%		
Urease Inhibitors – Emission Reduction Lower Bound	Percent	41%	41%	61%
Urease Inhibitors – Emission Reduction Upper Bound	Percent	61%		
Nitrification Inhibitors – Change in Yield Lower Bound	Percent	10%	0%	10%
Nitrification Inhibitors – Change in Yield Upper Bound	Percent	10%		
Urease Inhibitors – Change in Yield Lower Bound	Percent	11%	0%	13%
Urease Inhibitors – Change in Yield Upper Bound	Percent	11%		
Nitrification and Urease Inhibitors – Fertilizer Reduction	Percent	9%[c]	4.5%	13.5%

[a] All acres that adopt use of inhibitor result in 22% reduction in GHGs.
[b] All acres that adopt use of inhibitor result in 25% reduction in GHGs.
[c] Evaluated 50% increased and decrease.

We estimated the national mitigation potential by changing the values. Exhibit 28 presents the national mitigation potential for each change in variable. As indicated, change in yield does not impact the emission reduction potential.

Exhibit 28: Resulting 2030 Mitigation Potential Based on Change in Variable for Applying Inhibitors (Million Metric Tons of CO_2-eq)

Variable	Using Lower Bound Value	Using Upper Bound Value
Base Case	11.30	
Nitrification Inhibitors – Emission Reduction Lower Bound Nitrification Inhibitors – Emission Reduction Upper Bound	10.70	11.89
Urease Inhibitors – Emission Reduction Lower Bound Urease Inhibitors – Emission Reduction Upper Bound	10.55	12.04
Nitrification Inhibitors – Change in Yield Lower Bound Nitrification Inhibitors – Change in Yield Upper Bound	11.30	11.30
Urease Inhibitors – Change in Yield Lower Bound Urease Inhibitors – Change in Yield Upper Bound	11.30	11.30
Nitrification and Urease Inhibitors – Fertilizer Reduction	8.61	13.98

3.1.5.2. Technical, Economic, and Policy Risk Factors

Summarized below are key factors that impact the adoption and resulting mitigation potential associated with the strategy of applying inhibitors.

- **Challenges in use of Inhibitors**. Farmers prefer to apply fertilizer in the fall when they have more time available rather than the spring. However, nitrogen losses are usually highest when applied in the early spring, when soil is particularly water-saturated (Schwab and Murdock, 2010). Volatilization losses are also highest when soil temperatures are warm, which also occurs in the spring, so inhibitors are most effective when used on wet, warm soils in the spring (Schwab and Murdock, 2010; Thapa et al., 2015). A meta-analysis of corn-producing areas in the U.S. using NBPT (Agrotain) also showed that N_2O emission response rates to the inhibitors varies by land resource region (Snyder et al., 2014). Consensus in the literature is limited on the extent of variability by region.
- **Timing of Application**. The timing of inhibitor application can have serious impacts on the effectiveness of inhibitors, as we have discussed.
- **Uncertainty in Changes in Yield Impact Adoption**. Crop yield can increase through the use of inhibitors, mainly due to the increase in nutrients actually available for crop use. An Iowa State University study on corn found that the yield response to the nitrification inhibitor N-Serve averaged a 10% increase, and four studies applying NBPT (i.e., urease inhibitor) on corn in Kansas found yield increases ranging from 4% to 18% with an average yield change of 13% (Trenkel, 2010). However, Schwab noted the dependency of the yield change on the baseline crop yield. Optimally, the costs savings for fertilizer saved and/or revenue increase for higher yield will offset the costs for the inhibitor, thereby encouraging the application of inhibitors. However, due to such variability in yield and change in fertilizer use, and the uncertainties of applying inhibitors in optimal conditions, there is uncertainty in changes in yield. This uncertainty will impact the ultimate adoption of inhibitors.
- **Limited Availability of Inhibitors**. Trenkel lists Dow AgroSciences, Conklin Company, Nutra-Flo, and Tessenderlo Kerley as the U.S. producers of nitrification inhibitors, and Dow AgroSciences is the only one that produces nitrapyrin, one of the most extensively studied and effective inhibitors (Trenkel, 2010). A few other options in the U.S. include Instinct and Nutrisphere-N, but the options are limited. Trenkel lists Agrotain International as the sole producer of urease inhibitors in the United States, showing the urease inhibitor market's further limitation in the country. While thousands of nitrification and urease inhibitors have been tested in the United States and internationally, very few of them meet the stringent requirements of being non-toxic, effective, compatible with common fertilizers, and relatively inexpensive (Trenkel, 2010).
- **Relatively high uncertainty for indirect N_2O emission reductions.** As mentioned in Chapter 2, estimates of indirect N_2O emissions are highly uncertain as evidenced by the U.S. EPA indicating a range of -46% to 160% for the U.S. inventory at the 95% confidence level (EPA, 2015a).

3.1.6. References

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3.2. Precision Agriculture: Variable Rate Technology for Fertilizer Application and Swath Control

In this section we present the use precision agriculture by evaluating two options: variable rate technology and swath control. Although both variable rate technology and swath control can be applied at the same time, we lacked data on the emission reduction potential for the combined practices, hence, we evaluate the implementation of them as stand-alone management strategies. However, we evaluated the national mitigation potential based on the assumption that a landowner who was not currently using precision agriculture would transition to either the use of variable rate technology or swath control. We used this approach to avoid double-counting national mitigation potential associated with future use of precision agriculture.

3.2.1. Variable Rate and Swath Control Technologies

3.2.1.1. Variable Rate Technology

Key Considerations in Use of Variable Rate Technology

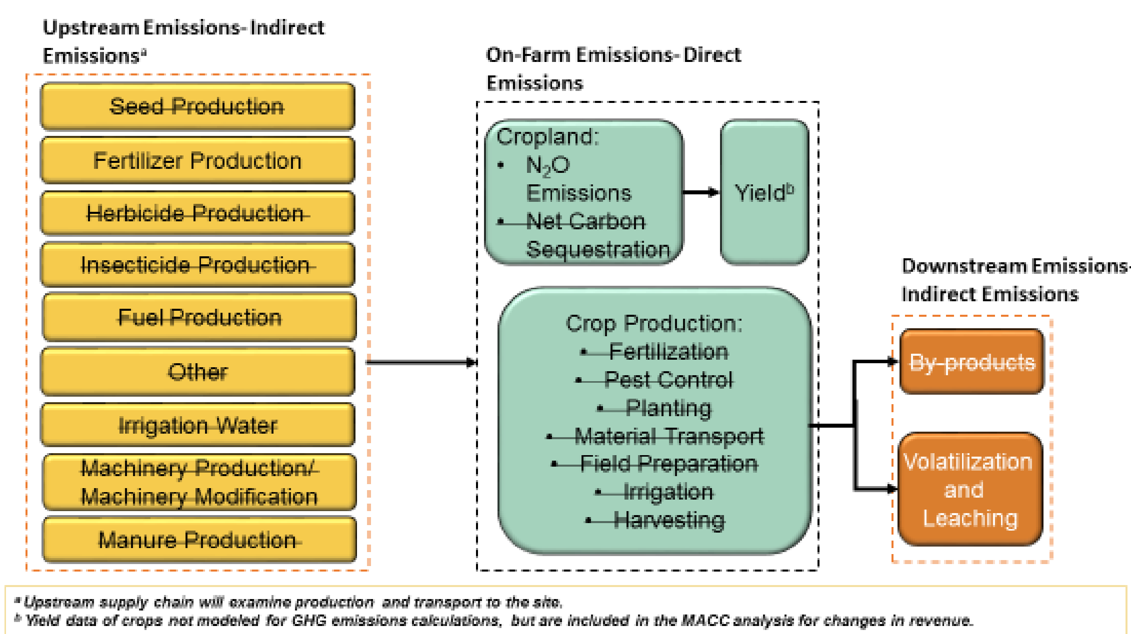
- Optimizes the rate of fertilizer application.
- Reduction in fertilizer application reduces upstream, on-site, and downstream GHG emissions

As discussed previously, precision agriculture includes many types of technologies that optimize inputs on a field. This section focuses on variable rate technology (VRT), primarily used for fertilizer application, that uses advanced GPS and GIS technologies to optimize the use of fertilizers. VRT covers a broad spectrum of sophistication. It can range from a web-based computer program that takes in field sampling data and creates a map of input needs to a fully automated technology system for tractors that creates maps, calculates nitrogen rates, and regulates the actual application of nitrogen. Mooney describes these two ends of the spectrum as either map-based VRT approaches or sensor-based VRT approaches. In particular, map-based VRT is a system that connects a variable-rate controller on an applicator to a computer program prescription map linked to (often purchased) special data; sensor-based VRT, on the other hand, obtains spatial data on the go using vehicle-mounted sensors (Mooney et al., 2009). Some of the most sophisticated VRT systems are sensor-based technologies that also track GPS data. However, despite this range in options, there is not sufficient data in the literature to differentiate results from the adoption of this wide variety of VRT technologies; therefore, for this study, we focus on the use of a sophisticated variable rate technology for fertilization application, such as GreenSeeker™, as a representative option. This crop sensing system efficiently manages crop inputs by observing crop status and regulating nitrogen input. The high-level optical sensing technology allows farmers to quantify crop health and nitrogen needs, and nitrogen is then recommended based on the yield potential and crop responsiveness to nitrogen (N Tech Industries, 2015). To regulate nitrogen inputs, sensors mounted on nitrogen application equipment communicate different optimal application rates for different zones. This regulation allows farmers to minimize their input costs and reduce their emissions by avoiding overuse of nitrogen. Exhibit 29, below, summarizes the up-stream, on-farm, and down-stream emissions impacted from the use of a VRT system.

Key Considerations in Use of Swath Control

- Swath control reduces the overlap of application of fertilizer, herbicide, or insecticide on fields.
- Can also be used on seed planters, to reduce the overlap of planted rows, which would increase the yield.
- Input savings depend on the shape of the field, with highest savings occurring on non-rectangular fields.

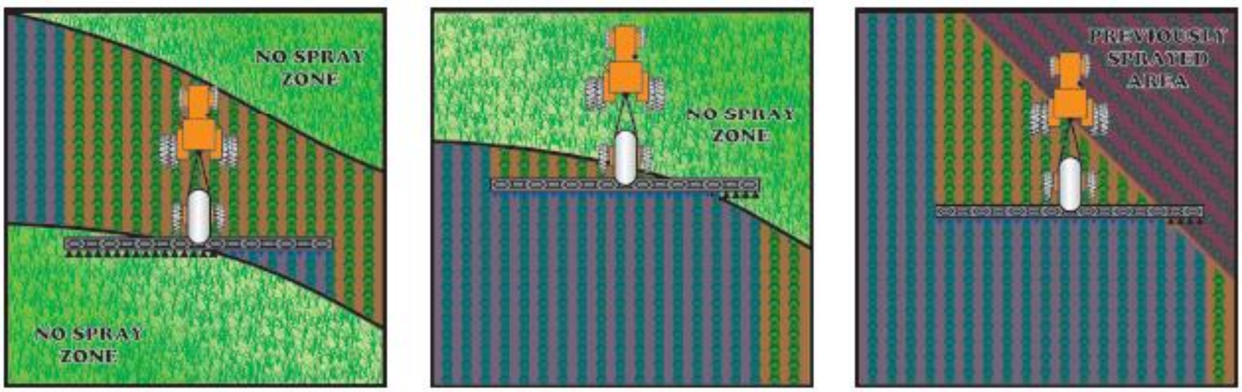
Exhibit 29: LCA Accounting Boundaries for Use of Variable Rate Technology



3.2.1.2. Swath Control

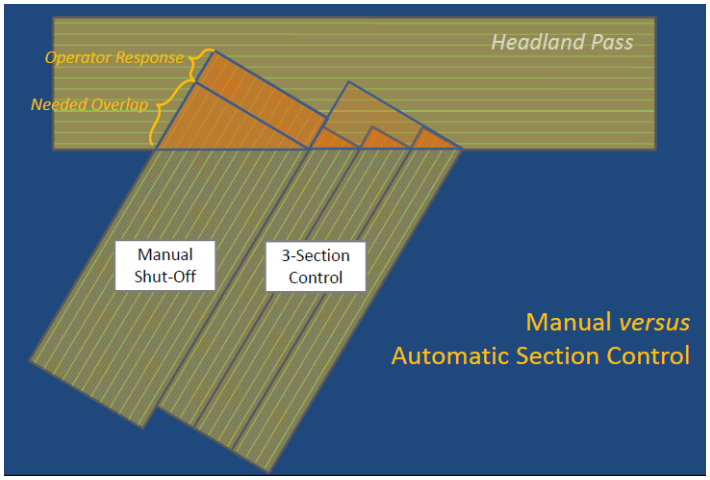
Swath control is the precision application of chemicals and seeds using global positioning satellite (GPS) technology. Also known as "Automatic Section Control" technology, it controls the sprayers, nozzles, and rows via a centralized computer system. The system records the areas that have been applied, and when the machine traverses across this area again, the machine automatically shuts off the sprayer, nozzle or row, and therefore reduces over-application. Another benefit to swath control is the ability to eliminate application of fertilizers, insecticides, and herbicides on unwanted areas, such as waterways and buffer strips (Fulton, n.d.). Exhibit 30 and Exhibit 31 illustrate how swath control works, and how it reduces overlap. ICF estimated the net GHG emissions associated with the processes mentioned in Exhibit 32 below.

Exhibit 30: Depiction of the Swath Control Technology



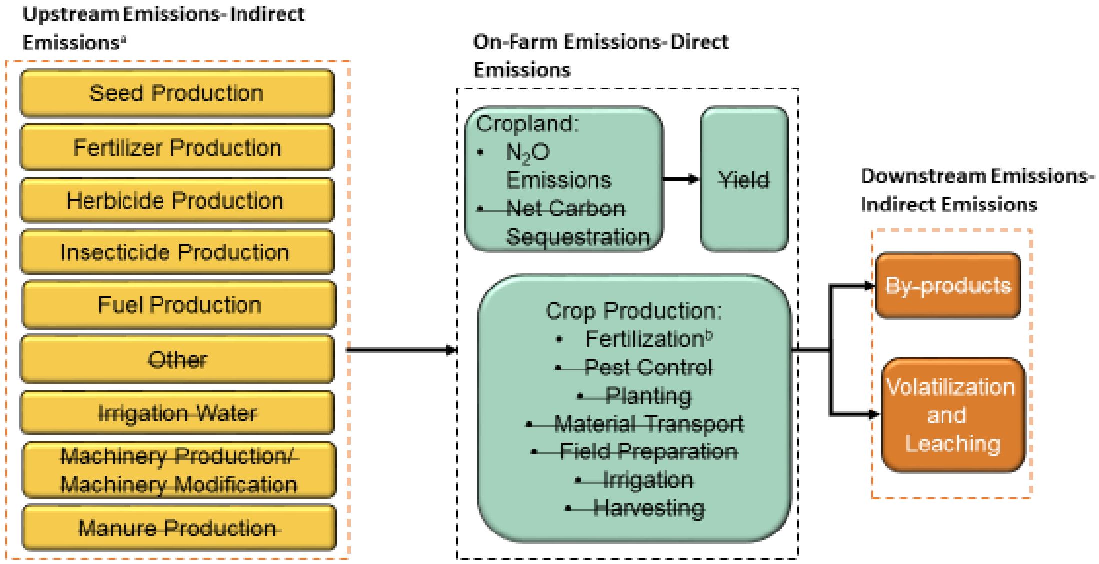
Source: Ohio Valley Ag (2015).

Exhibit 31: Demonstration of the Benefit of Swath Control



Source: Fulton (n.d.).

Exhibit 32: LCA Accounting Boundaries for Use of Swath Control

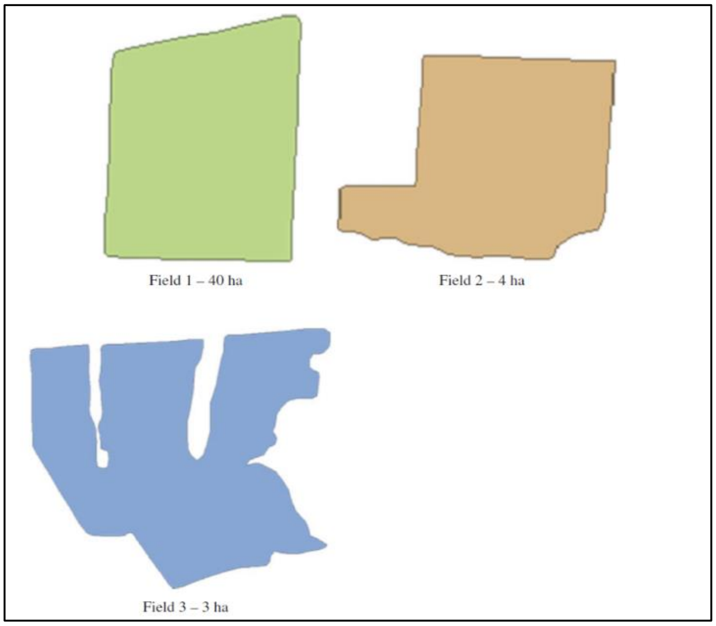


[a] *Upstream supply chain will examine production and transport to the site*
[b] *Includes mobile combustion from application.*

The effectiveness of swath control depends on the shape of the field. For example, swath control on a rectangular field will not have as high of savings as a non-rectangular field because the overlap will not be as significant. On a non-rectangular field, or if there are trees and other objects that the machinery needs to avoid, then swath control can realize significant reduction in inputs for the farmer, and therefore reduce input costs. As the size of the field increases, the shape of the field becomes less important Shockley et al. (2012). Exhibit 33 shows the fields that were modeled in the Shockley study. According to Shockley et al. (2012), the average reduction in overlap was approximately 9% when utilized on the sprayer and 6% when utilized on the planter.

Reduction in fertilizer, herbicide, and insecticide use. Due to the reduction in overlap, the amount of inputs applied to the field is reduced. To account for variability in field shapes, we modeled three different field shapes as indicated in Exhibit 34. The shapes for these fields are indicated in Exhibit 33. We used the application rates provided in Chapter 2 by crop type, estimated the resulting savings per field type, and used the life-cycle GHG emission factors to estimates the upstream production GHG savings per each input (i.e., fertilizer, pesticide, insecticide, and seed) based on reductions of inputs as indicated in Exhibit 34.

Exhibit 33: Field Shapes used for the Overlap Scenarios in Shockley et al. (2012)



Source: Shockley et al. (2012).

Exhibit 34: Overlap With and Without Section Control (percent)

Use of Section Control	Field 1	Field 2	Field 3
No section control	4.4%	12.6%	17.0%
With section control	0.66%	1.3%	1.7%
Percent Reduction	3.9%	11.3%	15.2%

Source: Shockley et al. (2012).

Reduction in fuel use. Brown et al. (2012) estimates that the use of swath control results in sprayer fuel savings of 15.6%. Swath control does not result in fuel savings for operating the tractor as traversing path of the tractor would not be altered under this scenario. These fuel savings reduce on-site GHG emissions and indirect emissions from fuel production.

3.2.2. Emission Reductions

This section presents the data for estimating emission reductions associated with the use of variable rate technology and swath control.

3.2.2.1. Emission Reductions for Variable Rate Technology

While the literature on emissions reductions from the use of VRT systems is very limited, ICF is using the results of a study done by Gabriel Vazquez Amabile in Argentina to evaluate the use of variable rate fertilization. This study, from 2013, found that the use of variable rate fertilization decreased GHG emissions from 19 to 35 percent in shallow soil ranges (Vazquez Amabile, 2013). While we would prefer to use emission reduction data from a study based in the United States, this percent reduction range is consistent with that used by ICF and the USDA in previous reports. A prior study found similar results. In particular, in 2003, Sehy, Ruser, and Munch determined that the use of VRT and GPS decreased N_2O emissions by up to 34 percent in low-yielding areas (ICF International, 2013).

In calculating mitigation potential, ICF also took into account input savings from variable rate technology. As cited by Snyder, a field-scale study of corn at 16 sites in Missouri showed savings-potential of 8.92 to 44.61 pounds per acre (10 to 50 kg of N/ha) in N rates (Roberts, 2010; Snyder, 2014). Using a baseline application rate of 156.8 pounds of N per acre in Missouri (i.e., the rate the Corn Belt region), VRT could result in a decrease of 5.7 to 28.4 percent in fertilizer use. These bounds average to 17 percent. Consequently, ICF assumed a 17 percent reduction in fertilizer use with lower and upper bounds of 5.7 and 28.4 percent, respectively. This potential fertilizer reduction influences both the lifecycle GHG emissions of crop-production and the operating and management costs of purchasing fertilizer.

As discussed in the previous section on application of inhibitors, N_2O emissions per acre are as provided by USDA in the report entitled *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory* (Eve et al., 2014). Direct N_2O emission reductions are the product of the N_2O emissions per acre and the percent reduction scenario. Similarly, the indirect N_2O emissions emission reductions are the product of the indirect N_2O emissions per acre (expressed as a ratio of the direct N_2O emissions) and the percent reduction scenario. Finally, as in the inhibitor analysis, we assumed that the net change in use of mobile equipment is zero; hence, the net change in GHGs from use of mobile equipment is zero.

3.2.2.2. Emission Reductions for Swath Control

As mentioned in Chapter 2: Summary of Methodology, N_2O emissions per acre are as provided by USDA in the report entitled *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory* (Eve et al., 2014). Direct N_2O emission reductions are the product of the N_2O emissions per acre and the percent reduction indicated in Exhibit 34. Similarly, the indirect N_2O emissions emission reductions are the product of the indirect N_2O emissions per acre (expressed as a ratio of the direct N_2O emissions) and the percent reduction indicated in Exhibit 34.

Reductions in Fuel Use

Per Brown et al. (2012) the net fuel savings for the sprayer is 15.6%. We used this data on fuel use for a tractor and a sprayer and estimated the fuel savings relative to the total fuel for application of fertilizer. We assumed that the net change in emissions from the fuel savings from the sprayer was 2.4% of total fuel use, which was calculated from Brown et al. (2012) data and is shown in Exhibit 35. We estimated GHG reductions for the fuel savings based on the life-cycle emission factors provided in Chapter 2.

Exhibit 35: Reductions in Fuel Use for Swath Control

	Baseline Fuel Use (gallons)[a]	Swath Control Fuel Use (gallons)[a]	Fuel Savings (gallons)	% Reduction
Tractor Fuel	12,558	12,558	-	
Sprayer Fuel	2,247	1,897	350	15.6%
Total Fuel	14,805	14,455	350	2.4%

[a] Brown et al. (2012) Table 2.

3.2.3. Adoption Potential

We based the adoption potential on the acreage that are applying fertilizer and are not using precision agriculture per the ARMS Survey. Exhibit 36 indicates the percent of acres that are using precision agriculture as reported in 2010 in the ARMS Survey. As indicated, the ARMS survey only provided data for the use of precision agriculture in 23 states. Exhibit 24 in Section 4.1: Application of Inhibitors indicates the percent of acres that apply fertilizer. Rapeseed is not included, as ARMS does not have data on rapeseed. For rapeseed, ICF assumed the same usage by state as barley. The acres of cropland where VRT and swath control can be applied are limited to acres in states that both apply nitrogen and do not yet use precision agriculture. We assumed that for 50% of those acres that are currently fertilizing and utilizing precision agriculture will adopt VRT and the other 50% will adopt swath control.

Exhibit 36: Use of Precision Agriculture

State	Barley	Corn	Rapeseed	Sorghum	Soybeans	Wheat
Alabama						
Alaska						
Arizona		16%		42%		11%
Arkansas					13%	
California	14%		14%			
Colorado		16%		42%		11%
Connecticut	18%	4%	18%			
Delaware	18%	4%	18%			
Florida						

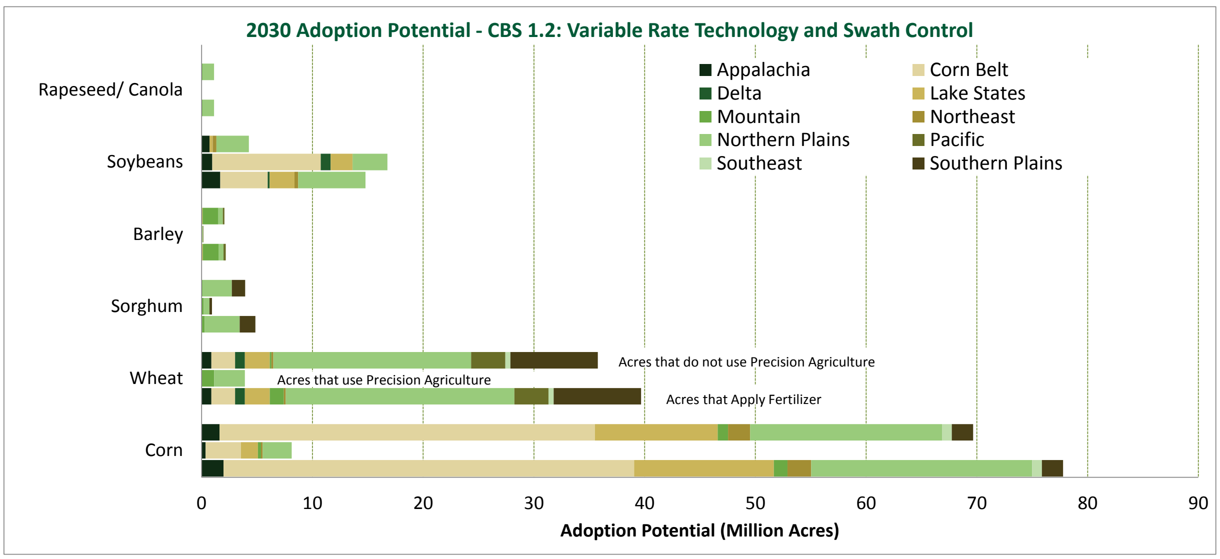
State	Barley	Corn	Rapeseed	Sorghum	Soybeans	Wheat
Georgia						
Hawaii						
Idaho		16%		42%		11%
Illinois		8%			28%	
Indiana		8%			28%	
Iowa		8%			28%	
Kansas	14%	13%	14%	16%	17%	13%
Kentucky	7%	11%	7%		20%	
Louisiana					13%	
Maine	18%	4%	18%			
Maryland	18%	4%	18%			
Massachusetts	18%	4%	18%			
Michigan	7%	11%	7%		18%	
Minnesota	7%	11%	7%		18%	
Mississippi					13%	
Missouri		8%			28%	
Montana		16%		42%		11%
Nebraska	14%	13%	14%	16%	17%	13%
Nevada		16%		42%		11%
New Hampshire	18%	4%	18%			
New Jersey	18%	4%	18%			
New Mexico		16%		42%		11%
New York	18%	4%	18%			
North Carolina	7%	11%	7%		20%	
North Dakota	14%	13%	14%	16%	17%	13%
Ohio		8%			28%	
Oklahoma				10%		
Oregon	14%		14%			
Pennsylvania	18%	4%	18%			
Rhode Island	18%	4%	18%			

State	Barley	Corn	Rapeseed	Sorghum	Soybeans	Wheat
South Carolina						
South Dakota	14%	13%	14%	16%	17%	13%
Tennessee	7%	11%	7%		20%	
Texas				10%		
Utah		16%		42%		11%
Vermont	18%	4%	18%			
Virginia	7%	11%	7%		20%	
Washington	14%		14%			
West Virginia	7%	11%	7%		20%	
Wisconsin	7%	11%	7%		18%	
Wyoming		16%		42%		11%

Sources: USDA ERS (2015b).

Exhibit 37 presents the resulting adoption potential by acres of cropland. The lower bar represents the acres of cropland that apply nitrogen, the upper bar represents acres that the ARMS data indicates are not applying inhibitors, and, hence represent the acres for which application of inhibitors could be adopted. ARMS data only indicated use of inhibitors on corn cropland, hence, the adoption potential for the other crop types is equivalent to those acres that apply nitrogen.

Exhibit 37: Adoption Potential for Variable Rate Technology and Swath Control



3.2.4. Mitigation Potential for 2020, 2030, 2040, and 2050

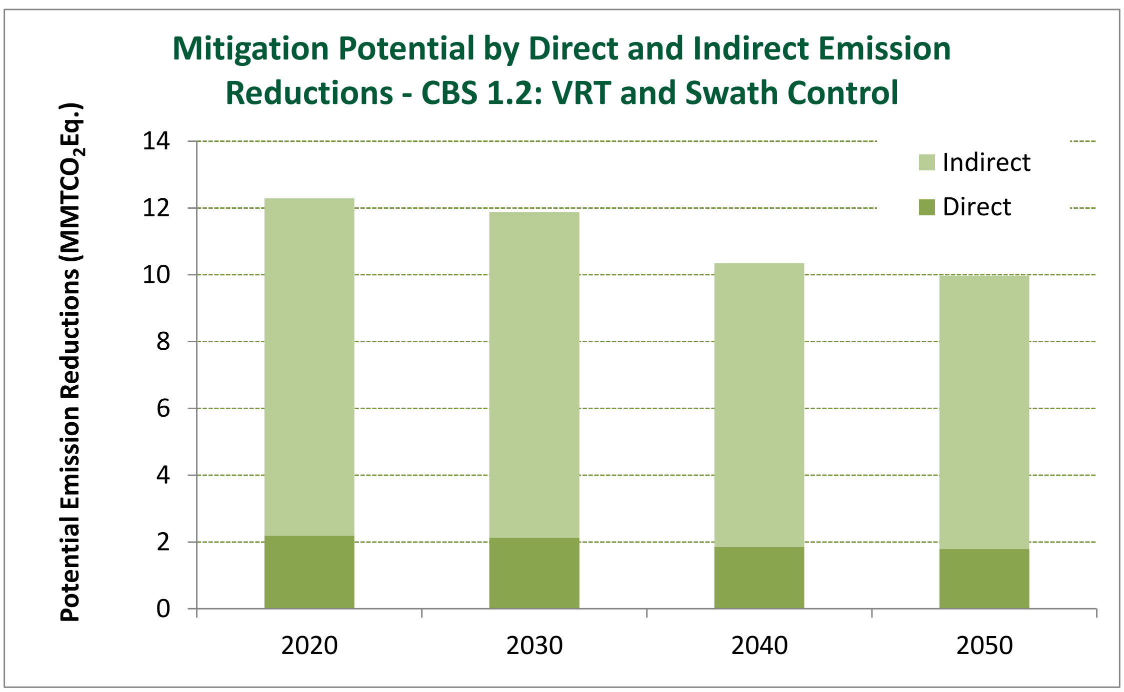
Key assumptions include:

- Adoption of VRT and swath control is split evenly between the two technologies; and
- Emission reduction are based on reduction in overlap for each of the field scenarios for VRT and reductions in fertilizer and other inputs for swath control.

The mitigation potential is presented in Exhibit 38 for direct and indirect emission reduction. The indirect emission reductions are greater than the direct on-site emission reductions. This relatively large difference is due to the reduction in upstream production of fertilizer, herbicides, insecticides, and seeds. The key findings include:

- As yield increases over time as indicated in the Monsanto Model, acreage declines, consequently, the mitigation potential decreases over time as acreage declines;
- Majority of VRT and swath control emission reductions are indirect, from upstream reductions of inputs;
- Effectiveness of VRT depends on soil and condition variability within a field; effectiveness of swath control depends on shape of field;
- Limited data exist on the effectiveness of VRT and swath control; and
- Very limited data exists on using VRT and swath control in combination.

Exhibit 38: Mitigation Potential for 2020, 2030, 2040 – CBS2.2: Variable Rate Technology and Swath Control



3.2.5. Sensitivity Analysis and Risk Factors

3.2.5.1. Sensitivity Analysis

Exhibit 39 indicates the upper and lower bounds and the source of the values for selected input variables. Exhibit 40 presents the national mitigation potential for each change in variable.

Exhibit 39: Lower and Upper Bound Estimates for Input Variables for CBS on VRT and Swath Control

Variable	Units	Value Used in Base Case	Lower Bound	Upper Bound
Variable Rate Technology				
Lower Bound Emission Reduction	Percent	19%	19%[a]	35%[b]
Upper Bound Emission Reduction	Percent	35%		
Reduction in Fertilizer Use	Percent	17%[c]	8.5%	25.5%
Swath Control				
Emission Reduction in GHGs and in Inputs for Field Types	Percent	4%, 11%, 15%	4%[d]	15%[e]

[a] All acres that adopt use of VRT result in 19% reduction in GHGs.
[b] All acres that adopt use of VRT result in 35% reduction in GHGs.
[c] Evaluated 50% increased and decrease.
[d] All acres that adopt use of swath control result in 4% reduction in inputs.
[e] All acres that adopt use of swath control result in 15% reduction in inputs.

Exhibit 40: Resulting Mitigation Potential Based on Change in Variable for VRT and Swath Control (Million Metric Tons of CO_2-eq)

Variable	Using Lower Bound Value	Using Upper Bound Value
Baseline Value	9.55	
Variable Rate Technology		
Lower Bound Emission Reduction Upper Bound Emission Reduction	8.99	10.10
Reduction in Fertilizer Use	9.46	14.30
Swath Control		
Emission Reduction in GHGs and in Inputs for Field Types	9.38	13.09

3.2.5.2. Technical, Economic, and Policy Risk Factors

Summarized below are key factors that impact the adoption and resulting mitigation potential associated with the strategy of adopting the use of VRT and swath control.

Variable Rate Technology

- **Challenges in use of VRT.** While it is well established that VRT helps optimize the rates of input application, the level of effectiveness of VRT is highly dependent on soil types, production year, and soil depth (Porter et al., 2012; Vazquez-Amabile et al., 2013). In particular, multiple studies found that the use of VRT was more successful in shallow soil ranges, and less useful in deep soil ranges (Porter et al., 2012; Vazquez-Amabile et al., 2013). Additionally, a field with more internal variability will see more improvement from VRT than a relatively uniform field.
- **Uncertainty in fertilizer savings.** The savings from use of VRT are seen through decreasing fertilizer needs .As discussed previously, the literature supports a significant decrease in fertilizer use; however, there is no guarantee that this will occur on a particular field. In particular, while uncommon, it is possible that a farmer could be under-applying fertilizer, and a VRT would recommend increasing the fertilizer application rate, therefore increasing the cost of fertilizer.
- **Uncertainty in VRT's impact on fertilizer rates.** As we have described, most studies find that use of VRT will reduce the overall application rate of fertilizer. This reduction allows for a decrease in both input costs and direct GHG emissions. However, several studies indicate that VRT can also increase the application rate of fertilizer, in particular if the farmer prefers to apply higher rates to increase yield. As Schieffer and Dillon describe, "a heavier average application could be used to increase yields and net returns" (Schieffer and Dillon, 2015). They ran a computer model of a representative grain farm and found that VRT can increase nitrogen use (Schieffer and Dillon, 2015). In addition, if a farmer is consistently under-applying nitrogen, then VRT systems would result in an increase the fertilizer application rate.
- **Lack of U.S.-based emission reduction data.** While studies in the United States look at the effectiveness of VRT with fertilizer use, they do not discuss changes in GHG emissions from VRT use. Therefore, ICF used values from a study in Argentina to model the emission reductions; however, ICF did a quality check on the values and found them to be similar to U.S. findings in 2003. We used lower and upper bound scenarios to model two potential outcomes and take into account the uncertainty of emission reductions.
- **Uncertainty in adoption.** ICF downloaded publicly available data from USDA ARMS on Crop Production Practices, which is the best publicly available data in the United States on acres using precision agriculture. Under the category of Precision Agriculture, ICF used the data entitled "VRT used for Any Purpose", which is defined as "Variable Rate Technology used for Any Purpose, expressed as a percent of planted acres" (USDA ARMS Data dictionary). ICF did

not use the higher level category of 'Precision Agriculture Used' as this broader category includes use of yield monitors, soil maps, and evaluation of soil properties that do not preclude the future use of VRT or swath control (i.e., if we used the broader category of precision agriculture the adoption potential would be significantly underestimated as well over 50% of cropland use a form of precision agriculture).

- **Use of high-efficiency irrigation technology**. High-efficiency application irrigation technologies similar to the precision agriculture technologies provide another opportunity to reduce GHGs, however, this technology is not included in this report.

Swath Control

- **Lack of Data on Environmental Benefits.** Limited data exists on the environmental benefits of using swath control technology. However, adoption of swath control has been increasing with a 10% adoption of guidance systems as of 2004, and increasing to 35% adoption by 2009 (Erickson, 2013).
- **Emission Reductions**. We assumed that the emission reductions are directly proportional to the reduction in overlap as provided in Exhibit 34. The actual reductions will depend on soil conditions and actual fertilizer application rates.
- **Dependence on shape/configuration of the field**. The effectiveness of swath control depends on the shape of the field. The shape of the field was not modeled in this study, due to limitations on data. Different states have different typical shapes of fields, but this level of evaluation was not included in the model. Instead, we assumed that each of the fields (i.e., 1, 2, and 3) comprise approximately 1/3 of the total acreage available for adoption of swath control in each region.
- **Size of the Sprayer**. The amount of overlap increases with the size of the sprayer, and therefore the potential reductions in overlap increase with the size of the sprayer (Fulton, n.d.). A variety of sprayer sizes was not modeled in this analysis, due to the lack in data and increased complexity.
- **Potential for Yield Increases.** Research suggests a potential increase in yield. In particular, the Farm Journal Test Plots found an average yield increase of 30 bushels per acre (Fischer, 2008). Studies like Fischer's have shown that because swath control reduces overplanting, it increases yield, though typically, these yield increases are relatively small. These yield increases are a co-benefit to the use of swath control.

3.2.6. References

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4. CBS 2: Sustainable Tillage and Cover Crops

CBS 2 Field Management Options

- CBS 2.1 Reducing Tillage Intensity
  - Switching from Conventional to Reduced till (CT-RT)
  - Switching from Conventional to No-till (CT-NT)
  - Switching from Reduced till to No-till (RT-NT)
- CBS 2.2 Cover Crop Rotations
  - Adding a legume as a winter cover crop to cash crops grown under each of the three tillage practices
  - Adding a grass as a winter cover crop to cash crops grown under the three tillage practices

The Intergovernmental Panel on Climate Change's (IPCC's) Fifth Assessment Report (AR5) (IPCC, 2014)) suggests that reducing carbon losses from managed agricultural soils by changing management practices is a key opportunity to reduce greenhouse gas (GHG) emissions in the Agriculture, Forestry, and Other Land Uses (AFOLU) sector. These changes in management practices include switching from conventional tillage to conservation tillage (i.e., reduced tillage and no tillage) and planting winter cover crops. In the United States, adoption of no tillage ("no-till") has been estimated to sequester an additional 18-36 Tg CO_2 annually via soil organic carbon (SOC) (Lal et al., 2007) while cover-crop rotations are estimated to be able to sequester 6.2 Tg CO_2-eq yr^{-1} in the US and as much as 100-140 Tg C (367-513 Tg CO_2-eq) yr^{-1} globally (Eagle et al., 2012; Poeplau and Don, 2015). CBS 2.1 evaluates the reductions in GHG emissions associated with adopting conservation tillage practices and CBS 2.2 evaluates the reduction in GHG emissions associated with adding a winter cover crop rotation to cash crops.

4.1. Conservation Tillage

4.1.1. Tillage Practices and Impacts on Greenhouse Gas Emissions

Conventional tillage (frequently using a moldboard plow) (CT) typically leaves less than 15% of crop residues remaining on the soil; reduced tillage (*not* using a moldboard plow) (RT) leaves between 15% and 30% of cover/residues on the soil; and no-till (NT) practices leave at least 30% of cultivated crop residues on the soil (Heimlich, 2003). Tillage of soil increases the mineralization of SOC to carbon dioxide (CO_2). A strong correlation exists between the tillage intensity (i.e., the volume of soil disturbed) and the amount of SOC lost to the atmosphere as gaseous CO_2. Consequently, implementing conservation tillage practices is an option to decrease net CO_2 emissions from crop production (Balkcom et al., 2013; Franzluebbers, 2010; ICF International, 2013; Lal et al., 2007; West and Post, 2002).

Although there is wide agreement that employing conservation tillage practices results in increased carbon sequestration, there is not a consensus on the magnitude of the impact. Factors that impact the amount of carbon sequestered include: the types of crops being cultivated, continuous vs. rotated crop cultivation, soil types (e.g., histosols or alfisols), regional climate, and the permanence of the reduced tillage intensity (i.e., the frequency that farmers till soil). The majority of the SOC cycling occurs in the top 30 cm of the soil (and often even only the top 15 cm of soil) (Balkcom et al., 2013; Franzluebbers, 2010; West and Post, 2002).

Key Considerations in Switching from Conventional to Conservation Tillage

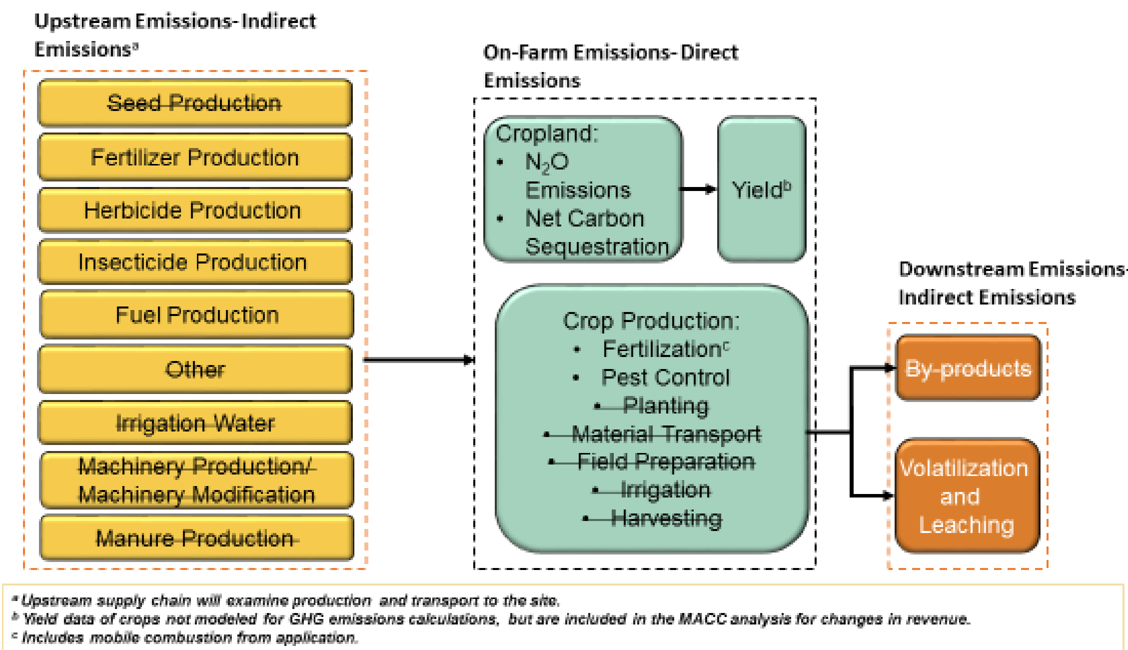
- Conservation tillage (reduced and no till) can increase soil carbon storage and soil moisture and decrease erosion and sedimentation
- Conservation tillage can reduce fuel and labor inputs
- Switching to conservation tillage requires new equipment and management practices and may reduce crop yield
- The amount of soil carbon sequestered varies regionally and by soil type and moisture

In addition to increasing soil carbon, conservation tillage practices result in other benefits for the farmer and the soil. These include reduced soil erosion and sedimentation, improved soil quality, increased soil water conservation and reduced equipment, time and energy use. There are also negative effects associated with conservation tillage including increased need for weed and insect control (including chemical applications, though the relationship between tillage practices and chemical applications is not uniform), increased risk of soil compaction, risks of yield reduction, the potential need for new farm machinery (e.g., no-till drill seeder, but the benefits of purchasing a new seeder do not always outweigh the cost and is therefore not included in this study) (Eppelin, 2015; Orlowski et al., 2012), and higher levels of management skills (ICF International, 2013; Lal et al., 2007).

The LCA estimates the total changes in GHG emissions associated with reducing tillage intensity. As depicted in Exhibit 41, upstream emissions for the LCA of *CBS 2.1: Reduced Tillage* include the CO_2, CH_4, and N_2O associated with changes in diesel fuel production, pesticide production, and fertilizer production. On-farm emissions include changes in SOC storage associated with reducing tillage intensity; changes in diesel combustion emissions from field operations for crop production, which include fertilization, field preparation, and pest/weed control; changes in emissions due to the temporary (likely several years) increases in the amount of fertilizer and pesticide used (though increases are not uniformly-experienced across crop types and regions); and changes in nitrous oxide (N_2O) emissions resulting from the application of N fertilizer. We do not include on-farm CH_4 emissions (e.g., from cropland) within the boundaries of CBS 2.1 as such emissions are typically marginal compared to CO_2 and N_2O. Downstream emissions include only the changes in volatilization and leaching from the on-farm application of N fertilizer.

Excluded from the evaluation of conservation tillage are the emission sources and processes that are constant between tillage practices. These practices include: machinery production; seed production; irrigation or irrigation equipment production; manure production; waste management; byproducts; and harvesting.

Exhibit 41: LCA Accounting Boundaries for Tillage Practices



On average, yields tend to decline after reducing tillage intensity. To offset some of the yield loss, farmers can apply additional nitrogen, phosphorous, and potassium fertilizers, which would increase net life cycle GHGs. Recent survey data indicate that differences in fertilizer application rates between CT, RT, and NT are quite variable. For example, the amount of nitrogen applied to corn seems slightly higher under conservation tillage practices, while both phosphorus and potassium fertilizer rates decrease. Wheat nitrogen application rates either decrease or stay approximately the same under conservation tillage practices, while phosphorus and potassium application rates both increase (USDA ERS, 2015a). We note that there is likely to be variation in reporting practices for tillage practices—farmers may report their tillage practice as NT, but may actually be tilling seasonally or every couple of years, depending on crop types and whether they rotate crops. Herbicide application rates are higher under conservation tillage practices for all crop types other than soybeans,[9] which appears to receive less herbicide. Patterns in insecticide application rates, like fertilizers, are variable amongst the different crop types. Insecticide application rates per acre are much less impactful on production costs than either fertilizers or

[9] Reliable data on changes in herbicide and insecticide application rates for rapeseed under RT and NT were not available; consequently, we use the same application rate assumptions for RT and NT practices as barley.

herbicides.

In this study, we consider the change in inputs that will change when adopting conservation tillage practices. In particular, we consider changes in fertilizer application, herbicide application, insecticide application, and diesel fuel use. The sources for the data utilized in this study are provided in Exhibit 42. Exhibit 43, Exhibit 44, and Exhibit 45 provide the data for calculating changes in production inputs for CT-RT, CT-NT, and RT-NT, respectively. Exhibit 46 provides a detailed example of the modeled changes in production inputs for switching corn cultivation from CT-NT within each USDA region.

Exhibit 42: Data Sources for Cultivating Crops under Each Tillage Practice

Data	Source
Quantity and Type of N, P, and K Fertilizers Applied to Each Crop Type (Except Rapeseed), by USDA Farm Production Region	USDA NASS (2015).
Quantity and Type of Herbicides Applied to Each Crop Type (Except Rapeseed), by USDA Farm Production Region	USDA NASS (2015).
Quantity and Type of Insecticides Applied to Each Crop Type (Except Rapeseed), by USDA Farm Production Region	USDA NASS (2015).
Ratios of Chemical Applications for Each Crop Type (Except Rapeseed) between Tillage Practices (e.g., lbs N applied to NT corn relative to lbs N for CT corn)	USDA ERS (2015a).
Quantity and Type of Herbicides Applied to Rapeseed, by Tillage Practice	Canola Council (2015a).
Fuel Use, All Crops and Tillage Practices	University of Tennessee (2015).
Soil Moisture Regimes (for Determining Yield Reductions)	USDA NRCS (2015).
Quantity and Type of N, P, and K Fertilizers Applied to Rapeseed by Yield	Canola Council (2015b).

Exhibit 43: Changes in Production Inputs Associated with Switching from Conventional Till to Reduced Till (CT-RT)

Changes in Inputs, Relative to CT Practices	USDA Farm Production Regions									
	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Barley										
Nitrogen Fertilizer Application (lbs/acre) [a]	-0.8	-0.8	-0.8	-0.6	-1.2	-0.5	-0.9	-0.8	-0.8	-0.8
Potassium Fertilizer (lbs/ acre) [a]	-1.9	-1.3	-1.3	-2.1	-1.0	-1.5	-0.6	-0.6	-1.3	-1.3
Phosphorus Fertilizer (lbs/acre) [a]	-2.9	-2.0	-2.0	-2.0	-2.4	-2.3	-1.8	-0.9	-2.0	-2.0
Herbicide Application (lbs/acre) [a]	-0.3									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	-1.1									
Corn										
Nitrogen Fertilizer Application (lbs/acre) [a]	0.7	0.8	0.7	0.6	0.7	0.5	0.7	0.7	0.7	0.7
Potassium Fertilizer (lbs/ acre) [a]	-4.3	-4.6	-2.9	-3.8	-2.9	-2.0	-1.7	-2.9	-2.9	-1.1
Phosphorus Fertilizer (lbs/acre) [a]	-4.9	-4.5	-3.4	-3.0	-3.4	-2.4	-2.8	-3.4	-3.4	-2.7
Herbicide Application (lbs/acre) [a]	2.1									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	-1.1									
Rapeseed										
Nitrogen Fertilizer Application (lbs/acre) [a]	0.0	0.0	0.0	-1.0	-1.1	0.0	-1.1	0.0	0.0	0.0
Potassium Fertilizer (lbs/ acre) [a]	1.4	1.4	1.4	2.2	1.0	1.4	1.0	1.4	1.4	1.4
Phosphorus Fertilizer (lbs/acre) [a]	0.9	0.9	0.9	1.4	0.6	0.9	0.6	0.9	0.9	0.9
Herbicide Application (lbs/acre) [a]	-0.1									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre) [b]	-1.1									

Changes in Inputs, Relative to CT Practices	USDA Farm Production Regions: Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Sorghum										
Nitrogen Fertilizer Application (lbs/acre) [a]	3.3	3.3	3.3	3.3	2.5	3.3	3.9	3.3	3.3	3.5
Potassium Fertilizer (lbs/ acre) [a]	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
Phosphorus Fertilizer (lbs/acre) [a]	-1.3	-1.3	-1.3	-1.3	-1.0	-1.3	-1.6	-1.3	-1.3	-1.4
Herbicide Application (lbs/acre) [a]	-2.1									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre) [b]	-1.0									
Soybeans										
Nitrogen Fertilizer Application (lbs/acre) [a]	0.1	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.1
Potassium Fertilizer (lbs/ acre) [a]	0.9	1.0	0.9	0.9	0.8	0.8	0.4	0.8	0.8	0.8
Phosphorus Fertilizer (lbs/acre) [a]	2.0	2.2	2.0	1.4	1.8	1.8	1.7	1.8	1.8	1.8
Herbicide Application (lbs/acre) [a]	-0.9									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre) [b]	-1.3									
Wheat										
Nitrogen Fertilizer Application (lbs/acre) [a]	-12.6	-16.5	-12.6	-12.6	-12.8	-12.6	-10.2	-13.8	-12.6	-10.0
Potassium Fertilizer (lbs/ acre) [a]	2.3	5.7	2.3	2.3	1.3	2.3	1.3	2.3	2.3	1.1
Phosphorus Fertilizer (lbs/acre) [a]	1.8	3.3	1.8	1.8	1.4	1.8	1.6	1.1	1.8	1.6
Herbicide Application (lbs/acre) [a]	1.7									
Insecticide Application (lbs/acre) [a]	-0.1									
Diesel Fuel (gallons/acre)[b]	-1.1									

Sources: [a]USDA NASS (2015). [b]University of Tennessee (2015).

Exhibit 44: Changes in Production Inputs Associated with Switching from Conventional Till to No-Till (CT-NT)

Changes in Inputs, Relative to CT Practices	USDA Farm Production Regions									
	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Barley										
Nitrogen Fertilizer Application (lbs/acre) [a]	-18.6	-17.8	-17.8	-13.3	-26.3	-11.7	-19.6	-17.3	-17.8	-17.8
Potassium Fertilizer (lbs/ acre) [a]	-5.8	-3.8	-3.8	-6.1	-2.9	-4.4	-1.7	-1.9	-3.8	-3.8
Phosphorus Fertilizer (lbs/acre) [a]	-7.7	-5.5	-5.5	-5.3	-6.4	-6.1	-4.8	-2.4	-5.5	-5.5
Herbicide Application (lbs/acre) [a]	0.5									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	-2.3									
Corn										
Nitrogen Fertilizer Application (lbs/acre) [a]	3.0	3.3	2.8	2.6	2.8	2.1	2.8	2.8	2.8	3.1
Potassium Fertilizer (lbs/ acre) [a]	-5.0	-5.3	-3.4	-4.5	-3.4	-2.3	-2.0	-3.4	-3.4	-1.3
Phosphorus Fertilizer (lbs/acre) [a]	-1.3	-1.2	-0.9	-0.8	-0.9	-0.7	-0.8	-0.9	-0.9	-0.7
Herbicide Application (lbs/acre) [a]	0.2									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	-2.2									
Rapeseed										
Nitrogen Fertilizer Application (lbs/acre) [a]	0.0	0.0	0.0	-21.7	-24.4	0.0	-24.4	0.0	0.0	0.0
Potassium Fertilizer (lbs/ acre) [a]	3.7	3.7	3.7	4.8	3.2	3.7	3.2	3.7	3.7	3.7
Phosphorus Fertilizer (lbs/acre) [a]	2.3	2.3	2.3	3.0	2.0	2.3	2.0	2.3	2.3	2.3
Herbicide Application (lbs/acre) [a]	0.3									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	-2.3									
Sorghum										

Changes in Inputs, Relative to CT Practices	USDA Farm Production Regions: Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Nitrogen Fertilizer Application (lbs/acre) [a]	-9.3	-9.3	-9.3	-9.3	-7.0	-9.3	-11.1	-9.3	-9.3	-9.9
Potassium Fertilizer (lbs/ acre) [a]	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7	-0.7
Phosphorus Fertilizer (lbs/acre) [a]	-1.6	-1.6	-1.6	-1.6	-1.1	-1.6	-1.9	-1.6	-1.6	-1.7
Herbicide Application (lbs/acre) [a]	1.3									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	--2.1									
Soybeans										
Nitrogen Fertilizer Application (lbs/acre) [a]	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Potassium Fertilizer (lbs/ acre) [a]	1.8	2.1	1.8	1.8	1.7	1.7	0.7	1.7	1.7	1.7
Phosphorus Fertilizer (lbs/acre) [a]	4.1	4.7	4.1	3.0	3.9	3.9	3.6	3.9	3.9	3.9
Herbicide Application (lbs/acre) [a]	-0.2									
Insecticide Application (lbs/acre) [a]	0.0									
Wheat										
Nitrogen Fertilizer Application (lbs/acre) [a]	1.2	1.5	1.2	1.2	1.2	1.2	0.9	1.3	1.2	0.9
Potassium Fertilizer (lbs/ acre) [a]	7.0	16.9	7.0	7.0	3.9	7.0	4.0	6.8	7.0	3.3
Phosphorus Fertilizer (lbs/acre) [a]	3.5	6.3	3.5	3.5	2.7	3.5	3.1	2.0	3.5	3.1
Herbicide Application (lbs/acre) [a]	1.3									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	-2.3									

Sources: [a]USDA NASS (2015). [b] University of Tennessee (2015).

Exhibit 45: Changes in Production Inputs Associated with Switching from Reduced Till to No-Till (RT-NT)

Changes in Inputs, Relative to RT Practices	USDA Farm Production Regions									
	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Barley										
Nitrogen Fertilizer Application (lbs/acre) [a]	-17.7	-17.0	-17.0	-12.7	-25.1	-11.2	-18.8	-16.6	-17.0	-17.0
Potassium Fertilizer (lbs/ acre) [a]	-3.8	-2.5	-2.5	-4.1	-1.9	-2.9	-1.2	-1.2	-2.5	-2.5
Phosphorus Fertilizer (lbs/acre) [a]	-4.8	-3.4	-3.4	-3.3	-4.0	-3.8	-3.0	-1.5	-3.4	-3.4
Herbicide Application (lbs/acre) [a]	0.8									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	-1.1									
Corn										
Nitrogen Fertilizer Application (lbs/acre) [a]	2.3	2.5	2.1	2.0	2.1	1.6	2.1	2.1	2.1	2.3
Potassium Fertilizer (lbs/ acre) [a]	-0.7	-0.8	-0.5	-0.6	-0.5	-0.3	-0.3	-0.5	-0.5	-0.2
Phosphorus Fertilizer (lbs/acre) [a]	3.6	3.3	2.5	2.2	2.5	1.8	2.1	2.5	2.5	2.0
Herbicide Application (lbs/acre) [a]	-1.9									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	-1.1									
Rapeseed										
Nitrogen Fertilizer Application (lbs/acre) [a]	0.0	0.0	0.0	-20.7	-23.3	0.0	-23.3	0.0	0.0	0.0
Potassium Fertilizer (lbs/ acre) [a]	2.3	2.3	2.3	2.5	2.2	2.3	2.2	2.3	2.3	2.3
Phosphorus Fertilizer (lbs/acre) [a]	1.4	1.4	1.4	1.6	1.3	1.4	1.3	1.4	1.4	1.4
Herbicide Application (lbs/acre) [a]	0.4									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	-1.1									
Sorghum										

Changes in Inputs, Relative to RT Practices	USDA Farm Production Regions									
	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Nitrogen Fertilizer Application (lbs/acre) [a]	-12.6	-12.6	-12.6	-12.6	-9.4	-12.6	-15.0	-12.6	-12.6	-13.4
Potassium Fertilizer (lbs/ acre) [a]	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
Phosphorus Fertilizer (lbs/acre) [a]	-0.3	-0.3	-0.3	-0.3	-0.2	-0.3	-0.3	-0.3	-0.3	-0.3
Herbicide Application (lbs/acre) [a]	3.4									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	--1.0									
Soybeans										
Nitrogen Fertilizer Application (lbs/acre) [a]	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1
Potassium Fertilizer (lbs/ acre) [a]	0.9	1.0	0.9	0.9	0.8	0.8	0.4	0.8	0.8	0.8
Phosphorus Fertilizer (lbs/acre) [a]	2.2	2.5	2.2	1.6	2.0	2.0	1.9	2.0	2.0	2.0
Herbicide Application (lbs/acre) [a]	0.8									
Insecticide Application (lbs/acre) [a]	0.0									
Diesel Fuel (gallons/acre)[b]	-1.3									
Wheat										
Nitrogen Fertilizer Application (lbs/acre) [a]	13.8	18.0	13.8	13.8	14.0	13.8	11.1	15.0	13.8	10.9
Potassium Fertilizer (lbs/ acre) [a]	4.6	11.2	4.6	4.6	2.6	4.6	2.6	4.5	4.6	2.2
Phosphorus Fertilizer (lbs/acre) [a]	1.7	3.1	1.7	1.7	1.3	1.7	1.5	1.0	1.7	1.5
Herbicide Application (lbs/acre) [a]	-0.4									
Insecticide Application (lbs/acre) [a]	0.1									
Diesel Fuel (gallons/acre)[b]	-1.1									

Sources: [a] USDA NASS (2015). [b] University of Tennessee (2015).

Exhibit 46: Example—Detailed Activity Data Associated with Switching Corn Production from Conventional Till to No-Till (CT-NT)

Changes in Activity Data, per Acre (CT-NT)	Corn									
	Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Energy										
Diesel (gallons)[a]	-2.19	-2.19	-2.19	-2.19	-2.19	-2.19	-2.19	-2.19	-2.19	-2.19
Fertilizer Use [b]										
Nitrogen--Anhydrous Ammonia (lbs)	1.00	1.09	0.93	0.93	0.68	0.93	0.93	0.93	0.93	1.02
Nitrogen--Urea (lbs)	1.00	1.09	0.93	0.93	0.68	0.93	0.93	0.93	0.93	1.02
Nitrogen--Liquid N (lbs)	1.00	1.09	0.93	0.93	0.68	0.93	0.93	0.93	0.93	1.02
Phosphorous (lbs)	-1.30	-1.20	-0.91	-0.91	-0.65	-0.75	-0.91	-0.91	-0.91	-0.73
Potassium (lbs)	-5.01	-5.33	-3.40	-3.40	-2.31	-2.02	-3.40	-3.40	-3.40	-1.27
Herbicide Use [b]										
Herbicide Use (lb/acre) [b]	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22

Sources: [a]USDA NASS (2015). [b] University of Tennessee (2015). (Note: Nitrogen application type not provided. We assumed 1/3 of N applied as anhydrous ammonia (82% N), 1/3 as urea (45% N), and 1/3 as liquid N (30% N). Using N content of each, calculated fertilizer application rates.)

4.1.2. Emission Reductions

Switching from conventional tillage to conservation tillage results in changes in GHG emissions from multiple source categories previously mentioned in Section 4.1. These source categories include:

- Soil carbon sequestration
- Production and use of fertilizers, herbicides, and insecticides
- Mobile diesel combustion emissions from farm equipment use
- Direct and indirect N_2O emissions from application of N fertilizer

The source of values the assumptions made for each these sources are described below.

Soil carbon sequestration

Annual national soil carbon sequestration values for CT and NT for cultivation of corn, wheat, and soybeans are based on meta-analysis values from West and Post (2002), who analyzed results from 276 paired treatments. In our study, we used the values for the regression analysis between CT and NT SOC trends in continuous monocultures of corn, soybeans, and wheat. The values for barley, sorghum and rapeseed are based on the average regression between CT and

NT SOC trends for all continuous monocultures. In our study, the carbon sequestration for RT for each of the crops was assumed to be half of the increased sequestration value of NT (when compared to sequestration under CT) as there were no data for this tillage practice. We compared these values to those provided in a number of other studies (each with narrower applicability than the paired treatments in the West and Post (2002) study) and found a similar order of magnitude in most cases (Balkcom et al., 2013; Franzluebbers, 2010; ICF International, 2013; Lal, 2004; Lal et al., 2007).

ICF annualized the West and Post values on the increase in SOC in grams per square meter over the average length of study and used these values to estimate the change in carbon flux between CT and RT, CT and NT, and RT and NT. We used the same values for each of the 10 USDA regions.

Exhibit 47: SOC Sequestered in Response to Changing from Conventional Tillage to No-Till

Continuous Crop Type	Average Study Duration (Years)	Mean Cumulative Increase in SOC (MT CO_2-eq/ acre) under CT During Duration of Study[α]	Linear Regression Between CT and NT (MT CO_2-eq/acre)	Mean Annual Increase in CO_2-eq , CT-NT (MT CO_2-eq/ acre/ year)	Mean Annual Increase in CO_2-eq, CT-RT (MT CO_2-eq/ acre/ year)	Mean Annual Increase in CO_2-eq, RT-NT (MT CO_2-eq/acre/ year)
Corn	25	13.83	y = 0.97x + 16.18	0.63	0.32	0.32
Soybeans	10	8.04	y = 1.08x + 5.70	0.47	0.24	0.24
Wheat	12	4.35	y = 1.15x - 1.35	-0.06	-0.03	-0.03
All Continuous Monocultures (Barley, Rapeseed, Sorghum)	16	10.45	y = 1.13x + 2.16	0.22	0.11	0.11

Source: West and Post (2002). No values are provided for RT; consequently, we averaged the NT and CT values.

Production and use of fertilizers and pesticides

ICF estimated specific insecticide and herbicide application per acre using the most recent USDA NASS data (USDA NASS, 2015) by crop type and USDA Farm Production Region (data are provided for farms irrespective of crop type, so we used these rates for conventionally-till farms). In ARMS, we then queried total herbicide and insecticide application rates by tillage practice and crop type (pounds/acre) to determine the ratio of each herbicide and insecticide from NASS that are applied to reduced tillage and no till fields (USDA ERS, 2015a).

Using the change in total use of herbicides and insecticides that occurs when changing tillage practices, we estimated the net change in upstream CO_2, CH_4 and N_2O LCA emissions for each specific pesticide and herbicide as the product of the net change in application of herbicide and or pesticide a given combination of crop/tillage type/Farm Production Region and the LCA emission factor. For more information on how emissions per pound of pesticide and herbicide were determined please see Appendix 2.A.

Direct and indirect emissions from farm equipment diesel fuel use

Direct emissions from equipment use for transitioning to each of the conservation tillage systems are based on the farm production practices associated with CT and NT as described in UT (University of Tennessee, 2015). The fuel use under RT is assumed to be the average of the use under CT and NT for each crop type. We used a rate of 9.04 kg CO_2 direct emissions for each gallon of diesel fuel combusted (EIA, 2014).

The upstream (indirect) emissions from producing diesel fuel are 10.8 kg CO_2 per gallon of fuel (Argonne National Laboratory, 2014).

Direct and indirect N_2O emissions from N fertilizer application

As mentioned in Chapter 2: Summary of Methodology, N_2O emissions per acre are as provided by USDA in the report entitled *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory* (Eve et al., 2014).

Direct N_2O emissions from N fertilizer application are provided for CT practices in each USDA Farm Production Region for each crop type and by soil/sediment size (coarse, medium, fine) per Eve (2014). Per Grandy et al. (2006), long-term studies indicate a 9.4% increase in direct N_2O emissions from crops that are cultivated under either RT or NT, compared to CT (no statistically significant difference in emissions from RT and NT). In this study, we added 9.4% to the N_2O emissions for crops cultivated as RT or NT. As described in Chapter 2, indirect N_2O emissions are calculated as a ratio of the direct N_2O emissions (the ratio is the same under all tillage practices).

4.1.3. Adoption Potential

We assumed that all cropland under conservation tillage could convert to RT or NT, with a 50/50 split between RT and NT. We also assumed that all cropland under reduced tillage as of 2020, 2030, 2040, and 2050 could be converted to NT. We used Monsanto projections for planted acreage in the United States through 2050 and assumed that the current allocation of acreage for each crop type (excluding soybeans and rapeseed), according to ARMS (USDA ERS, 2015a), is the allocation in future years. For soybeans and rapeseed, we used the national distribution among the tillage practices, according to Conservation Technology Information Center (2015). We developed the adoption potential for RT and NT, expressed in acres, based on the current acreage under conventional and reduced tillage and the assumed adoption rates.

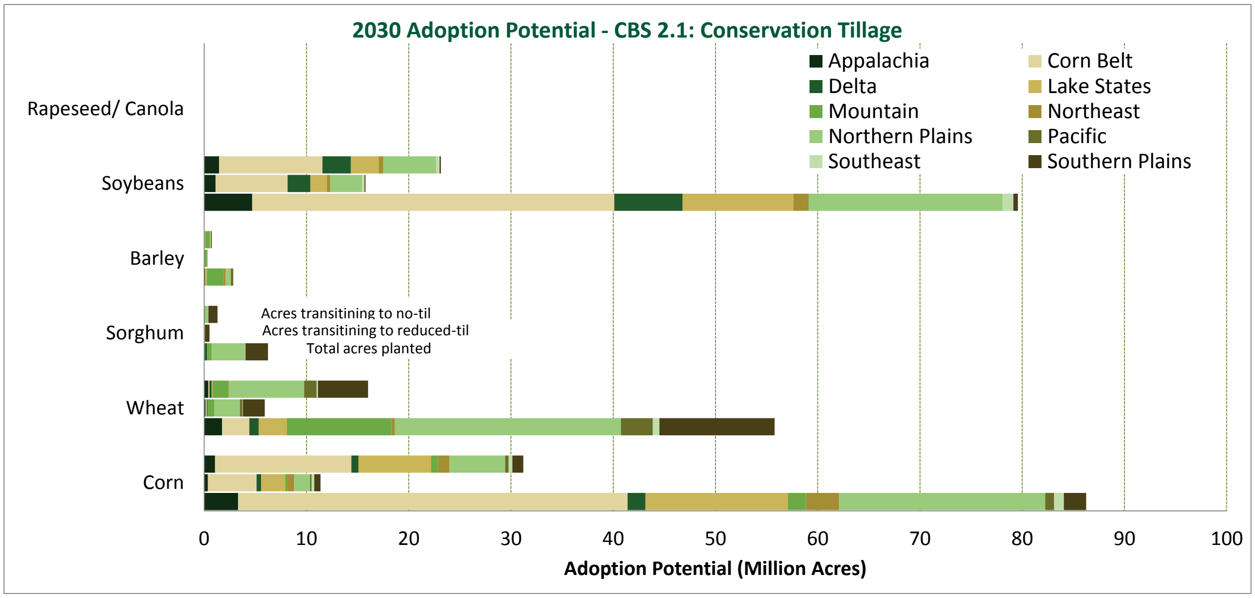
Exhibit 48: Current Distribution of Acres to CT, RT, and NT

Crops/ Tillage Distribution	USDA Farm Production Regions: Appalachia	Corn Belt	Delta	Lake States	Mountain	Northeast	Northern Plains	Pacific	Southeast	Southern Plains
Barley[a]										
CT	11.1%	20.3%	20.3%	29.4%	27.9%	15.4%	5.5%	32.4%	20.3%	20.3%
RT	8.9%	18.3%	18.3%	31.4%	12.9%	15.4%	9.3%	32.1%	18.3%	18.3%
NT	80.0%	61.4%	61.4%	39.2%	59.2%	69.2%	85.3%	35.5%	61.4%	61.4%
Corn[a]										
CT	21.6%	25.0%	51.6%	34.0%	23.9%	40.0%	15.5%	35.4%	55.4%	51.6%
RT	20.9%	22.5%	14.3%	33.9%	25.7%	14.6%	19.3%	20.7%	21.0%	14.3%
NT	57.6%	52.5%	34.1%	32.1%	50.4%	45.4%	65.2%	43.9%	23.5%	34.1%
Rapeseed[b]										
CT	36.5%	36.5%	36.5%	36.5%	36.5%	36.5%	36.5%	36.5%	36.5%	36.5%
RT	24.1%	24.1%	24.1%	24.1%	24.1%	24.1%	24.1%	24.1%	24.1%	24.1%
NT	39.4%	39.4%	39.4%	39.4%	39.4%	39.4%	39.4%	39.4%	39.4%	39.4%
Sorghum[a]										
CT	17.2%	17.2%	17.2%	17.2%	9.7%	17.2%	1.6%	17.2%	40.2%	17.2%
RT	9.8%	9.8%	9.8%	9.8%	0.0%	9.8%	9.0%	9.8%	20.2%	9.8%
NT	73.1%	73.1%	73.1%	73.1%	90.3%	73.1%	89.3%	73.1%	39.6%	73.1%
Soybeans[b]										
CT	47.6%	39.7%	66.7%	29.9%	43.4%	43.4%	32.9%	43.4%	43.4%	43.4%
RT	7.2%	8.7%	8.3%	10.1%	9.0%	9.0%	10.8%	9.0%	9.0%	9.0%
NT	45.2%	51.6%	24.9%	60.0%	47.6%	47.6%	56.3%	47.6%	47.6%	47.6%
Wheat[a]										
CT	16.1%	8.6%	16.1%	0.0%	12.7%	16.1%	22.6%	14.9%	37.9%	16.1%
RT	14.9%	0.0%	14.9%	2.9%	8.8%	14.9%	21.8%	31.5%	24.6%	14.9%
NT	68.9%	91.4%	68.9%	97.1%	78.5%	68.9%	55.6%	53.6%	37.5%	68.9%

[a] USDA ERS (2015a). [b] Conservation Technology Information Center (2015).

Exhibit 49 presents that adoption potential for conservation tillage. As indicted, the greatest adoption potential in 2030 is for transitioning corn and soy crops to no till practices, as these two crops are projected to have the greatest overall acreage in the United States. The Corn Belt provides the greatest adoption potential for both crops.

Exhibit 49: Adoption Potential for Conservation Tillage

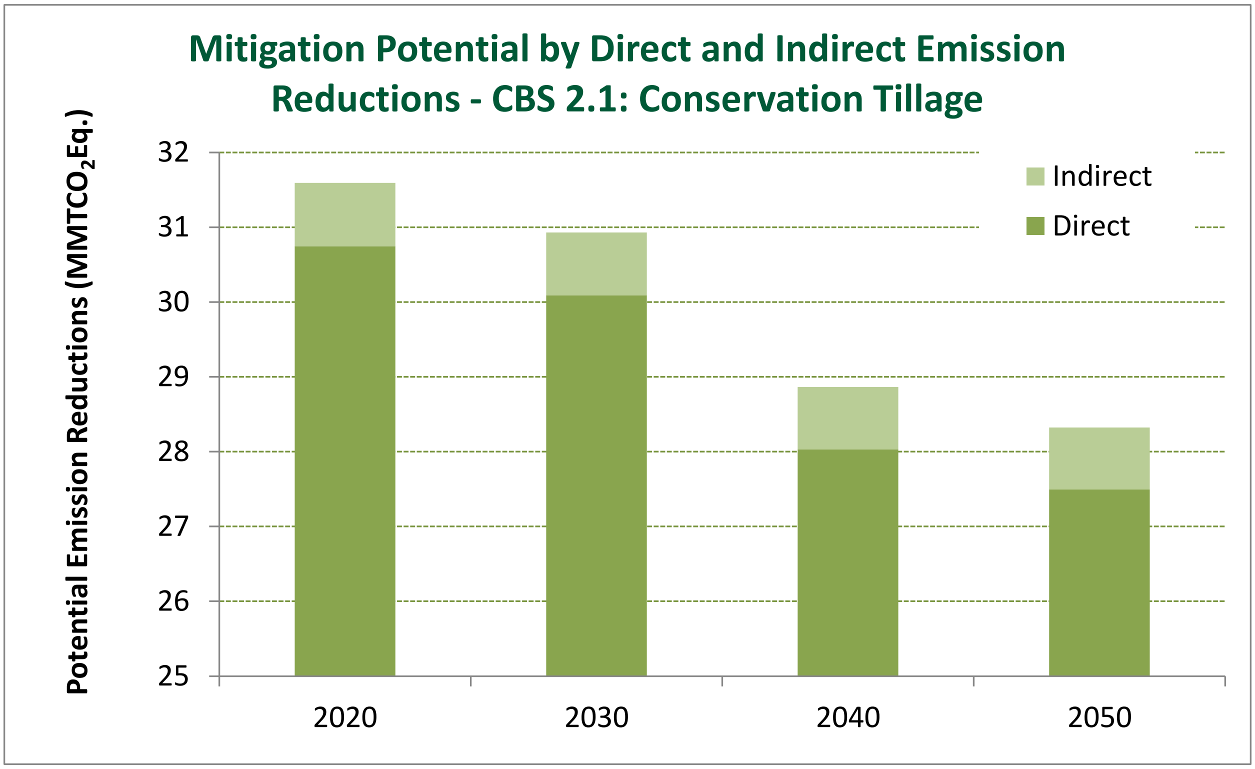


4.1.4. Mitigation Potential for 2020, 2030, 2040, and 2050

The national mitigation potential by direct and indirect emission reductions is presented in Exhibit 50. The key findings include:

- As yield increases over time as indicated in the Monsanto Model, acreage declines; consequently, the carbon sequestration benefit decreases over time as acreage declines;
- On-site soil carbon sequestration is greater than indirect emission reductions due to a greater per-acre GHG benefit for carbon sequestration than the GHG reductions associated with the net change in inputs and reduced fuel use.
- The greatest mitigation potential related to conservation tillage practices exists in the Corn Belt and Northern Plains regions due to the large adoption potential for corn and soybean crops.

Exhibit 50: Mitigation Potential for CBS 2.1 Conservation Tillage



4.1.5. Sensitivity Analysis and Risk Factors

4.1.5.1. Sensitivity Analysis

Exhibit 51 indicates the upper and lower bounds and the source of the values for selected input variables. Exhibit 52 presents the national mitigation potential for each change in variable.

Exhibit 51: Lower and Upper Bounds for Input Variables

Variable	Units	Value Used in Base Case	Lower Bound	Upper Bound
Soil carbon sequestration due to switching CT-NT[a]	MT CO_2-eq/ac	Varies by crop type. Average = 0.305	-0.10	1.3
Soil carbon sequestration due to switching CT-RT (or other conservation tillage practice, other than NT)[a]	MT CO_2-eq/ac	Varies by crop type. Average = 0.305	-0.22	0.56
Change in herbicide use (RT compared to CT, across all crops)[b]	%	Varies by crop type. Average = +13.2%	-5.7%	+44.3%

Change in herbicide use (NT compared to CT, across all crops)[b]	%	Varies by crop type. Average = +35.9%	-11.1%	+196.4%
Change in nitrogen fertilizer use (RT compared to CT, across all crops)[b]	%	Varies by crop type. Average = -23.3%	-20.5%	+6.8%
Change in nitrogen fertilizer use (NT compared to CT, across all crops)[b]	%	Varies by crop type. Average = -0.6%	-31%	+3%

Sources: [a] Eagle et al. (2012). [b] USDA ERS (2015).

Exhibit 52: Resulting 2030 Mitigation Potential Based on Change in Variable (Million Metric Tons of CO_2-eq)

Variable	Using Lower Bound Value	Using Upper Bound Value
Baseline Value	31.98	
Soil carbon sequestration due to switching CT-NT	15.92	61.36
Soil carbon sequestration due to switching CT-RT (or other conservation tillage practice, other than NT)	23.76	68.73
Change in herbicide use (RT compared to CT, across all crops)	31.65	32.01
Change in herbicide use (NT compared to CT, across all crops)	31.78	30.48
Change in nitrogen fertilizer use (RT compared to CT, across all crops)	32.89	31.08
Change in nitrogen fertilizer use (NT compared to CT, across all crops)	36.56	31.36

4.1.5.2. Technical, Economic, and Policy Risk Factors

Summarized below are key factors that impact the adoption and resulting mitigation potential associated with the strategy of adopting reduced or no till practices.

- **Permanence of Carbon Storage.** Uncertainty exists regarding whether farmers will periodically till cropland. We assumed a 15 year project lifespan with no interim tillage occurring.
- **Nitrogen Application Rates Vary by Region.** The amount of N applied regionally is dependent on soil moisture, climate factors, predominant soil types, and type of nitrogen used.
- **Variation of Seeding Methods**. Although farmers may purchase no-till drill seeders, it is not likely to be economically-beneficial for farms under 600 acres. Consequently, we assumed that farmers can use existing seeding equipment as they transition to reduced till or no till practices. Consequently, seeding under use of alternative tillage practices has no impact on the net LCA of GHGs.
- **Variation in Types of Fertilizers**. There is wide variation, in practice, of the types of nitrogen

fertilizer used by farmers—by region and by crop type. For this study, we assumed one-third of nitrogen is applied as urea (45% N), one-third as anhydrous ammonia (82% N), and one-third as liquid nitrogen (30% N).

- **Variation in Yield Reductions**. Yield changes are not consistent and depend on larger crop rotations, soil quality, and soil moisture regime. For example, Van Kessel et al. (2013) noted that in dry regions, farms switching from CT to NT or RT incurred an 11% reduction in yield and, that in wet regions, farms incurred a 3% reduction in yield. However, variation exists in estimates provided by the literature. Landowners' perception of the risks of yield reductions will impact the rate of adoption of reduced tillage practices.
- **Amount of carbon stored**. The literature provides variable estimates for changes in SOC due to changes in tillage practices. The West and Post (2002) meta-analysis, utilized in our study, provides close to 300 paired treatments and determined the statistical relationship between CT and NT SOC changes for continuous monocultures and also for rotational cultivation. Our review of other studies indicated results of comparable magnitude (Balkcom et al., 2013; Franzluebbers, 2010; ICF International, 2013; Lal, 2004; Lal et al., 2007).
- **Farm size impacts cost-effectiveness of tillage practices**. Several studies indicate that purchasing a no-till drill seeder is likely to be economically-beneficial for farms over 600 acres, but not for smaller farms. Consequently, larger farms may be more willing to reduce tillage compared to smaller farms.

4.1.6. References

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4.2. Winter Cover Crops

Cover crops are plants that are grown with the purpose of improving soil quality. Cover crops can be grown during the period when the main crop is not grown (i.e., over the winter for corn or soy or during the summer for winter wheat) or intercropped/grown simultaneously with the main crop. Plants grown as cover crops, generally fall into three main categories: beans or legumes, grasses and brassicas or mustards. Cover crops can be grown as monocultures (i.e., just one species) or a mix of multiple species, depending on the soil conditions and the goals of the farmer. Adding cover crops to a plant rotation can increase soil carbon sequestration and reduce fertilizer-based N_2O emissions through reduced fertilizer use and/or reduced nitrate leaching (Clark, 2012; Eagle et al., 2012).

Key Considerations in Growing Cover Crops

- Cover crops can increase soil carbon storage and soil moisture and decrease nitrate leaching, erosion and sedimentation
- Cover crops can reduce fertilizer, herbicide .and pesticides needs and increase yield
- Growing cover crops requires precision planning, increased management practices and may reduce crop yield
- The amount of soil carbon sequestered and the amount of nitrate leaching reduced varies by cover crop, regionally and by soil type and moisture.

In addition to reducing GHG emissions, cover crops can provide multiple other benefits to the soil and the farmer. These benefits include: reducing soil loss and erosion; reducing pest pressure (both weeds and insects); reducing fertilizer needs of the cash crop; conserving water resources; improving overall soil quality and increasing cash crop yield (Clark, 2012; Eagle et al., 2012). There are also negative effects associated with including cover crops in rotations, these include: increased pest pressure (including insects and pests) resulting in increased use of pesticides; increased risk of soil compaction; risks

Choosing a Cover Crop

- Farmers chose their cover crops based on:
- Which crop(s) best fits their specific environmental needs (e.g., increasing soil N, decreasing soil erosion, increasing soil carbon)
- Which crop(s) grows well in their area
- Which crop(s) fits into their cash crop planting and harvesting schedules (Clark, 2012).
- The Cover Crop surveys report the planting of a variety of grains, legumes, brassicas and mixtures as cover crops (SARE, 2013, 2014, 2015)
- In 2015, ~ 45% of reported acres were planted with cereal rye and ~ 28% were planted with clovers (SARE, 2015).

of yield reduction; need for new farm machinery and higher levels of management skills (Clark, 2012; Eagle et al., 2012). Note that for multiple factors, cover crops are associated with both positive and negative effects (i.e., both increasing and decreasing pest pressure). These seemingly conflicting effects are due to differences in local environments, including local pest pressure, cover crop species or mix used, differences in production practices, including cash crops grown and crop rotations, and other factors.

For the purpose of this study, one legume (crimson clover, *Trifolium incarnatum* L) and one grass (cereal rye, *Secale cereale* L.*)* are modeled as winter cover crops grown before corn, soy and summer and Durham wheat under different tillage systems (i.e., conventional tillage, reduced tillage and no tillage) and under different crop rotations. For this report, we assumed that half of farmers grow cereal rye before their corn, soy or wheat crop and half of farmers grow crimson clover before their corn, soy or wheat crop. For corn, rotations include corn/soy rotations and "other" corn rotations (corn/soy/wheat) under CT, RT and NT. For soy, rotations include corn/soy rotations and "other" soy rotations (corn/soy/wheat) under CT, RT and NT. For wheat, rotations include "other" wheat rotations (corn/soy/wheat) under CT, RT and NT. Winter cover crop rotations with barley and sorghum are not considered due to lack of available data in the literature. Winter cover crop rotations with canola are not considered as canola is a winter crop and cannot be grown in rotation with winter cover crops. We additionally model aerial seeding (also used as a conservative proxy for drill seeding as described below in Section 4.2.1) for both of the cover crops, and three termination methods (herbicide, tillage and winter kill) for both of the cover crops.

The LCA estimates the total changes in GHG emissions associated with growing cover crops, including any changes to cash crop production (i.e., reduction in N fertilization) or emissions related to cash crop production (i.e., reduced nitrate leaching). As depicted in Exhibit 53, upstream emissions for the LCA of CBS 2.2: Winter Cover Crops include the CO_2, CH_4, and N_2O emissions associated with cover crop seed production, diesel fuel production, pesticide production, and fertilizer production. On-farm emissions include changes in SOC storage associated with growing cover crops in rotation with cash crops; diesel combustion emissions from field operations for cover crop production, which include planting and termination. We do not include on-farm CH_4 emissions (e.g., from cropland) within the boundaries of CBS 2.2 as such emissions are typically marginal compared to CO_2 and N_2O. Cover crops can result in a change in yield; however,

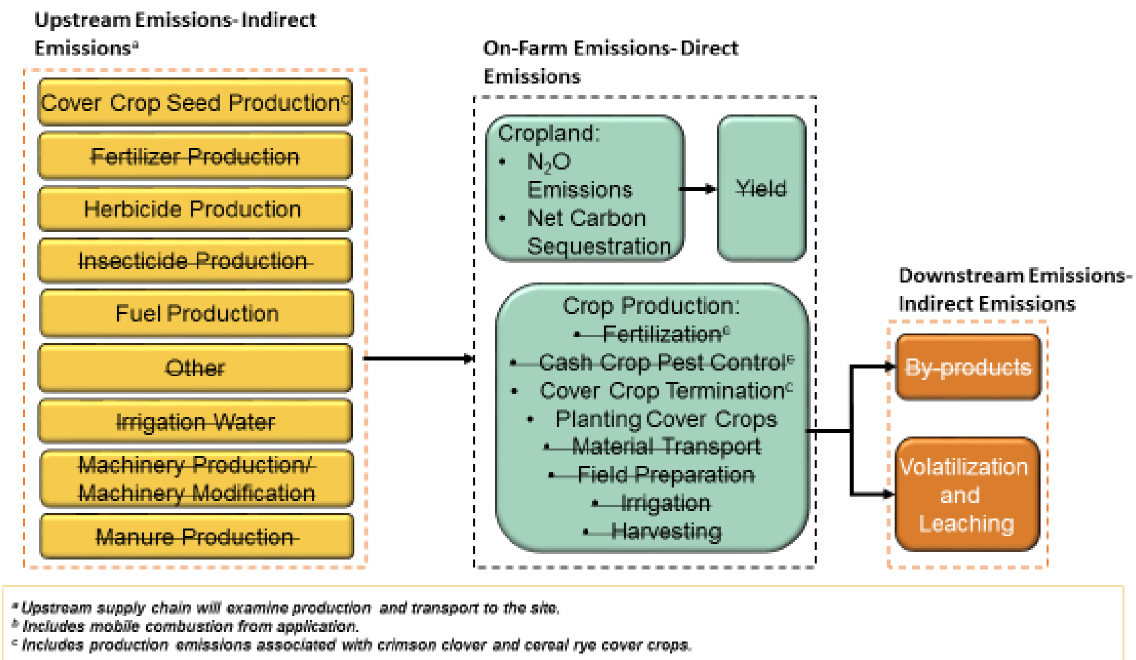
Cover Crop Rotations

A variety of cover crop rotations were reported in the Cover Crop Surveys (SARE, 2013, 2014, 2015). In the 2015 Survey:

- 25% of respondents indicated that they grew cover crops before both corn and soy
- 21% responded that they grew cover crops after small grains
- 16% responded that they grew cover crops following soybean and before corn
- 16% responded that they grew cover crops

changes in GHGs associated with changes in yield are not modeled (e.g., increased fuel use in a harvester). Downstream emissions are not included, except for changes in nitrate leaching and volatilization.

Exhibit 53: LCA Accounting Boundaries for Use of Winter Cover Crops



Cover crops can be planted using multiple methods depending on: season, production method (i.e., conventional or conservation tillage), life cycle stage of the cash crop (i.e., whether the cash crop is still on the field when the cover crop is planted), weather conditions, seed size, desired seed depth, and farmer needs (Clark, 2012). According to the National Cover Crop Surveys (SARE, 2014, 2015), the most to least commonly reported planting methods are (average of 2014 and 2015 data):

- Drill seeding (42%)
- Aerial seeding (19%)
- Broadcast seeding with light incorporation (19%)
- Seeding with seeds left on surface (i.e., with a fertilizer spreader) (11.5%)
- High clearance seeder (7%)[10]
- Precision with corn or soybean planter (3.5%)
- With manure (0.75%)

[10] Only in 2015 survey, not included in 2014 survey.

A range of suggested seeding rates are published for both crimson clover and cereal rye, depending on planting method, specific variety and geographic location. For crimson clover, seeding rates of 12-20 pounds/acre are recommended for drill seeding and 22-30 pounds/acre are recommended for aerial or broadcast seeding (Anderson, 2010; Clark, 2012; USDA ARS, 2014; Young-Mathews, 2013). For cereal rye, seeding rates of 50-200 pounds/acre are recommended for all seeding methods, with 60-120 pounds/acre recommended specifically for drill seeding and 112-160 pounds/acre for aerial seeding (Allamakee SWCD, 2012; Casey, 2012; Clark, 2012; Marshall, 2012; USDA ARS, 2014; USDA NRCS, 2010). As a general rule, USDA recommends 25- 50% higher seeding rates for aerial seeding than for drill seeding (USDA NRCS, 2010). Given the wide range of seeding rates, we modeled emissions from values of 12 pounds/acre for crimson clover and 35 pounds/acre for cereal rye for drill seeding and increased the value by 37.5% (the midpoint of the suggested 25- 50% increase) for aerial seeding to 16.50 pounds/acre for crimson clover and 48.13 pounds/acre for cereal rye.

Depending on the specific cover crop and local soil conditions, farmers may use nitrogen fertilizer to increase growth. As crimson clover is a legume and fixes nitrogen, it is generally not fertilized (Duiker et al., 2010). Grasses may or may not be fertilized depending on specific soil conditions and farmer needs. In particular cereal rye responds well to low levels of fertilizer (Grubinger, 2010). The published range of suggested nitrogen fertilizer for cereal rye ranges from 0 – 50 pounds/acre (Casey, 2012; Mannering et al., 2007). For this report we modeled no fertilizer application for crimson clover or cereal rye.

Changes in application rates for crop inputs associated with growing cash crops in rotation with cover crops

Including cover crops in cash crop rotations can result in changes to cash crop fertilizer rates. For example, crimson clover fixes nitrogen in the soil resulting in a reduced nitrogen fertilizer requirement for the following corn crop. The amount of nitrogen fixed depends on: the variety of crimson clover, local conditions, how much biomass the clover accumulates over the season and how the biomass is managed after termination (Young-Mathews, 2013). Published values for available nitrogen or nitrogen replacement supplied by crimson clover for the next crop range from ~ 50 - 150 pounds/acre (Anderson, 2010; Nair et al.; Young-Mathews, 2013). For this report we did not model any nitrogen application reductions associated with growing crimson clover in rotation with corn, soy or wheat.

Including cover crops in cash crop rotations can result in changes to cash crop pesticide application rates. Application rates can increase or decrease depending on: local environments, including local pest pressure, cover crop species or mix used, differences in production practices, including cash crops grown and crop rotations, and other factors. Cover crops have been shown to have statistically significant effects on suppressing weeds and breaking up pest cycles (Mitchell and Moore, 2014). Additionally, recent farmer presentations showed that cover crop rotations with cash crops reduced their use of insecticides and herbicides with the cash crops (Rulon Enterprise, 2015; Brandt, 2013). However, pest suppression is not as reliable or as complete with cover crops as with pesticides or mechanical tillage (Mitchell and Moore, 2014; Wiggins et al., 2015). As cover crops do not have an easily generalizable effect on pesticide use, we have not modeled any potential effects of cover crops on application rate of these chemicals.

Changes in crop inputs associated with terminating cover crops

Cover crops can be terminated using a variety of methods depending on: specific cover crop grown, season, production method (i.e., conventional or conservation tillage) weather conditions, herbicide sensitivity of the following crop, and farmer needs (Clark, 2012). According to the National Cover Crop Surveys (2014, 2015), the most to least commonly reported termination methods are (average of both years combined):

- Herbicide (53.5%)
- Winter kill (21.5%)
- Tillage (15.5%)
- Mowing (7%)
- Other (5%)
- Roller crimping (1%)

For our report, we estimated changes in GHGs for herbicide termination, winter kill and tillage termination. Key assumptions for estimating changes in direct and indirect GHGs include:

- Herbicide
  - For herbicide application we estimated:
    - glyphosate (1 pound/acre) for cereal rye (USDA-ARS-NSDL, 2014); and
    - 2, 4-D (0.5 pounds/acre) and Dicamba (0.5 pounds/acre) for crimson clover, (Parker, 2014).
  - These herbicides were selected for their high rate of effectiveness in terminating cereal rye and crimson clover. However, other herbicides are also effective in terminating cereal rye and crimson clover and could also be used, depending on farmer needs.
- Winter kill
  - For winter kill no additional actions are required by the farmer and therefore no change in GHGs.
- Tillage
  - For tillage termination, we assumed:
    - Moldboard ploughing for CT
    - Chisel ploughing for RT
    - No tillage termination for crops grown under no-till.

4.2.1. Emission Reductions

Direct Emission Reductions

Three sources exist for impacting on-site direct emissions: carbon storage, and mobile combustion.

Mobile combustion emissions result from seeding (drill and aerial) and termination (herbicide application and tillage). The emission factors for combustion from mobile sources are provided in Chapter 2. The quantity of fuel combusted by vehicle is presented in section on costs in Exhibit 54.

Exhibit 54: Fuel Use for Planting and Termination of Cover Crop and Quantities of Additional Inputs for Estimating Associated Net Change in GHGs

Component	Quantity	Data Source
Seeds (lbs)- Clover/Legume[a]	16.50	Anderson (2010); Young-Mathews (2013); USDA ARS (2014); Clark (2012)
Seeds (lbs)- Rye/Grass[a]	48.13	Casey, 2012; USDA ARS (2014); USDA NRCS (2010); Allamakee SWCD (2012); Marshall (2012); Clark (2012)
Aviation Gasoline for Seeding (gallons)[b]	5	Air Tractor (2015)
Tillage Termination		
Chisel Plough – Diesel use (gallons)[b]	0.87	University of Tennessee (2015)
Moldboard Plough – Diesel use (gallons)[b]	1.32	Lazarus (2015)
Herbicide Termination		
2,4,-D and Dicamba for Clover/Legume		Parker (2014)
• 2,4-D (lbs/acre)[a]	0.5	
• Dicamba (lbs/acre)[a]	0.5	
Glyphosphate for Grass-Rye (lbs / acre)[a]	1.00	USDA ARS (2014)
Diesel use (gallons)[b]	0.11	University of Tennessee (2015)

[a] We use the quantity of seed and herbicides to estimate the GHG associated with seed production.

[b] We use gasoline use to estimate LCA of its use from production to on-site combustion.

The effect of cover crops on direct N_2O emissions are conflicting; some studies indicate cover crops increase N_2O emissions while other studies indicate they decrease N_2O emissions or have no effect (Blanco-Canqui et al., 2011; McSwiney et al., 2010)(Iqbal et al, 2015; Mitchell, 2012). A meta-analysis conducted by Basche et al. (2014) showed that cover crops decreased N_2O emissions in 40% of observations and increased N_2O emissions in 60% of observations. The authors found a significant interaction between nitrogen fertilization rate and the type of cover crop (where legumes were associated with higher N_2O emissions at lower N rates than non-legumes), and higher N_2O emissions were significantly associated with cover crop residue incorporation, and geographies with high levels of total precipitation. As cover crops do not have an easily generalizable effect on N_2O emissions, we did not model potential effects of cover crops on these emissions.

The increase carbon storage is the main contributor to net changes in GHG emissions. We used estimates on change in carbon flux from several data sources. These data sources include:

- Blanco-Canqui et al. (2013) for no-till wheat carbon sequestration
- Paul et al. (2015) for conventional till corn, soy, wheat carbon sequestration
- Snapp et al. (2010) for reduced till corn, soy wheat rotations carbon sequestration
- Olson et al. (2014) for conventional, reduced and no-till corn, soy carbon sequestration
- Ashworth et al. (2014) for no-till corn and soy rotations carbon sequestration
- Balkcom et al. (2013) for reduced till corn, cotton, wheat carbon sequestration

Exhibit 55 presents the resulting flux for CO_2 storage. We could not find carbon sequestration data for all cover crop/cash crop rotations in all tillage types in all regions. In these cases, we substituted values from similar cover crop/cash crop rotations, tillage systems and regions. Due to these substitutions, some of the carbon sequestration values likely over-estimate the amount of carbon stored, while others likely underestimate the amount of carbon sequestered, depending on the data available. For example, the carbon sequestration data from Olson et al. (2014) is from Southern Illinois, where the mild climate allows for a long cover crop growing season, resulting in higher carbon sequestration values. These values likely overestimate the amount of carbon sequestered in colder northern regions with shorter cover crop growing seasons. Conversely, as the carbon sequestration values from Blanco-Canqui (2013) are for continuous wheat, not wheat rotations, they likely underestimate the carbon sequestration values for wheat rotations.

Exhibit 55: CO_2 Flux for CO_2 Storage for Cover Crops (metric tons CO_2/acre)

Crop Type	Use of Legume Cover Crop (Crimson Clover)		Use of Grass Cover Crop (Rye)	
	Appalachia and Delta Regions	Other Regions[a]	Appalachia and Delta Regions	Other Regions[a]
Corn - Corn/soy rotation- CT	0.19[g]	0.15[b]	0.081[g]	0.15[b]
Corn -Corn/soy rotation- RT	0.19[g]	0.73[b]	0.081[g]	0.73[b]
Corn - Corn/soy rotation- NT	0.19[g]	1.31[b]	0.081[g]	1.31[b]
Corn - Other rotation - CT	0.13[c]	0.13[c]	0.32[f]	0.13[c]
Corn - Other rotation - RT	0.50[d]	0.50[d]	032[f]	0.50[d]

Crop Type	Use of Legume Cover Crop (Crimson Clover)		Use of Grass Cover Crop (Rye)	
	Appalachia and Delta Regions	Other Regions[a]	Appalachia and Delta Regions	Other Regions[a]
Corn - Other rotation - NT	1.31[b]	1.31[b]	0.32[f]	0.32[f]
Wheat – Other rotation CT	0.13[c]	0.13[c]	0.13[c]	0.13[c]
Wheat – Other rotation RT	0.50[d]	0.50[d]	0.50[d]	0.50[d]
Wheat – Other rotation NT	0.12[e]	0.12[e]	0.74[e]	0.74[e]
Soybean - Soy/corn rotation CT	0.19[g]	0.15[b]	0.081[g]	0.15[b]
Soybean - Soy/corn rotation RT	0.19[g]	0.73[b]	0.081[g]	0.73[b]
Soybean - Soy/corn rotation NT	0.19[g]	1.31[b]	0.081[g]	1.31[b]
Soybean - Other rotation CT	0.13[c]	0.13[c]	0.13[c]	0.13[c]
Soybean - Other rotation RT	0.50[d]	0.50[d]	0.50[d]	0.50[d]
Soybean - Other rotation NT	1.31[b]	1.31[b]	1.31[b]	1.31[b]

[a] Other regions include Corn Belt, Lake States, Mountain, Northeast, Northern Plains, Pacific, Southeast, and Southern Plains.
[b] Olson et al., 2014.
[c] Paul et al., 2015.
[d] Snapp et al., 2010.
[e] Blanco-Canqui et al., 2013.
[f] Balkcom et al., 2013.
[g] Ashworth et al., 2013.

Indirect Emission

We accounted for changes in upstream processes and the resulting net change in production related emissions. Sources of upstream indirect emissions include:

- Fuel Use
- Seed production (crimson clover (legume) and cereal rye (grass)
- Herbicide production for herbicide termination
- For crimson clover we used the following herbicides for termination:
  - 2,4-D (0.5 lbs/acre)
  - Dicamba (0.5 lbs/acre)
- For cereal rye we used the following herbicide for termination:
  - Glyphosate (1 lbs/acre)

The quantities for the fuel use and inputs are provided in Exhibit 54.

Downstream Indirect Emission Reductions:

We calculated the magnitude of the GHG reductions in downstream indirect N_2O emissions by applying a percent reduction to the indirect N_2O emissions for corn, wheat, and soybean cropland based on type of cover crop. Exhibit 56 presents the percent reductions. Methods for modeling indirect emissions from N fertilization of corn are described in Chapter 2.

Exhibit 56: Reduction in Indirect N_2O Emissions (Percent)

Cover Crop	All Regions
Grass (Cereal Rye)[a]	70%
Legume (Crimson Clover)[b]	32%

[a] Value is an average of the values for grasses in Tonitto et al. (2006) and Dabney (2010).

[b] Value is an average of the values for legumes in Tonitto et al. (2006) and Dabney (2010).

4.2.2. Adoption Potential

Winter cover crops can be applied to winter wheat, corn, and soybeans. For estimating the acres that can adopt cover crops we used a four-step process:

1) **Estimated the number of acres corn, soybeans, and wheat that are managed using conventional tillage, reduced tillage, and no till.** The percent of acres in each tillage practice are summarized in Appendix 4.A in Exhibits 4.A-1, 4.A-2, and 4.A-3.

2) **Estimated the percent of acres of corn, soybeans, and wheat that currently use cover crops, accounting for the percent of wheat that is winter wheat**. We obtained an estimate of the national total acreage of cover crops and distributed the acres to soybeans, corn, and wheat based on relative acres of cropland. We then determined the percent of corn, wheat, and soybeans that have cover crops. Finally, based on the national distribution of cover crops by tillage type, we estimated the percent of acres of each crop type and associated tillage regime that use cover crops. We used these estimates for calculating the number of acres that could adopt winter cover crops.

Exhibit 57: Steps to Estimate Percent of Each Crop Type that Use Cover Crops

Oil Seed and Grain	Planted Acres	Percent of Oils/Grains	Cover Crops	Cropland With Cover Crops
1) Determine total acreage cover crops.				
Cover Crops (Acres)	4,446,060[a]			
2) Distribute cover crops across crops and determine percent of cropland with cover crops.				
Oils (Acres)				
Soybeans	77,404,000	38%	1,679,716	2.2%[b]
Canola	1,448,800	1%	31,440	
Rapeseed	2,300	0%	50	
Cottonseed	10,974,200	5%	238,147	
Sunflower Seeds	1,951,500	1%	42,349	
Peanuts	1,288,000	1%	27,950	
Grains				
Corn	88,192,000	43%	1,913,822	2.2%
Spring and Durum Wheat	15,664,000	8%	339,919	2.2%
Rice	3,636,000	2%	78,903	
Sorghum	1,448,800	1%	31,440	
Barley	2,872,000	1%	62,324	
	204,881,600	100%	4,446,060	
3) Estimate percent of acres of total wheat that are winter wheat.				
Winter Wheat	31,219,000			
Total Wheat	46,883,000			
Percent of Total Wheat that is winter wheat is		33 %		
4) Adjust for use of cover crops by tillage practice to estimate percent of acres that current use cover crops.				

	Use of Cover Crops[c]	Soybeans[d]	Corn	Spring and Durum Wheat of Total Wheat
All crops - Conventional Tillage	20%	0.43%	0.43%	0.15%
All crops - Reduced Tillage	28%	0.61%	0.61%	0.20%
All crops - No Tillage	52%	1.13%	1.13%	0.38%
Total	100%	2.17%	2.17%	0.73%

[a] USDA NASS (2014). Acres are taken from the category: “cropland planted to a cover crop (excluding CRP) farming oilseed and grain”.

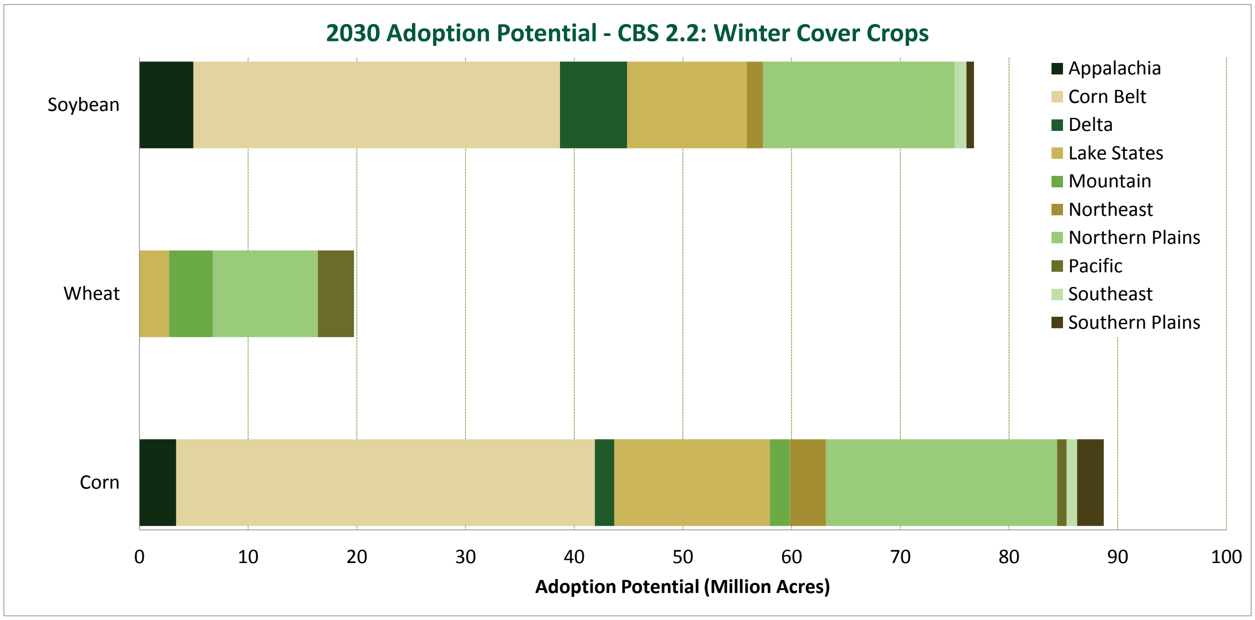
[b] Approximately 2.2% of soybean acres are grown in rotation with cover crops.

[c] As indicated, most cover crops are grown in rotation with cash crops grown under no till conditions (48% of cover crops are on acres with no till).

[d] Percent of soybeans grown using conventional till and in rotation with cover crops equals percent of cover crops in conventional tillage (i.e., 20%) times cover crops on soybean acreage (i.e., 2.2%).

3) **Estimated number of acres that can transition to applying cover crops.** The acres that can adopt winter cover crops are the total acres in each tillage practice minus the acres that are currently applying cover crops. Exhibit 58 presents the resulting acres that are not utilizing cover crops.

Exhibit 58: Adoption Potential for Use of Winter Cover Crops



4) **Evenly distributed the crop land under conventional till, reduced till, and no till to the options for cover crops (legume or grass), planting of cover crop (aerial or drill seeding)**. For termination of the cover crops, we distributed acres in conventional or reduced till evenly to the three termination options (i.e., herbicide, tillage, and winter-kill), and we distributed acres in no till to only the herbicide and winter kill termination options. We distributed corn acres to corn/soy and other rotations; soybeans to soy/corn and other rotations; and all of wheat to wheat rotation. Exhibit 59 presents the options that we evaluated for each type of crop and tillage practice.

Exhibit 59: Allocation of Crop Acres to Options for Winter Cover Crops

Cash Crop	Options: Cover Crop	Options: Cash Crop Rotation	Options: Termination
Corn – CT	Legume Grass	Corn/soy Other	Herbicide Tillage Winter-kill
Corn – RT	Legume Grass	Corn/soy Other	Herbicide Tillage Winter-kill
Corn - NT	Legume Grass	Corn/soy Other	Herbicide Winter-kill
Soybeans – CT	Legume Grass	Soy/Corn Other	Herbicide Tillage Winter-kill
Soybeans – RT	Legume Grass	Corn/soy Other	Herbicide Tillage Winter-kill
Soybeans – NT	Legume Grass	Corn/soy Other	Herbicide Winter-kill
Wheat – CT	Legume Grass	Other	Herbicide Tillage Winter-kill
Wheat – RT	Legume Grass	Other	Herbicide Tillage Winter-kill
Wheat – NT	Legume Grass	Other	Herbicide Winter-kill

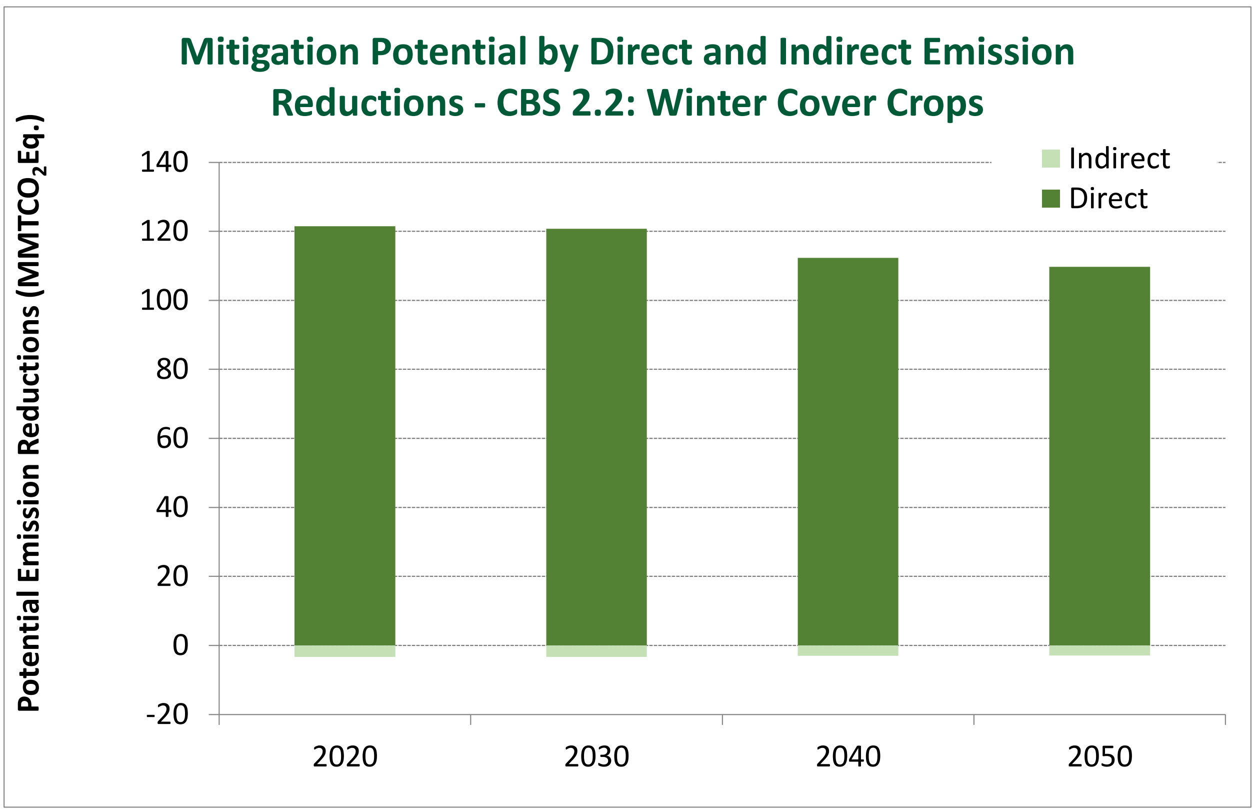
4.2.3. Mitigation Potential for 2020, 2030, 2040, and 2050

The mitigation potential by direct and indirect emission reduction are presented in Exhibit 62. The key findings include:

- As yield increases over time as indicated in the Monsanto Model, acreage declines, consequently, the C sequestration decreases over time as acreage declines.
- Indirect emission reductions (i.e., GHGs from production of inputs) are negative (i.e., indirect emissions increase rather than decrease with the use of cover crops) due to fuel use during application and termination of cover crops.
- Limited data exists on cover crops- including planting and termination methods, acres planted, types of cover crops grown, impacts on yield of cash crop, amount of carbon sequestered, and impacts on N_2O emissions and N leaching.

- Currently there is low use (~ 2-3%) of cover crops in rotations with corn, wheat and soybean. Therefore, very high adoption potential exists (i.e., almost 100% of these cash crops can be grown in rotation with cover crops).
- Growing cover crops can increase soil organic matter (leading to increased yield), reduce compaction, and reduce soil erosion. Cover crops can also result in reduced insect and weed pressure, however we did model these co-benefits in accounting for direct and indirect GHG emission reductions.
- Cover crops have a relatively high national abatement potential compared to other CBSs due to high adoption potential and potentially high levels of carbon sequestration.
- The carbon sequestration potential is highly uncertainty due to lack of data on C storage across crop types, soil and climate regimes.

Exhibit 84: Mitigation Potential for Winter Cover Crops



4.2.4. Sensitivity Analysis and Risk Factors

4.2.4.1. Sensitivity Analysis

Exhibit 60 indicates the upper and lower bounds and the source of the values for selected input variables. Exhibit 61 presents the national mitigation potential for each change in variable.

Exhibit 60: Lower and Upper Bound for Input Variables for CBS on Winter Cover Crops

Variable	Units	Value Used in Base Case	Lower Bound	Upper Bound
CO_2 Flux For CO_2 Storage for Use of Cover Crop[c]	CO_2-eq per acre	0.081	0.041[f]	0.12[f]
CO_2 Flux For CO_2 Storage for Use of Cover Crop[c]	CO_2-eq per acre	1.32	0.66[f]	1.98[f]
Increase in Yield relative to No Cover Crops				
– Corn[d]	Percent	2 to 5%	1%[f]	7.5%[f]
– Soybeans	Percent	2 to 5%	1%[f]	7.5%[f]
– Wheat	Percent	0%	0%	0%

[a] Dabney et al. (2010); Tonitto et al. (2006); Quemda et al. (2013).
[b] Dabney et al. (2010); Kladivko et al. (2014); Quemda et al. 2013.
[c] Eagle et al. (2012); Franzleubbers, (2010); Poeplau and Don (2015).
[d] Quemda et al. (2013); Carlson (2012).
[e] Based on meta-analysis of multiple cash crops with a legume cover crop. Non-legume cover crops did not significantly impact yield. From Quemda et al. (2013).
[f] Evaluated 50% increased and decrease.

Exhibit 61: Resulting Mitigation Potential Based on Change in Variable for Winter Cover Crops (Million Metric Tons of CO_2-eq)

Variable	Using Lower Bound Value	Using Upper Bound Value
Baseline Value	158.65	
CO_2 Flux For CO_2 Storage for Use of Cover Crop	95.72	221.62

4.2.4.2. Technical, Economic, and Policy Risk Factors

Landowners perception of cover crops. The Cover Crop Surveys (SARE 2013, 2014, 2015) ask:

- Farmers currently growing cover crops: "what are the biggest challenges with using cover crops?" and

- Farmers not currently using cover crops "what are the factors that prevent you from using cover crops on your farm?"

Responses from both of these groups indicate that the following risk factors are associated with adopting cover crops, or are preventing farmers from adopting cover crops:

- Perception that cover crops reduce yields
- Perception that cover crops are difficult to terminate
- Perception that cover crops are costly
- Availability of equipment and service providers
- Availability of cover crop seeds
- Access to trusted advisors on cover crops
- Amount and availability to accurate data on cover crops
- Amount and availability of financial incentives
- Increased time/labor required for planting and increased management
- Increased insect pest potential
- Increased overall crop production risk
- Potential for nitrogen immobilization
- Challenge of selecting correct cover crop
- Risk of no measurable economic return

Permanence of carbon storage. While cover crops have been shown to increase soil carbon storage, the amount of carbon stored and the length of time the carbon is stored in the soil is not well established (Ashworth et al., 2014; Balkcom et al., 2013; Blanco-Canqui et al., 2013; Olson et al., 2014; Paul et al., 2015; Snapp et al., 2010). For example, Blanco-Canqui et al. (2013) found that in Nebraska, no till wheat/cover crop rotation increases in soil carbon sequestration were not detectable 9 months after cover crops were terminated. It is not currently known if similar soil carbon patterns occur with other cash crop/cover crop rotations in other regions. Soil carbon loss may also occur when cover crop/cash crop rotations are changed or farmers change from conservation to conventional tillage practices.

Co-benefits of cover crops. Cover crops can result additional gains from: increasing soil nitrogen (legumes), increasing soil organic matter, conserving water, reducing compaction, reducing erosion, reducing pesticide use and increasing yield (Anderson, 2010; Blanco-Canqui et al., 2015; Brandt, 2013; Mitchell and Moore, 2014; Nair et al.; Pratt et al., 2014; Wiggins et al., 2015; Young-Mathews, 2013). However, these benefits vary depending on multiple factors, including farmer experience, regional differences, cover crop/cash crop rotations, production methods and soil type. Incorporation of these co-benefits in the mitigation potential would increase the quantity of emission reductions.

Yield. Including cover crops in cash crop rotations can impact the cash crop yield. Studies have shown that cover crops can increase, decrease or have no impact on cash crop yields (Fawcett et al., 2014; Iowa Learning Farms and Practical Farmers of Iowa, 2014; Midwest Cover Crops Council, 2015; Wells, 2014). The different impacts on yield are due to: environmental conditions, weather conditions, cover crop and cash crop rotations, specific cover crop used, termination timing, termination method and farmer experience (Clark, 2012; SARE, 2013). The most comprehensive data on the impact of cover crops on corn and soy yield comes from the Cover Crop Surveys (SARE, 2013, 2014, 2015). National level data from the 2013 Cover Crop Survey found a 9% increase in corn yield and a 10% increase in soy yield compared to similar fields that had not been cover cropped (SARE, 2013). In 2014, the Survey found a 3.2% increase in corn yield and 4.3% increase in soy yield, and in 2015, corn planted with cover crops experienced a 2.1% increase in yield and soy experienced a 4.2% increase in yield (SARE, 2014, 2015). The dramatic increase in yield in 2013 is thought to be due to the 2012 drought conditions which may have made the benefits of cover crops more vital (SARE, 2015). Changes in yield will impact the rate of adoption of cover crops.

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Appendix 4.A: Current Tillage Practices

This appendix presents state specific data on tillage practice by crop type and by state. ICF used these data to estimate the number of acres by state and crop type that utilize conventional till, reduced till, and no till. ICF estimated the number of acres in each tillage regime and state that are currently using cover crops. Those acres not using cover crops can adopt winter cover crops. We adjusted the estimates for wheat to only cover spring wheat (i.e., cover crops cannot be used for winter cover crops). Exhibits 4.A-1, 4.A-2, and 4.A-3 present the percent of acres using conventional till, reduced till, and no till, respectively.

Exhibit 4.A-1: Cropland Managed Using Conventional Till (Acres)

State	Barley	Corn	Rapeseed/ Canola	Sorghum	Soybeans	Wheat
Alabama	20%	52%	37%	17%	43%	16%
Alaska	N/A	N/A	N/A	N/A	N/A	N/A
Arizona	28%	24%	37%	10%	43%	13%
Arkansas	20%	52%	37%	17%	67%	16%
California	32%	35%	37%	17%	43%	15%
Colorado	28%	24%	37%	10%	43%	13%
Connecticut	15%	40%	37%	17%	43%	16%
Delaware	15%	40%	37%	17%	43%	16%
Florida	20%	52%	37%	17%	43%	16%
Georgia	20%	52%	37%	17%	43%	16%
Hawaii	N/A	N/A	N/A	N/A	N/A	N/A
Idaho	28%	24%	37%	10%	43%	13%
Illinois	20%	25%	37%	17%	40%	9%
Indiana	20%	25%	37%	17%	40%	9%
Iowa	20%	25%	37%	17%	40%	9%
Kansas	6%	15%	37%	2%	33%	23%
Kentucky	11%	22%	37%	17%	48%	16%
Louisiana	20%	52%	37%	17%	67%	16%
Maine	15%	40%	37%	17%	43%	16%
Maryland	15%	40%	37%	17%	43%	16%
Massachusetts	15%	40%	37%	17%	43%	16%
Michigan	29%	34%	37%	17%	30%	0%
Minnesota	29%	34%	37%	17%	30%	0%
Mississippi	20%	52%	37%	17%	67%	16%
Missouri	20%	25%	37%	17%	40%	9%
Montana	28%	24%	37%	10%	43%	13%
Nebraska	6%	15%	37%	2%	33%	23%

State	Barley	Corn	Rapeseed/ Canola	Sorghum	Soybeans	Wheat
Nevada	28%	24%	37%	10%	43%	13%
New Hampshire	15%	40%	37%	17%	43%	16%
New Jersey	15%	40%	37%	17%	43%	16%
New Mexico	28%	24%	37%	10%	43%	13%
New York	15%	40%	37%	17%	43%	16%
North Carolina	11%	22%	37%	17%	48%	16%
North Dakota	6%	15%	37%	2%	33%	23%
Ohio	20%	25%	37%	17%	40%	9%
Oklahoma	20%	55%	37%	40%	43%	38%
Oregon	32%	35%	37%	17%	43%	15%
Pennsylvania	15%	40%	37%	17%	43%	16%
Rhode Island	15%	40%	37%	17%	43%	16%
South Carolina	20%	52%	37%	17%	43%	16%
South Dakota	6%	15%	37%	2%	33%	23%
Tennessee	11%	22%	37%	17%	48%	16%
Texas	20%	55%	37%	40%	43%	38%
Utah	28%	24%	37%	10%	43%	13%
Vermont	15%	40%	37%	17%	43%	16%
Virginia	11%	22%	37%	17%	48%	16%
Washington	32%	35%	37%	17%	43%	15%
West Virginia	11%	22%	37%	17%	48%	16%
Wisconsin	29%	34%	37%	17%	30%	0%
Wyoming	28%	24%	37%	10%	43%	13%

Source: USDA, ARMS Data for 2010.

Exhibit 4.A-2: Cropland Managed Using Reduced Till (Acres)

State	Barley	Corn	Rapeseed/ Canola	Sorghum	Soybeans	Wheat
Alabama	18%	14%	24%	10%	9%	15%
Alaska	N/A	N/A	N/A	N/A	N/A	N/A
Arizona	13%	26%	24%	0%	9%	9%
Arkansas	18%	14%	24%	10%	8%	15%
California	32%	21%	24%	10%	9%	32%
Colorado	13%	26%	24%	0%	9%	9%
Connecticut	15%	15%	24%	10%	9%	15%
Delaware	15%	15%	24%	10%	9%	15%

State	Barley	Corn	Rapeseed/ Canola	Sorghum	Soybeans	Wheat
Florida	18%	14%	24%	10%	9%	15%
Georgia	18%	14%	24%	10%	9%	15%
Hawaii	N/A	N/A	N/A	N/A	N/A	N/A
Idaho	13%	26%	24%	0%	9%	9%
Illinois	18%	23%	24%	10%	9%	0%
Indiana	18%	23%	24%	10%	9%	0%
Iowa	18%	23%	24%	10%	9%	0%
Kansas	9%	19%	24%	9%	11%	22%
Kentucky	9%	21%	24%	10%	7%	15%
Louisiana	18%	14%	24%	10%	8%	15%
Maine	15%	15%	24%	10%	9%	15%
Maryland	15%	15%	24%	10%	9%	15%
Massachusetts	15%	15%	24%	10%	9%	15%
Michigan	31%	34%	24%	10%	10%	3%
Minnesota	31%	34%	24%	10%	10%	3%
Mississippi	18%	14%	24%	10%	8%	15%
Missouri	18%	23%	24%	10%	9%	0%
Montana	13%	26%	24%	0%	9%	9%
Nebraska	9%	19%	24%	9%	11%	22%
Nevada	13%	26%	24%	0%	9%	9%
New Hampshire	15%	15%	24%	10%	9%	15%
New Jersey	15%	15%	24%	10%	9%	15%
New Mexico	13%	26%	24%	0%	9%	9%
New York	15%	15%	24%	10%	9%	15%
North Carolina	9%	21%	24%	10%	7%	15%
North Dakota	9%	19%	24%	9%	11%	22%
Ohio	18%	23%	24%	10%	9%	0%
Oklahoma	18%	21%	24%	20%	9%	25%
Oregon	32%	21%	24%	10%	9%	32%
Pennsylvania	15%	15%	24%	10%	9%	15%
Rhode Island	15%	15%	24%	10%	9%	15%
South Carolina	18%	14%	24%	10%	9%	15%
South Dakota	9%	19%	24%	9%	11%	22%
Tennessee	9%	21%	24%	10%	7%	15%
Texas	18%	21%	24%	20%	9%	25%
Utah	13%	26%	24%	0%	9%	9%
Vermont	15%	15%	24%	10%	9%	15%
Virginia	9%	21%	24%	10%	7%	15%

State	Barley	Corn	Rapeseed/ Canola	Sorghum	Soybeans	Wheat
Washington	32%	21%	24%	10%	9%	32%
West Virginia	9%	21%	24%	10%	7%	15%
Wisconsin	31%	34%	24%	10%	10%	3%
Wyoming	13%	26%	24%	0%	9%	9%

Source: USDA, ARMS Data for 2010.

Exhibit 4.A-3: Cropland Managed Using No Till (Acres)

State	Barley	Corn	Rapeseed/ Canola	Sorghum	Soybeans	Wheat
Alabama	61%	34%	39%	73%	48%	69%
Alaska	N/A	N/A	N/A	N/A	N/A	N/A
Arizona	59%	50%	39%	90%	48%	78%
Arkansas	61%	34%	39%	73%	25%	69%
California	35%	44%	39%	73%	48%	54%
Colorado	59%	50%	39%	90%	48%	78%
Connecticut	69%	45%	39%	73%	48%	69%
Delaware	69%	45%	39%	73%	48%	69%
Florida	61%	34%	39%	73%	48%	69%
Georgia	61%	34%	39%	73%	48%	69%
Hawaii	N/A	N/A	N/A	N/A	N/A	N/A
Idaho	59%	50%	39%	90%	48%	78%
Illinois	61%	52%	39%	73%	52%	91%
Indiana	61%	52%	39%	73%	52%	91%
Iowa	61%	52%	39%	73%	52%	91%
Kansas	85%	65%	39%	89%	56%	56%
Kentucky	80%	58%	39%	73%	45%	69%
Louisiana	61%	34%	39%	73%	25%	69%
Maine	69%	45%	39%	73%	48%	69%
Maryland	69%	45%	39%	73%	48%	69%
Massachusetts	69%	45%	39%	73%	48%	69%
Michigan	39%	32%	39%	73%	60%	97%
Minnesota	39%	32%	39%	73%	60%	97%
Mississippi	61%	34%	39%	73%	25%	69%
Missouri	61%	52%	39%	73%	52%	91%
Montana	59%	50%	39%	90%	48%	78%
Nebraska	85%	65%	39%	89%	56%	56%

State	Barley	Corn	Rapeseed/ Canola	Sorghum	Soybeans	Wheat
Nevada	59%	50%	39%	90%	48%	78%
New Hampshire	69%	45%	39%	73%	48%	69%
New Jersey	69%	45%	39%	73%	48%	69%
New Mexico	59%	50%	39%	90%	48%	78%
New York	69%	45%	39%	73%	48%	69%
North Carolina	80%	58%	39%	73%	45%	69%
North Dakota	85%	65%	39%	89%	56%	56%
Ohio	61%	52%	39%	73%	52%	91%
Oklahoma	61%	24%	39%	40%	48%	38%
Oregon	35%	44%	39%	73%	48%	54%
Pennsylvania	69%	45%	39%	73%	48%	69%
Rhode Island	69%	45%	39%	73%	48%	69%
South Carolina	61%	34%	39%	73%	48%	69%
South Dakota	85%	65%	39%	89%	56%	56%
Tennessee	80%	58%	39%	73%	45%	69%
Texas	61%	24%	39%	40%	48%	38%
Utah	59%	50%	39%	90%	48%	78%
Vermont	69%	45%	39%	73%	48%	69%
Virginia	80%	58%	39%	73%	45%	69%
Washington	35%	44%	39%	73%	48%	54%
West Virginia	80%	58%	39%	73%	45%	69%
Wisconsin	39%	32%	39%	73%	60%	97%
Wyoming	59%	50%	39%	90%	48%	78%

Source: USDA, ARMS Data for 2010.

5. CBS 3: Produce Ethanol from Corn and Corn Stover to Offset Fossil Fuel Emissions in the Transportation Sector

5.1. Ethanol Production and Impacts on Transportation Greenhouse Gas Emissions

Key Considerations in Switching from Gasoline to Ethanol through Integration of Corn Grain and Corn Stover Feedstocks

- GHG benefits are driven by the offset of CO_2 emitted during the combustion of ethanol in vehicles through the carbon uptake during the agricultural feedstock growth.
- Integrated ethanol production adds to corn-based ethanol life-cycle GHG benefits through additional reduction of fossil process energy use and its associated GHG emissions.
- Corn stover feedstock is available from the same land base already providing corn grain feedstock to existing ethanol plants.

Using ethanol as a vehicle fuel provides measurable greenhouse gas (GHG) emissions benefits compared with using gasoline. The carbon dioxide (CO_2) emitted during the combustion of ethanol (and other biologically-derived fuels) in vehicles is offset by carbon uptake during the corn plant growth stage (Wang et al., 2012; Wang et al., 2015). Corn ethanol is the predominant biofuel produced in the United States. It has been estimated that the use of corn-based ethanol instead of gasoline reduces the life-cycle GHG emissions by 19–52 percent depending on the source of energy use used during the ethanol production (DOE, 2014). The reduction is expected to increase to approximately 86 percent when the use of cellulosic ethanol material is taken into account because the cellulosic feedstocks require less fossil energy to produce ethanol; for example, cellulosic ethanol plants use co-product lignin instead of fossil fuel to generate the needed steam (see Wang et al., 2007). In the United States, corn stover is considered the potential main feedstock for cellulosic ethanol due to its availability; it is also the current feedstock considered for cellulosic plants that are near commercialization.

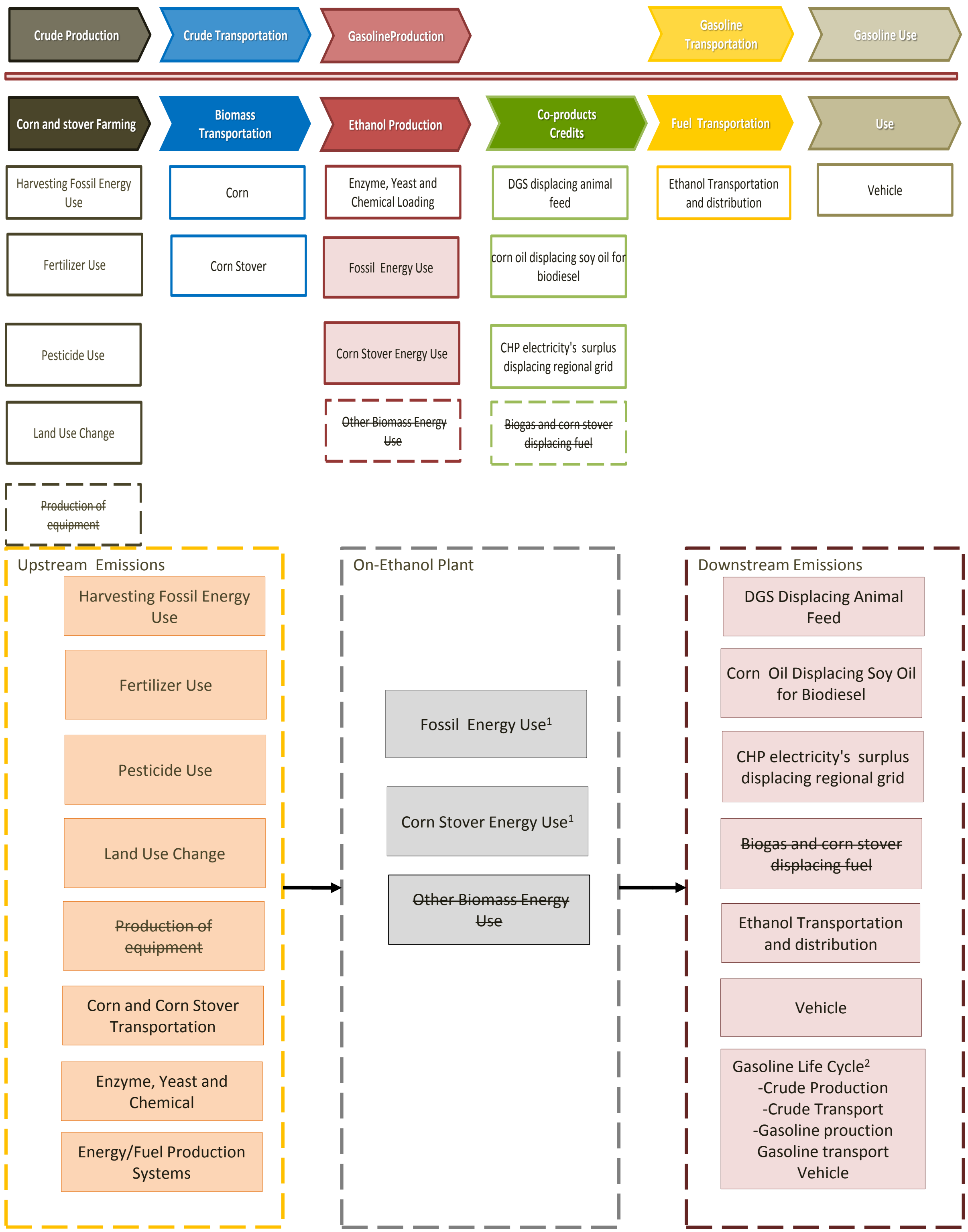
The integration of processes to use corn grain as well as corn stover as feedstocks for ethanol allows the possibility of reduction in process energy use and therefore in GHG emissions. When corn stover and corn ethanol plants are co-located, GHG life-cycle emissions associated with the production of ethanol are reduced due to the conversion of corn stover into biofuel; fossil fuel use is reduced and combustion emissions are offset by the carbon uptake when the cellulosic feedstock grows. Consequently, the implementation of co-located ethanol plants that use the corn grain plus the corn stover could decrease the life-cycle CO_2 emissions associated with ethanol production, offset impacts of land use, and provide a potential market for agricultural residues (see Wang et al., 2014).

The magnitude of the GHG emission benefits of using corn and corn stover to produce ethanol to be used as a transportation fuel on a life-cycle basis is a function of the interaction of several parameters. The most relevant parameters include corn and corn stover agricultural inputs, corn yield, ethanol yield, amount and quality of ethanol co-products, the source of process energy supply, and the amount of gasoline the ethanol can displace when used in vehicles. Note that corn yield per acre is a key factor in determining the total amount of land needed for a given amount of corn ethanol production and the resulting total land-use change emissions[11]. In addition, the life-cycle emission estimates and production factors associated with gasoline supply have an impact on the expected GHG benefits as emissions from the life cycle of ethanol are expected to displace life-cycle emissions from gasoline in the transportation sector; gasoline life cycle GHG emissions varies considerably (e.g., seeVenkatesh et al., 2010).

Crop-Based Strategy (CBS) 3 focuses on the GHG reductions associated with the use of excess corn grain and corn stover to produce ethanol in an integrated corn-corn stover ethanol production process with the hybrid corn-corn stover ethanol offsetting gasoline life-cycle emissions in the transportation sector. As depicted in Exhibit 62, upstream emissions for *CBS 3: Integrated Ethanol Production* include those associated with energy fuel production systems, pesticides production systems, fertilizer production systems, on-farm emissions, land-use change emissions, transportation of corn grain and corn stover to the ethanol plant, and enzyme, yeast and chemical production systems. On-site emissions include combustion emissions from process energy use in the integrated ethanol production system (and biogenic emissions associated with the fermentation process). Downstream emissions include credits from co-products systems, ethanol transportation, vehicle combustion, and gasoline life-cycle emissions. The production of the integrated ethanol includes the use of corn stover with 100 percent of the stover going into the production of ethanol (rather than a fraction being combusted upfront for process energy) and 100 percent of the lignin co-product from the stover being combusted for process energy, in a cogeneration system that provides all the electricity requirements for the integrated ethanol process. In addition, this process offsets some GHG emissions associated with an electricity surplus generation to be exported to the grid. In order to determine GHG benefits for each production region, specific regional grid mix GHG emissions are taken into account. Changes in adoption due to regional excess corn grain production and corn stover availability (based on harvested area) and the resulting abatement potential are modeled to estimate the national mitigation potential. The analysis includes carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) gases. Emission sources and processes excluded from CBS 3 are machinery production and changes in regional GHG emissions benefits associated with specific regional agricultural practices (e.g., regional harvesting and farming). Exhibit 62 illustrates the life-cycle boundaries considered for the analysis of the Integrated Ethanol Production.

[11] GREET1_2014 model includes a Carbon Calculator for Land Use Change from Biofuels Production. Land change area data is from Purdue University's Global Trade Analysis Project (GTAP) model, a computable general equilibrium (CGE) economic model. Feedstock- and spatially-explicit belowground carbon content data for the United States were generated with a surrogated model at the state level (see Argonne National Laboratory, 2014).

Exhibit 62: LCA Accounting Boundaries for Integrated Ethanol Production



[1] *Fossil energy use and corn stover energy use are combustion emissions at the ethanol plant.*
[2] *Gasoline life cycle is use as reference to determine the emissions offset by the ethanol production system.*

ICF used the GREET1_2014 model to model the life-cycle GHG benefits. The use of the model provides completeness and consistency in data use throughout the analysis of different energy and material systems. ICF used default input parameters to GREET that represent integrated ethanol production in the United States. Exhibit 63 indicates a high level overview of the data sources used for modelling major stages of the integrated ethanol production life cycle.

Exhibit 63: Main Data Sources for Calculating the Greenhouse Gas Benefits of Integrated Ethanol Production

Data	Source
U.S. corn on-farm chemical use and pest management practices	2010 U.S. Department of Agriculture's (USDA's) National Agricultural Statistics Service (NASS) Agricultural Chemical Use Program
Farming energy use (data is the most recent one available in public domain)	2005 U.S. Department of Agriculture's (USDA's) Farm Cost Surveys
2012 state of the industry data for corn ethanol production (i.e., corn ethanol yield, energy consumption and fuel type shares, and co-product yield including corn oil) at the biorefinery	Muller and Kwik, (2013)
Potential capacity for integrated ethanol production	POET DSM
Life cycle emission estimates for U.S. production and generation of fertilizers, pesticides, enzyme, yeast, and chemicals, natural gas, coal, petroleum, and electricity generation by fuel type source.	GREET1_2014

Similarly, Exhibit 64 presents the main values for GREET inputs. See Wang et al. (2014) for detailed documentation of data sources and other modelling parameters.

Exhibit 64: Main Data Inputs in GREET1_2014 for Calculating the Greenhouse Gas Benefits of Integrated Ethanol Production[a]

Changes in Inputs	Values
Biomass yield	
Corn Grain (bu/acre)	158[c]
Corn stover (dry ton/acre)	0.96
Multipass Farming Energy Use	
Corn grain (Btu/per bushel)	8,584

Changes in Inputs	Values
2nd pass for Corn stover (Btu/per dry ton)	192,500
Land-Use Change Scenario Options	
Select Corn Ethanol Case	Corn Ethanol 2011
Select Domestic Emissions Modeling Scenario	Century
Select International Emissions Modeling Scenario	Winrock
Domestic Emissions Modeling Scenario	yield_increase
Soil depth considered in modeling	100 cm
Harvested Wood Product (HWP) Scenario	HEATH
Land Management Practice for Corn and Corn Stover Production	Conventional Till
Share of Corn Ethanol Plant Types	
Corn Grain Ethanol Plant Scale (MGY)	55
Corn Grain Share of ethanol from each plant	73.3%
Corn Stover Ethanol Plant Scale (MGY)	20
Corn Stover Share of ethanol from each plant	26.7%
Ethanol Yield	
Dry Milling Plant w/ Corn Oil Extraction (gallons/bushel)	2.82
Corn Stover Plant Fermentation (gallons/dry Ton of Biomass)	80.0
Corn Stover Use	
Share of corn stover energy use in CHP	100%
Percentage of stover used for ethanol production (source of biogas and ligning)	100%
Life Cycle Analysis Methodological Choices	
Allocation of corn farming energy between corn grain and corn stover	Attributional
Share of generated energy to corn and corn stover ethanol	Fulfill corn stover ethanol demand first
Integrated Corn/Stover Ethanol Case	Combined Gallon
Key Assumptions Regarding Cellulosic Ethanol	Fermentation
Types of Electricity Displaced by Co-Produced Electricity in Biomass-based EtOH Plants for Export	Regional electricity grid mix
Method for dealing with co-products of corn ethanol w/ corn oil extraction	Displacement method

Changes in Inputs	Values
Method for dealing with co-products of corn oil w/ corn oil extraction	Process Level Energy Value-based Allocation
Global Warming Potentials of Greenhouse Gases Relative to CO_2	AR5/GWP, 100 year

[a] Data source: GREET1_2014 (Argonne National Laboratory, 2014).

[b] Regional electricity life-cycle emission factors are calculated using GREET1_2014.

[c] We used the default corn yield as provided in GREET. This value is comparable to the national average corn yield in 2010 based on the Monsanto Model. The yield is expected to increase over time, and GREET allow the user to change this (and other) input values.

For estimating the mitigation potential, we evaluated three options: (1) constructing a new integrated ethanol plant (50 MGY), (2) retrofitting an existing corn ethanol plant without increased capacity (50 MGY), and (3) retrofitting an existing corn ethanol plant with increased capacity (75 MGY).

5.2. Emission Reductions

Farming processes are responsible for more than 70 percent of the integrated ethanol production life-cycle emissions. Ethanol production associated emissions are the second largest life-cycle stage contributing to the emissions of ethanol at about 41 percent; however, ethanol production impacts are mitigated by co-product credits (i.e., the emission benefits lignin combustion and corn oil production) of 18 percent. In this regard, analysis of life-cycle emissions for ethanol fuel should include detailed evaluation of agricultural practices. Our study assumes one prevailing on-farm management practice for corn (and corn stover) production (i.e., conventional till). Regional differences in the adoption of less emissive on-farm management practices (e.g., conservation tillage, application of inhibitors, precision agriculture) were not modeled for this CBS. As a result, the life-cycle emissions estimated here for CBS 3 are conservative. The life-cycle GHG emission reductions for these alternate management practices are discussed in the preceding chapters.

Exhibit 65 shows the life-cycle emissions estimates for integrated ethanol for the Southern Plains.

Exhibit 65: Life Cycle Emissions Estimates for Integrated Ethanol for the Southern Plains (Combined Product from Corn and Corn Stover) in Grams per MMBtu of Fuel Throughput at Each Life-Cycle Stage

Life-Cycle Stage	CO_2	CH_4	N_2O	SF_6	CO_2-eq
Farming	21,611	31.60	53.88	-	36,837
Corn and Corn Stover Transport	2,138	3.50	0.04	-	2,252

Life-Cycle Stage	CO_2	CH_4	N_2O	SF_6	CO_2-eq
Ethanol Production	18,770	53.29	2.83	-	21,118
Direct	13,542	0.24	0.12	-	13,583
Indirect	5,227	53.06	2.70	-	7,535
Co-products Credit	−5,433	−16.35	−12.96	-	−9,358
Fuel Transportation	1,163	1.84	0.03	-	1,225
Vehicle Combustion	0	0.00	0.00	-	0
Total	**38,249**	**74**	**44**	**-**	**52,075**

However, when the boundaries of analysis are expanded to evaluate the ultimate function of the system (i.e., offsetting gasoline use), emission reduction results are driven by gasoline vehicle combustion emissions estimated to be equivalent to at least 1.5 times the life-cycle emissions for integrated ethanol production. Emissions from farming processes as well as ethanol production will not have as significant an emissions impact compared to the emissions reductions associated with the amount of gasoline that the ethanol can displace when used in vehicles. Exhibit 66 shows the life-cycle emissions estimates for gasoline.

Exhibit 66: Life-Cycle Emissions Estimates for Gasoline in Grams per MMBtu of Fuel Throughput at Each Life-Cycle Stage

Life-Cycle Stage	CO_2	CH_4	N_2O	SF_6	CO_2-eq
Upstream	24,809	143	4	-	30,131
Vehicle Combustion	76,705	2.34	1.48	-	77,168
Total	**101,515**	**145**	**5**	**-**	**107,299**

Using integrated ethanol in the transportation sector as a fuel implies 51 percent life-cycle emission reductions compared to those of gasoline (i.e., reductions of 54,866 MT/MJ Fuel compared to 107,299 MT/MJ gasoline life cycle of gasoline). A 10 percent improvement in emissions associated with agricultural practices would represent a 3.5 percent improvement in the GHG benefits. Similarly, a reduction of 10 percent in emissions associated with ethanol production would represent a 1.5 percent improvement in GHG benefits, and up to 2 percent if such improvement implies an increase in co-product credits.

The magnitude of the difference between gasoline upstream emissions and ethanol upstream emissions is important in the context of fuel production (Well-To-Pump systems) as opposed to the context of final product use (Well-To-Wheel systems). In this context, the emission estimates indicate that there are opportunities for the ethanol agricultural practices and ethanol production processes to improve the GHG benefits associated with displacing gasoline. In this example, the entire gasoline upstream emissions are slightly lower than emissions associated with only farming processes (which assumes conventional till practices for corn and corn stover production in this study). Although there is uncertainty in the gasoline upstream emission estimates due to changes in its gasoline supply chain such as the quality and origin of the crude feedstock, gasoline upstream emissions could increase by roughly 20 percent before they become equivalent to the estimated ethanol farming associated emissions.

For estimating national emission reductions, the life-cycle GHG emission estimates for integrated ethanol compared to gasoline were used to estimate indirect and direct emission reduction factors associated with ethanol produced at an integrated ethanol plant. Direct emission reductions refer to those emission reductions occurring on-site (i.e., the emission associated with the integrated ethanol plant), and indirect emission reductions refer to those emission reductions occurring off-site (i.e., upstream and downstream of the integrated ethanol plant). Exhibit 67 shows these direct and indirect emission reduction factors by GHG.

Exhibit 67: Greenhouse Gas Benefits from Ethanol Displacing Gasoline in MT per MJ of Fuel by Greenhouse Gas for Direct and Indirect Emission Source

Indirect Emission Reductions (MT/MJ Ethanol)				Direct (on-site) Emission Reductions (MT/MJ Ethanol)		
CO_2	CH_4	N_2O	SF_6	CO_2	CH_4	N_2O
7.28×10^{-5}	6.79×10^{-8}	-3.63×10^{-8}	-	-1.28×10^{-5}	-2.25×10^{-10}	-1.18×10^{-10}

It should be noted that for integrated ethanol production, all of the net emission reductions occur downstream of the integrated ethanol plant as the integrated ethanol displaces gasoline in the transportation sector.

5.3. Adoption Potential

The adoption potential for each USDA region (in unit of Mega joules (MJ) integrated ethanol) and option was estimated based on the amount of excess corn grain and corn stover available from each USDA region and the relative amounts of corn (2.82 corn ethanol gallons per bushel) and corn stover (80 corn stover gallons per metric ton corn stover) needed to produce gallons of ethanol at the integrated plant. For example, the amount of excess corn estimated for the South Plains in 2020 is 46.30 million bushels. Since 2.82 gallons of ethanol are made from each bushel of corn at the integrated plant (see Exhibit 64), this quantity of excess grain amounts to a production potential of 130,562,756 million gallons of corn ethanol (or 10,514,218,761 MJ ethanol).

Excess corn grain availability was estimated based on the difference between the maximum harvested area of corn and the future projected harvested area of corn in subsequent decades provided by Monsanto. The harvested area of corn is projected to be less in subsequent decades as future demand for corn is met through increases in corn yield rather than through increased corn area expansion. The excess corn grain was estimated from the difference in area multiplied by the corn yield per harvested area provided by Monsanto. As a result, the estimated excess corn grain represents the corn grain that could potentially be produced if the maximum harvested area of corn was maintained for corn production in future decades and not allowed to revert to other land uses.

Corn stover availability was estimated based on the future projected harvested area of corn provided by Monsanto multiplied by the corn stover yield per harvested area taken from the literature—1.4 dry Mg/acre/year (3.4 dry Mg/ha/year; Wang et al., 2014).[12]

ICF International (2016) Exhibit Annex-1 shows the projected harvested corn area, corn grain yield, and corn stover yield by USDA region. ICF International (2016) Exhibit Annex-2 shows the projected excess corn grain and corn stover by USDA region.

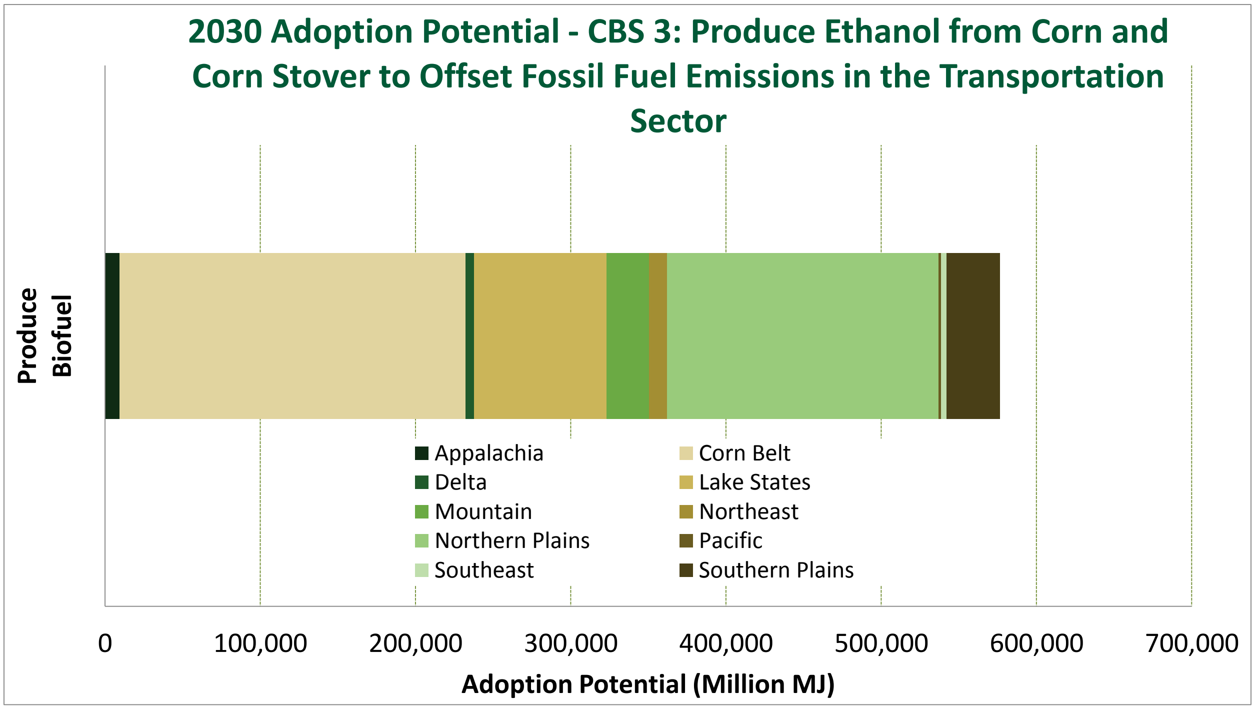
The estimated adoption potentials are based on the following assumptions:

- Production of integrated corn-corn stover ethanol at retrofitted plants with increased capacity (Option 3) is constrained according to the available nameplate capacity of existing corn grain ethanol plants that could be retrofitted.
- Production of integrated corn-corn stover ethanol at new plants (Option 1) is constrained according to both the amount of excess corn grain and remaining corn stover available (i.e., the amount of corn stover left over after meeting the increased ethanol capacity post retrofit).
- Production of integrated corn-corn stover ethanol at retrofitted plants without increasing capacity (Option 2) is perhaps unrealistic (e.g., the capital and recurring costs and the loss of revenues from the reduction in DDG would likely not justify a retrofit). As a result, we assumed a zero percent allocation to this option.
- Excess corn grain is processed at the new integrated corn-corn stover ethanol plants, and no additional corn grain is diverted from the market—i.e., the increase in integrated ethanol capacity from new plants is based on new corn and left-over corn stover.

Exhibit 68 presents the adoption potentials for integrated ethanol production by USDA region (see also ICF International, 2016, Exhibit Annex-3).

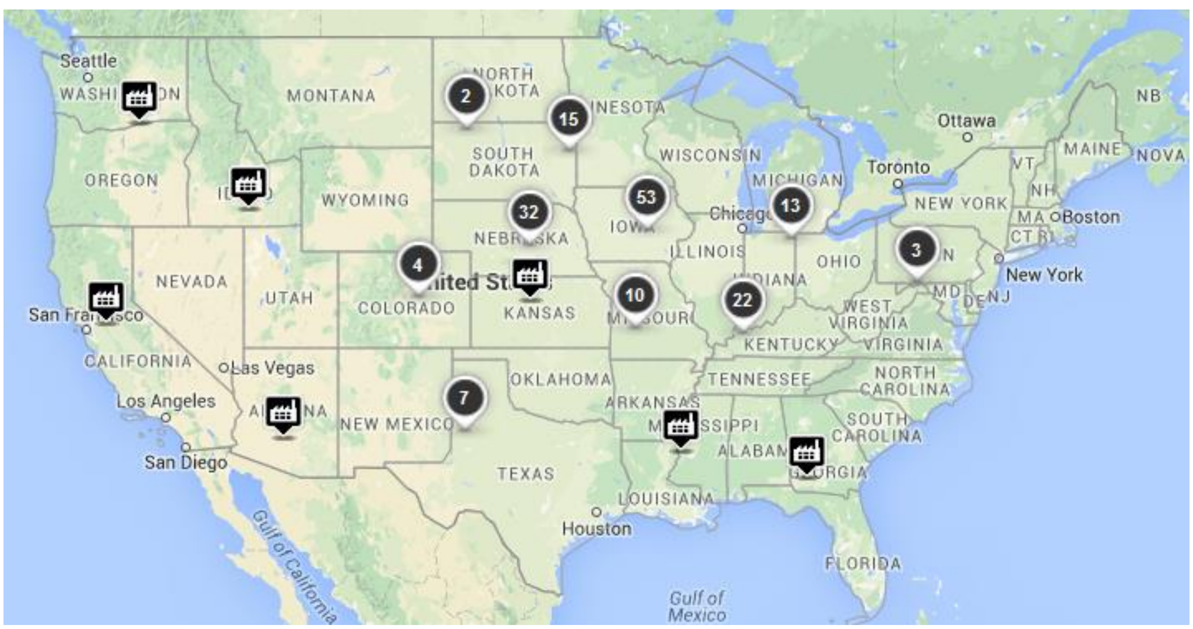
[12] According to Wang et al. (2014) only a fraction of the available stover in cornfields can be harvested to maintain and replenish soil organic carbon and prevent erosion.

Exhibit 68: Adoption Potential for Production of Ethanol from Corn and Corn Stover



As seen in Exhibit 68, adoption potential is significantly higher in those regions with larger areas of corn (e.g., Corn Belt, North Plains, Lake States). These areas also have larger numbers of existing corn ethanol plants (see Exhibit 69).

Exhibit 69: Map of Ethanol Production Facilities in the United States

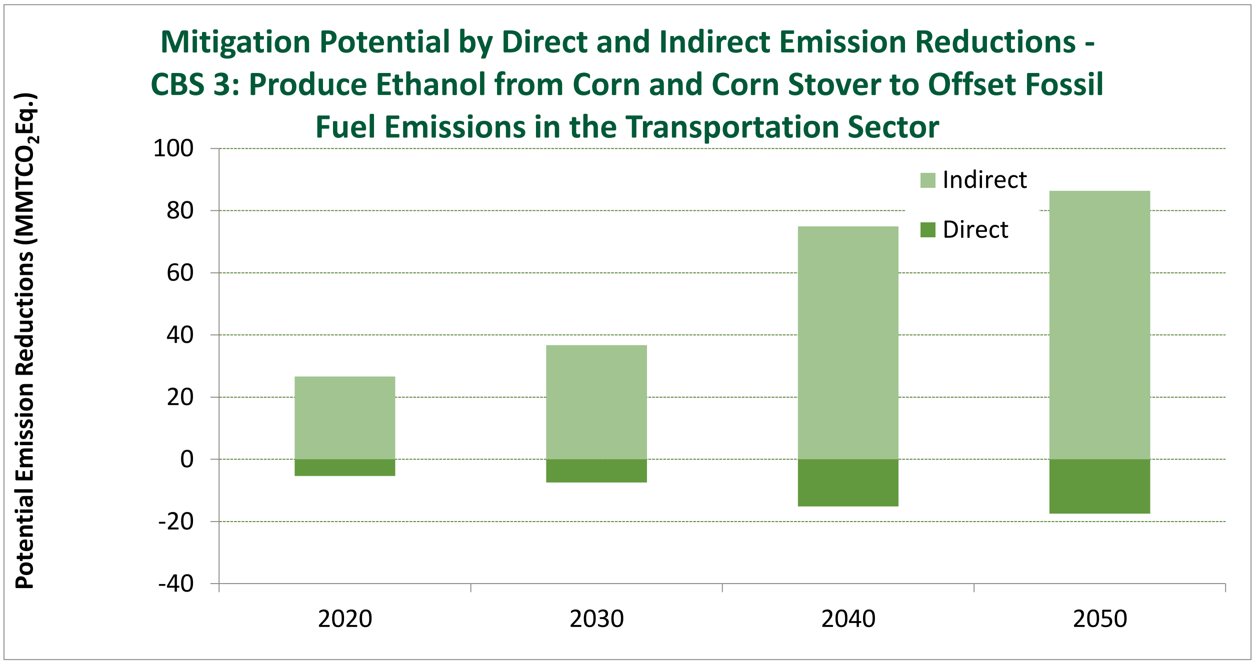


Source: EPA FLIGHT

5.3.1. Mitigation Potential for 2020, 2030, 2040, and 2050

The emission reductions associated with integrated ethanol production, were estimated for the three options: (1) constructing a new integrated ethanol plant (50 MGY), (2) retrofitting an existing corn ethanol plant without increased capacity (50 MGY), and (3) retrofitting an existing corn ethanol plant with increased capacity (75 MGY). The mitigation potential is presented in Exhibit 70 by direct and indirect emission reduction.

Exhibit 70: Mitigation Potential for Integrated Ethanol Production



The key findings include:

- For integrated ethanol production, all of the net emission reductions occur downstream of the integrated ethanol plant as the integrated ethanol displaces gasoline in the transportation sector.
- These downstream emission reductions more than offset the process (i.e., direct) emissions associated with the corn ethanol production at the integrated ethanol plants.
- Number of retrofitted and new integrated plants needed to process the available corn stover (and excess corn grain) is significant—e.g., 95 plants to produce the 7.16 billion gallons in 2030 (assuming a 75 MGY integrated ethanol plant).
- Excess corn is projected to provide an increasing share of the integrated ethanol—i.e., abatement potential—in future decades.

5.4. Sensitivity Analysis and Risk Factors

5.4.1. Sensitivity Analysis

Exhibit 71 indicates the upper and lower bounds and the source of the values for selected input variables. Exhibit 72 presents the national mitigation potential for each change in variable.

Exhibit 71: Lower and Upper Bounds for Input Variables for CBS on Integrated Ethanol

Variable	Units	Value Used in Base Case	Lower Bound	Upper Bound
Corn Stover Yield	Mg/ha/yr	3.4[a]	50%[b]	150%[b]
Indirect Emission Reductions	MT CO_2-eq/MJ	6.37×10^{-5}	63%[c]	158%[c]
Direct Emission Reductions	MT CO_2-eq/MJ	-1.29×10^{-5}	63%[c]	159%[c]

[a] 3.4 Mg/ha/yr ≈ 1.4 Mg/acre/yr

[b] Based on an assumption of ±50 percent.

[c] Based on ICF analysis using GHG Protocol Pedigree Matrix method.

Exhibit 72: Resulting 2030 Mitigation Potential Based on Change in Variable for Integrated Ethanol (Metric Tons of CO_2-eq)

Variable	Using Lower Bound Value	Using Upper Bound Value
Baseline Value	**29,289,428**	
Corn Stover Yield	17,429,753	29,509,256
Indirect Emission Reductions	15,840,979	50,494,888
Direct Emission Reductions	32,037,258	24,927,093

5.4.2. Technical, Economic, and Policy Risk Factors

Summarized below are key technical, economic, and policy risk factors that impact the adoption and resulting emission reductions associated with integrated ethanol production.

Emission Reductions: The life-cycle emission reductions results for integrated ethanol production are influenced by both the choice of life-cycle accounting boundaries as well as the life-cycle methodology choices (e.g., allocation of corn farming energy between corn grain and corn stover, method for dealing with co-products). Therefore, different choices would likely result in different emission reduction estimates. In addition the assumptions regarding the use of land management practice for corn (and corn stover) production (e.g., conventional till) and harvest (e.g., second pass for corn stover) as well as the corn yield (and corn stover collection rate) influence the emissions associated with agriculture life-cycle stage.

Abatement Potential: The adoption potential is based on the assumptions that the excess corn and corn stover collected from each USDA region would be processed at either retrofitted or new integrated ethanol plant—i.e., the study models abatement potential based on the maximum projected feedstock supply. As a result, the study does not consider any logistical constraints—e.g., the ability of a farmer/contractor to collect the available corn stover, the feasibility of transporting all of the available corn stover to an integrated ethanol plant, and whether a sufficient number of new plants will be available to process the excess corn and left-over corn stover—and does not consider alternative uses for the available corn stover (e.g., treated stover feed).

5.5. References

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6. CBS 4: Optimize the Use of Excess Crop Residues (Offset Fossil Fuel Emissions)

In this chapter, we evaluate two uses of excess crop residues: (1) pyrolysis of corn stover into liquid fuels and biochar including the field application of the biochar co-product; and (2) co-firing corn stover for electricity generation.

6.1. Pyrolysis of Corn Stover into Liquid Fuels and Biochar Including the Field Application of the Biochar Co-Product

Key Considerations in the Pyrolysis of Corn Stover into Liquid Fuels and Biochar Including the Field Application of the Biochar Co-Product

- GHG benefits are driven by the offset of CO_2 emitted during the combustion of pyrolysis-based liquid fuels in vehicles through the carbon uptake during the agricultural feedstock growth.
- Additional GHG benefits are associated with the field application of biochar including carbon sequestered in the biochar plus a reduction in N_2O and CH_4 emissions from soils, an increase in fertilizer efficiency, soil organic carbon, and crop yields.
- Corn stover feedstock is available from the same land base already providing corn grain feedstock to existing ethanol plants.

Using pyrolysis-based liquid fuels in vehicles provides measurable greenhouse gas (GHG) emissions benefits compared with using gasoline. The carbon dioxide (CO_2) emitted during the combustion of pyrolysis-based liquid fuels (and other biologically-derived fuels) in vehicles is offset by carbon uptake during the corn agriculture life-cycle stage (see Wang et al., 2014). In addition, biochar is a co-product from biomass pyrolysis which can sequester carbon when applied to soils on the farm. The field application of biochar may also suppress N_2O and CH_4 emissions from fertilized soils, improve fertilizer efficiency, increase soil organic carbon (SOC), and increase crop yields (Wang et al., 2014).

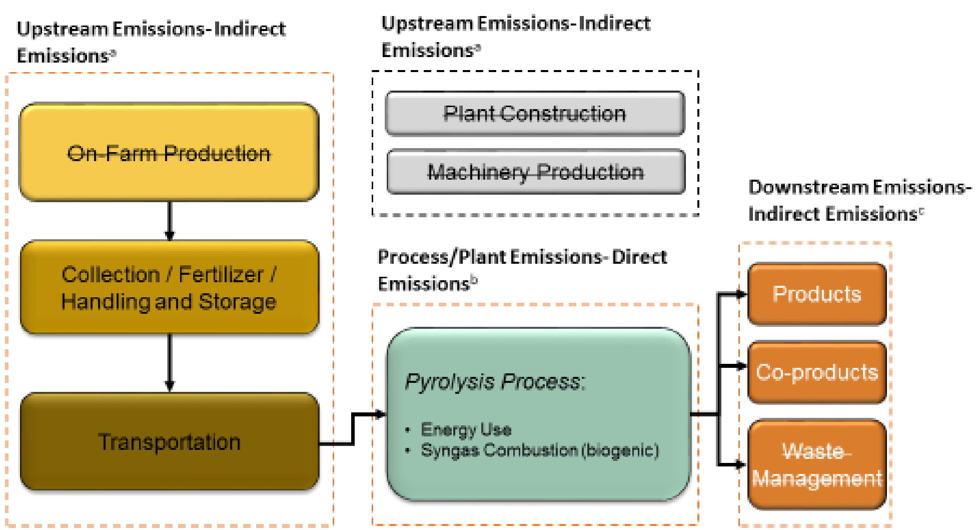
The inclusion of these agricultural effects as part of the life-cycle analysis (LCA) analysis of pyrolysis-based liquid fuels significantly influences the LCA results. For example, Wang et al. (2014) showed that overall the life-cycle GHG emissions for pyrolysis-based gasoline are lower when biochar is applied to soil than when it is combusted to produce electricity. They also showed that the carbon abatement (CA) values of fast and slow pyrolysis production systems are comparable (although the fast pyrolysis system produces less biochar co-product).

Crop-Based Strategy (CBS) 5 focuses on the GHG reductions associated with the use of corn stover to produce biochar for field application on the farm in either a fast or a slow pyrolysis production system using the carbon abatement values determined by Wang et al. (2014). That study uses corn stover as the feedstock for transportation fuel production in an integrated plant that includes both fast pyrolysis and pyrolysis oil upgrading. The plant is assumed to have a capacity of 2,000 Mg/day dry corn stover input. The study also evaluates slow pyrolysis using the pathway developed within GREET (Argonne National Laboratory, 2014) where biochar is the main product, and the co-product pyrolysis oil and fuel gas are combusted onsite to generate process heat and electricity (excess electricity is sold to the grid). Corn agriculture with stover harvest is treated the same in both the fast and slow pyrolysis scenarios in the study with only a fraction of the available corn stover (3.4 dry MG/ha/year) collected to maintain and replenish SOC and prevent erosion. The corn stover is treated as a by-product of corn agriculture—i.e., the on-farm emissions associated with corn production are allocated to the corn grain rather than the corn stover—although as is the case with CBS 3, make-up fertilizer to replenish the nutrient content from the removed corn stover is accounted for in the study. Again as in CBS 3, this study also assumes that the corn stover is harvested in a separate step from corn grain harvest.

Exhibit 73 show a simplified schematic of the LCA accounting boundaries for the pyrolysis of corn stover into liquid fuels and biochar including the downstream emissions associated with the pyrolysis-based gasoline product (i.e., displacement of fuel in the transport sector) and biochar co-product (i.e., carbon sequestration and agricultural effects from field application).

Exhibit 74 show the main data sources used to estimate the GHG benefits of the pyrolysis of corn stover into liquid fuels and biochar including the field application of the biochar co-product. See Wang et al. (2014) for detailed discussion and documentation of data sources and other modelling parameters.

Exhibit 73: LCA Accounting Boundaries for Pyrolysis of Corn Stover into Liquid Fuels and Biochar Including the Field Application of the Biochar Co-Product



[1] *Upstream emissions do __not__ include emissions from plant construction, machinery production, and on-farm production, but do include emissions from residue harvest, make-up fertilizer application, handling and storage, and transportation.*
[2] *Process/plant emissions include on-site process energy use and (biogenic) emissions from syngas combustion for process heat/electricity.*
[3] *Downstream emissions benefits include products (e.g., bio-oil, electricity) and co-products (e.g., biochar), but do __not__ include emissions from waste.*

Exhibit 74: Main Data for Estimating the Greenhouse Gas Benefits of Pyrolysis of Corn Stover into Liquid Fuels and Biochar Including the Field Application of the Biochar Co-Product[a]

Parameter	Value
Corn stover harvested	3.4 Mg/ha/year
Biochar yield (fast pyrolysis)	0.18 Mg/Mg dry corn stover
Biochar yield (slow pyrolysis)	0.30 Mg/Mg dry corn stover
Biochar carbon content (fast pyrolysis)	51 wt%
Biochar carbon content (slow pyrolysis)	67 wt%
Biochar application rate	30 Mg/ha
Time horizon for agricultural impacts	10 years
Fertilizer efficiency increase	10%
N_2O emission reductions	50%
CH_4 emission reductions	0%
SOC annual increase	0 Mg C/ha/year
Corn stover yield increase	0%

[a] Wang et al. (2014).

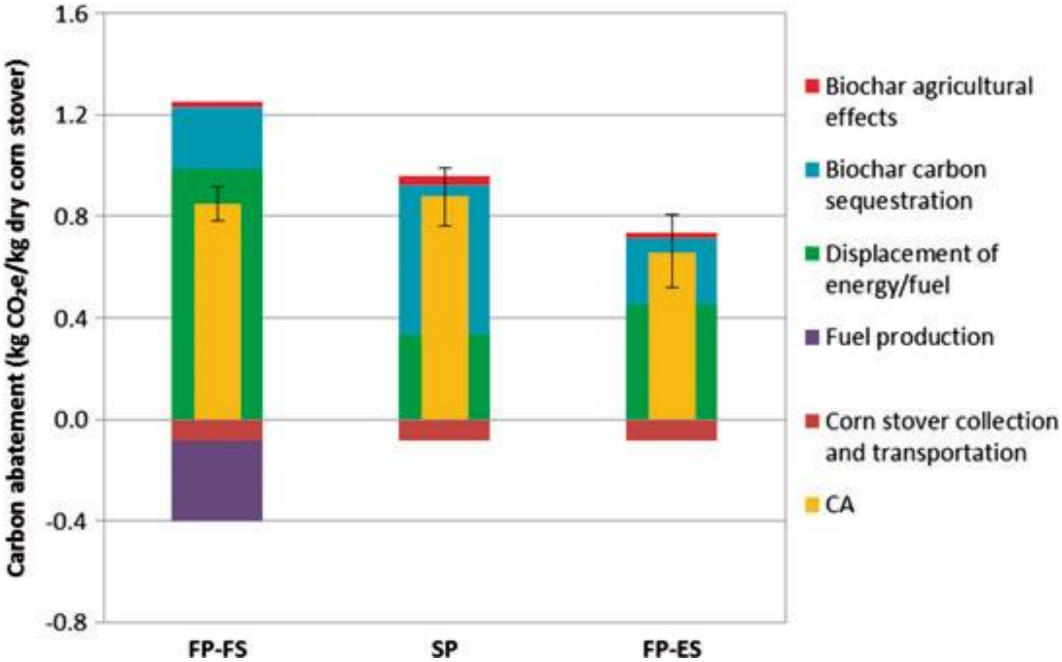
6.1.1. Emission Reductions

Emission reductions for the overall and life-cycle stages of fast and slow pyrolysis of corn stover into liquid fuels and biochar including the field application of the biochar co-product were calculated based on carbon abatement results reported by Wang et al. (2014).

Exhibit 75 shows the life-cycle carbon abatement estimates for fast and slow pyrolysis of corn stover into liquid fuels and biochar including the field application of the biochar co-product.

The carbon abatement is similar for fast pyrolysis with fuel production (0.86 kg CO_2-eq/kg dry corn stover) and slow pyrolysis (0.88 kg CO_2-eq/kg dry corn stover). Biochar's agricultural effects account for 2.7% (0.02 kg CO_2-eq/kg dry corn stover) and 4.4% (0.04 kg CO_2-eq/kg dry corn stover) of the total carbon abatement for fast pyrolysis with fuel production and slow pyrolysis, respectively. Biochar's carbon sequestration is largest (0.60 kg CO_2-eq/kg dry corn stover) for slow pyrolysis.

Exhibit 75: Life Cycle Carbon Abatement Estimates for Fast and Slow Pyrolysis of Corn Stover into Liquid Fuels and Biochar Including the Field Application of the Biochar Co-Product



Source: Wang et al. (2014).
FP-FS = Fast Pyrolysis with Fuel Production and with Biochar Soil Application.
SP = Slow Pyrolysis and with Biochar Soil Application.
FP-ES = Fast Pyrolysis without Fuel Production and with Biochar Soil Application.

The life-cycle carbon abatement estimates for fast and slow pyrolysis of corn stover into liquid fuels and biochar including the field application of the biochar co-product were used to estimate indirect and direct emission reduction factors per mass of biochar. Direct emission reductions refer to those emission reductions occurring on-site (i.e., the biochar agricultural effects plus the biochar carbon sequestration), and indirect emission reductions refer to those emission reductions occurring off-site (i.e., the displacement of energy/fuel minus fuel production minus corn stover collection and transportation). Exhibit 76 shows these direct and indirect emission reduction factors.

Exhibit 76: Greenhouse Gas Benefits from Fast and Slow Pyrolysis of Corn Stover into Liquid Fuels and Biochar Including the Field Application of the Biochar Co-Product for Direct and Indirect Emission Sources

Pyrolysis Process	Indirect Emission Reductions (MT CO_2-eq/MT biochar)	Direct (on-site) Emission Reductions (MT CO_2-eq/MT biochar)
Fast	3.27	1.48
Slow	0.83	2.11

On a per mass of biochar basis, the emission reduction factor values for fast pyrolysis are larger than those for slow pyrolysis. This is because the carbon abatement values are similar for fast pyrolysis with fuel production and slow pyrolysis, but the biochar yield for fast pyrolysis with fuel production is less than that for slow pyrolysis. For fast pyrolysis, displacement of energy fuel (i.e., indirect emission reductions) is the largest contribution to the carbon abatement value. That said, the direct (i.e., on farm) emission reduction factor value for slow pyrolysis is larger than that for fast pyrolysis which reflects the higher rates of biochar agricultural effects and biochar carbon sequestration for slow pyrolysis.

6.1.2. Adoption Potential

The adoption potential for each USDA region (in unit of metric tons (MT) biochar) and option was estimated based on the amount of corn stover available from each USDA region and the relative biochar yields at the fast and slow pyrolysis plants. For example, the amount of corn stover estimated for the South Plains in 2020 is 2,799,677 dry Mg and 50 percent is assumed to go to each pyrolysis process (i.e., fast and slow). Given a biochar yield of 0.18 Mg/Mg dry corn stover for a fast pyrolysis plant (see Exhibit 74), this available quantity of corn stover (1,399,838 dry Mg) amounts to a production potential of 251,971 Mg of biochar.

Corn stover availability was estimated based on the future projected harvested area of corn provided by Monsanto multiplied by the corn stover yield per harvested area taken from the literature—1.4 dry Mg/acre/year (3.4 dry Mg/ha/year; Wang et al., 2014).[13]

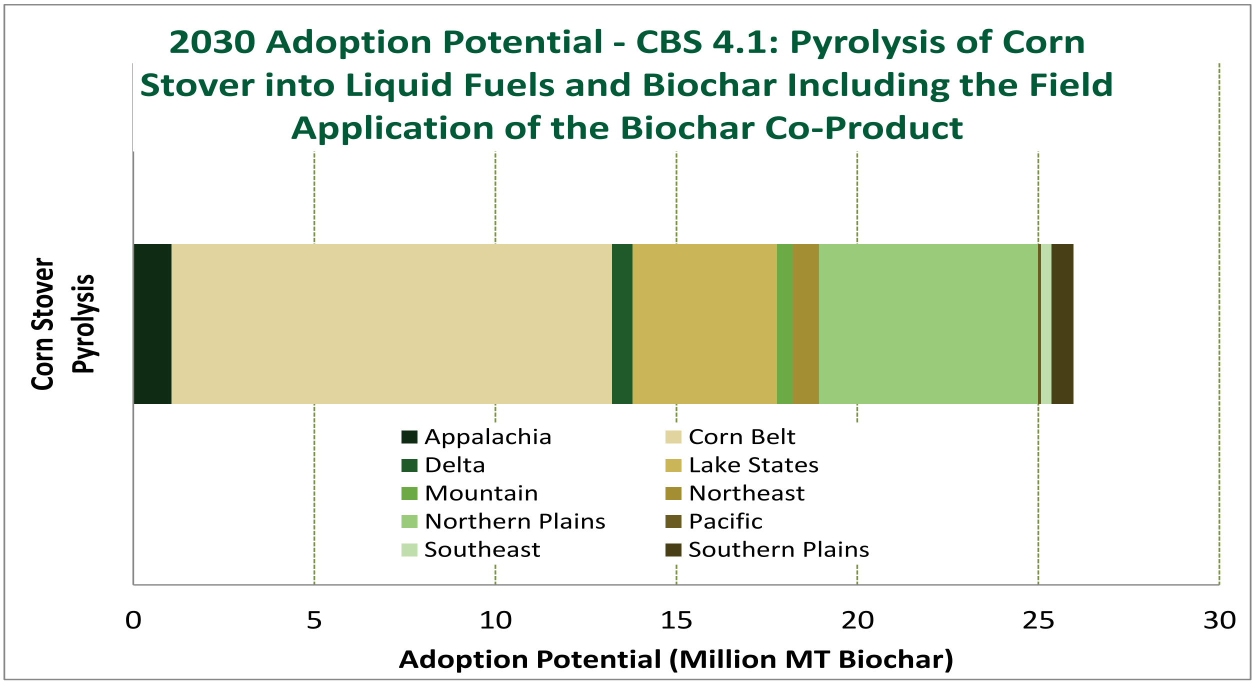
ICF International (2016) Exhibit Annex-4 shows the projected harvested corn area and corn stover yield by USDA region. Exhibit Annex-5 shows the projected corn stover by USDA region.

The estimated adoption potentials are based on the assumption that all of the available corn stover in a particular USDA region is processed into pyrolysis-based liquid fuel and biochar, and allocates 50 percent of the stover going to each of the two options: (1) Fast pyrolysis with fuel production and with biochar field application, and (2) slow pyrolysis with biochar field application.

Exhibit 77 shows the adoption potentials for fast and slow pyrolysis by USDA region (see also ICF International, 2016, Exhibit Annex-6).

[13] According to Wang et al. (2014) only a fraction of the available stover in cornfields can be harvested to maintain and replenish soil organic carbon and prevent erosion.

Exhibit 77: Adoption Potential for the Pyrolysis of Corn Stover



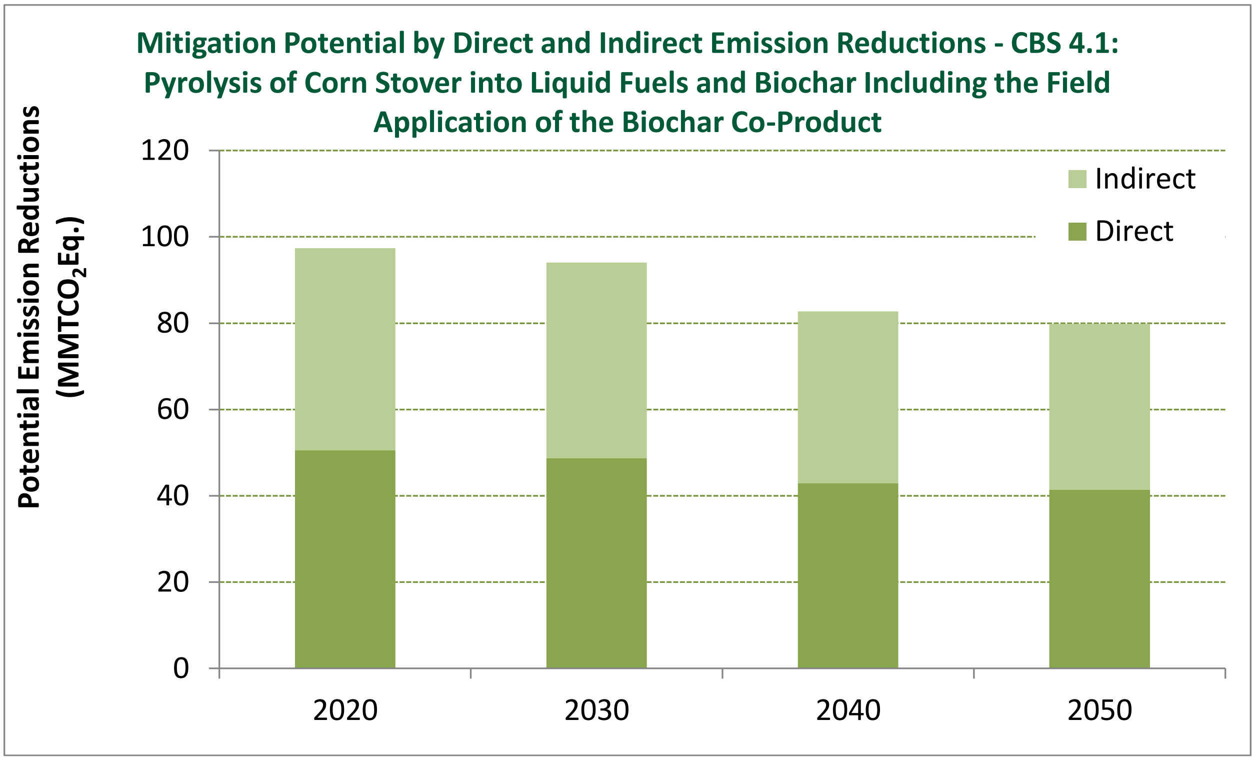
As seen in Exhibit 77 the adoption potential is significantly higher in those regions with larger areas of corn (e.g., Corn Belt, North Plains, Lake States).

6.1.3. Mitigation Potential for 2020, 2030, 2040, and 2050

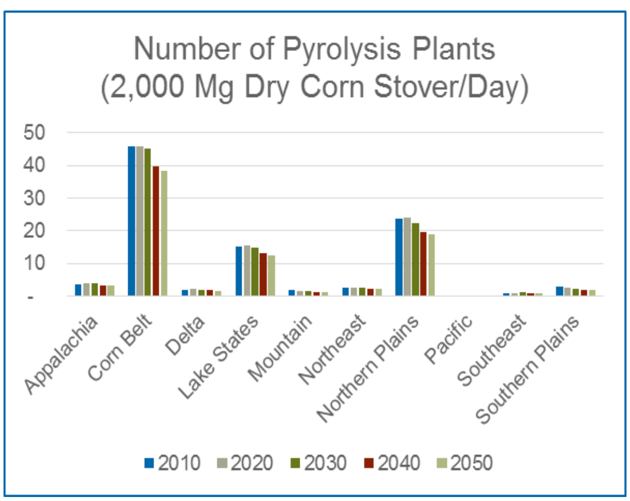
The mitigation potential is presented in Exhibit 78 by direct and indirect emission reductions. The key sources of emission reductions are the displacement of energy/fuel, biochar carbon sequestration, and biochar agricultural effects. The key findings include:

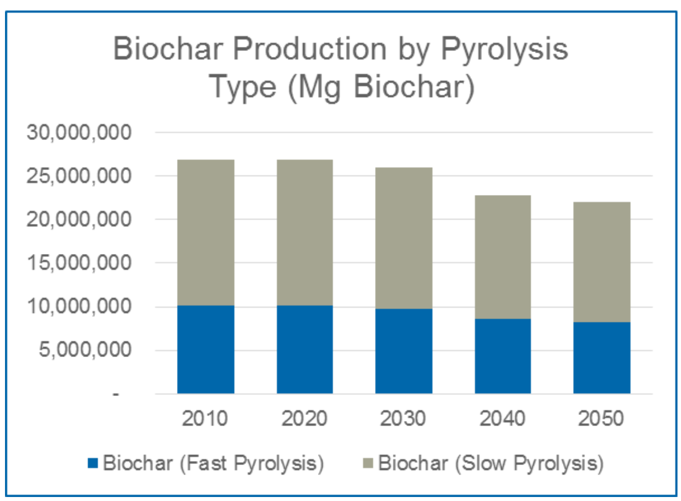
- Life-cycle carbon abatement is similar for fast pyrolysis with fuel production (0.86 kg CO_2-eq/kg dry corn stover) and slow pyrolysis (0.88 kg CO_2-eq/kg dry corn stover).
- Biochar's agricultural effects account for 2.7% (0.02 kg CO_2-eq/kg dry corn stover) and 4.4% (0.04 kg CO_2-eq/kg dry corn stover) of the total carbon abatement for fast pyrolysis with fuel production and slow pyrolysis, respectively.
- Biochar's carbon sequestration is largest (0.60 kg CO_2-eq/kg dry corn stover) for slow pyrolysis.
- Number of pyrolysis plants needed to process the available corn stover is significant— e.g., 198 fast (or 119 slow) pyrolysis plants to produce the 26.0 MMT biochar in 2030 (assuming a 131,400 MT biochar/year fast pyrolysis plant or a 219,000 MT biochar/year slow pyrolysis plant).
- Slow pyrolysis produces a larger yield of biochar—i.e., abatement potential—than fast pyrolysis.

Exhibit 78: Marginal Abatement Cost Curve for Pyrolysis of Corn Stover into Liquid Fuels and Biochar Including the Field Application of the Biochar Co-Product by USDA Region



This textbox presents the findings regarding plants and production. The first graphic shows the number of plants needed to process all of the available corn stover. The second graphic shows the amount of biochar that would be produced by these plants by allocating 50 percent of the available corn stover to fast pyrolysis plants and 50 percent to slow pyrolysis plants.





6.1.4. Sensitivity Analysis and Risk Factors

6.1.4.1. Sensitivity Analysis

Exhibit 79 indicates the upper and lower bounds and the source of the values for selected input variables. Exhibit 80 presents the national mitigation potential for each change in variable.

Exhibit 79: Lower and Upper Bound Estimates for Input Variables

Variable	Units	Value Used in Base Case	Lower Bound	Upper Bound
Corn Stover Yield	Mg/ha/yr	3.4[a]	50%[b]	150%[b]
Biochar Yield (Fast Pyrolysis)	Mg/Mg stover	0.18	0.15[c]	0.21[c]
Biochar Yield (Slow Pyrolysis)	Mg/Mg stover	0.30	0.28[c]	0.33[c]
Biochar Application Rate	Mg/ha	30	10[c]	50[c]

[a] 3.4 Mg/ha/yr ≈ 1.4 Mg/acre/yr.
[b] Based on an assumption of ±50 percent.
[c] Based on the key parameters for baseline and sensitivity analysis from Wang et al. (2014).

Exhibit 80: Resulting Mitigation Potential Based on Change in Variable (Metric Tons of CO_2-eq)

Variable	Using Lower Bound Value	Using Upper Bound Value
Baseline Value	**94,041,114**	
Corn Stover Yield	47,020,557	141,061,672
Biochar Yield (Fast Pyrolysis)	94,041,114	94,041,114
Biochar Yield (Slow Pyrolysis)	94,041,114	94,041,114
Biochar Application Rate	94,041,114	94,041,114

The mitigation potential is not sensitive to changes in the biochar yield or the biochar application rate. This finding is the result of the fact that the analysis is based on the assumption that all of the available corn stover is converted into biochar and applied to fields, so regardless of the number of plants required (influenced by biochar yield) or the field area available for application (influenced by biochar application rate) the mitigation potential is the same as the baseline (i.e., maximum achievable) value.

6.1.4.2. Technical, Economic, and Policy Risk Factors

Various technical, economic, and policy risk factors are evident for this CBS including:

Emission Reductions: The life-cycle emission reductions results for the pyrolysis of corn stover/field application of biochar are influenced by both the choice of life-cycle accounting boundaries as well as the life-cycle methodology choices (e.g., allocation of corn farming energy between corn grain and corn stover, method for dealing with co-products). Therefore, different choices would likely result in different emission reduction estimates. In addition, changing the assumptions regarding which land management practice are used for corn stover harvest (e.g., second pass for corn stover) influence the emissions associated with the corn stover collection and transportation life-cycle stage.

Abatement Potential: The adoption is based on the assumption that all of the corn stover harvested from each USDA region is available for processing at a pyrolysis plant—i.e., the study models maximum abatement potential. As a result, the study does not consider any logistical constraints—e.g., the ability of a farmer/contractor to harvest the available corn stover, the feasibility of transporting all of the available corn stover to a pyrolysis plant, and whether sufficient plants exist to process the corn stover—and does not consider alternative uses for the available corn stover (e.g., treated stover feed).

Offsetting Costs. Recurring costs to apply biochar to fields at the farm are partially offset by the revenues generated from increases in crop yields, and nutrients, lime and seed replacement savings (and the sale of the original corn stover if applicable). The extent of this offset will impact the adoption of use of biochar.

6.1.5. References

Argonne National Laboratory. *GREET*. Retrieved from https://greet.es.anl.gov/.

ICF International. 2016. *Charting a Path to Carbon Neutral Agriculture- Annex*. May 2016.

Wang, Z., J. Dunn, and M. Wang. 2014. *Updates to the Corn Ethanol Pathway and Development of an Integrated Corn and Corn Stover Ethanol Pathway in the GREET Model*. ANL/ESD-14/11. Argonne, IL: Argonne National Laboratory. https://greet.es.anl.gov/publication-update-corn-ethanol-2014.

6.2. Co-Firing Corn Stover For Electricity Generation

Key Considerations in Co-Firing Corn Stover for Electricity Generation

- GHG benefits are driven by the offset of CO_2 emitted during the combustion of corn stover through the carbon uptake during the agricultural feedstock growth.
- Additional GHG benefits are associated with the upstream emission reductions (e.g., coal bed methane) from the displaced coal.
- Economic (e.g., retrofit and feedstock costs) and technology (e.g., boiler modification, plant derating) considerations limit the maximum percentage adoption (e.g., 10–20%) for co-firing.
- Coal power plants are located across the United States including in those regions with significant availability of corn stover feedstock.

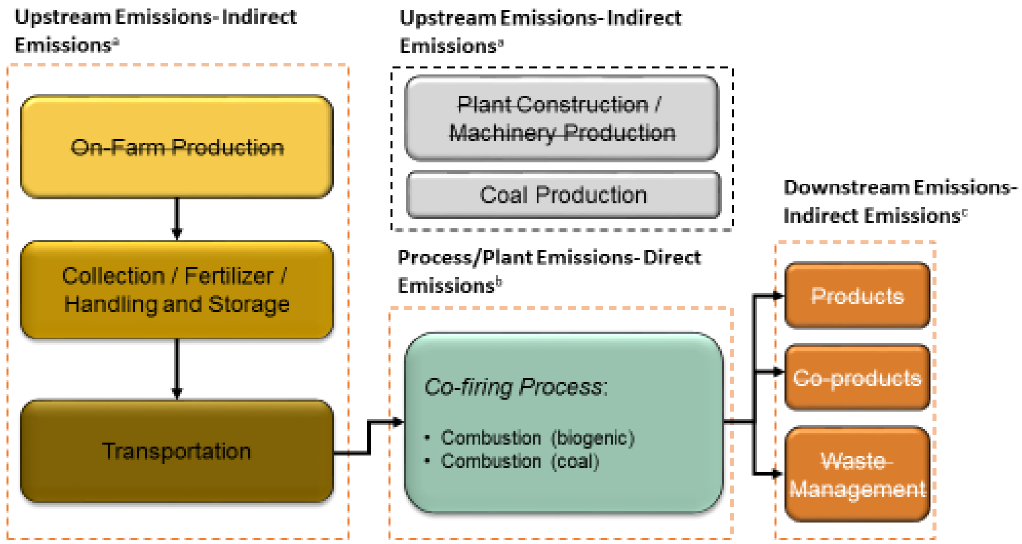
Co-firing corn stover for electricity generation provides measurable greenhouse gas (GHG) emissions benefits compared with using coal. The carbon dioxide (CO_2) emitted during the combustion of corn stover (and other biologically-derived feedstocks) in power plants is offset by carbon uptake during the corn agriculture life-cycle stage. In addition, there are GHG benefits associated with the upstream emissions reductions—e.g., a reduction in coal bed methane—from the displaced coal.

Crop-Based Strategy (CBS) 4.2 focuses on the GHG reductions associated with the use of corn stover to produce electricity. This analysis uses corn stover as the feedstock for electricity production in a retrofit power plant, and considers two co-firing percentages: (1) 10 percent, and (2) 20 percent replacement of the power plant output.[14] The existing base of coal plants in the United States is considered for the emission reduction estimates, and the estimated capital and recurring costs are modeled based on retrofitting a 550 MW capacity coal only power plant to co-fire 10 percent and 20 percent corn stover share by energy. The adoption potentials are estimated with only a fraction of the grown corn stover (3.4 dry MG/ha/year) collected to maintain and replenish SOC and prevent erosion. The corn stover is treated as a by-product of corn agriculture—i.e., the on-farm emissions associated with corn production are allocated to the corn grain rather than the corn stover—although as is the case with CBS 3, make-up fertilizer to replenish the nutrient content from the removed corn stover is accounted for in the study. Again as in CBS 3, our study is based on the assumption that the corn stover is harvested in a separate step from corn grain harvest.

Exhibit 81 show a simplified schematic of the LCA accounting boundaries for co-firing corn stover for electricity generation including the on-site emission reductions (i.e., displacement of coal in the energy sector) and indirect emissions reductions (i.e., coal mining and other coal life-cycle stage emissions) associated with displacing coal.

[14] The percent corn stover share by energy is actually constrained at a maximum of 50MW for large power plants as per other power sector analysis conducted by U.S. EPA, U.S. DOE, and others. This constraint is largely adopted to meet the technology implications imposed when co-firing biomass at coal power plants.

Exhibit 81: LCA Accounting Boundaries for Co-firing Corn Stover for Electricity Generation



[1] Upstream emissions do not include emission from plant construction, machinery production, and on-farm production, but do include emissions from residue harvest, make-up fertilizer application, handling and storage, transportation, and reduced coal production emissions from displaced coal.
[2] Process/plant emissions include (biogenic) emissions released from residue combustion for electricity generation and reduced coal combustion emissions from displaced coal.
[3] Downstream emissions do not include emissions from products (e.g., electricity), co-products (e.g., ash), and waste management.

Exhibit 82 show the main data sources used to estimate the GHG benefits of co-firing corn stover for electricity generation.

Exhibit 82: Main Data Sources for Estimating the Greenhouse Gas Benefits of Co-firing Corn Stover for Electricity Generation

Parameter	Value	Source
Corn stover harvested	3.4 Mg/ha/year	Wang et al. (2014)
Coal plant data	Various	EIA (2014)
Coal type data	Various	EIA (2014)
Coal upstream production emission factors by gas	Various (kg/kg coal at mine; kg/MJ)	NREL, (2008); Argonne National Laboratory (2014)
Coal combustion emission factors	Various (lbs/mmBtus)	EIA, 2014

6.2.1. Emission Reductions

ICF estimated emission reductions for the direct (i.e., on-site combustion) and indirect (i.e., upstream and downstream) life-cycle stages of co-firing of corn stover for electricity generation using coal combustion emission factors by coal mine state and coal type for CO_2 (see Exhibit 83), a coal combustion emission factor for CH_4 (1.0 g/GJ coal),[15] and a coal combustion emission factor for N_2O (1.5 g/GJ coal),[16] and using coal upstream production emission factors by coal type (see Exhibit 84).

Exhibit 83 presents the coal combustion emission factors by coal mine state and coal type.

Exhibit 83: Coal Combustion Emission Factors by Coal Mine State and Coal Type

State	Coal Type	CO_2 (lbs/MMBtu)
AK	AVG	216.6
AL	AVG	204.7
AR	AVG	202.8
AZ	BIT	207.1
AZ	SUB	209.2
AZ	AVG	208.2
CO	BIT	209.6
CO	SUB	212.8
CO	AVG	211.2
IA	AVG	202.8
IL	AVG	203.1
IN	AVG	203.1
KS	AVG	202.8
KY	AVG	203.0
KY (east)		206.4
KY (west)		203.1
LA	AVG	212.6
MD	AVG	204.7
MO	AVG	202.8
MS	AVG	203.1
MT	BIT	215.5
MT	SUB	215.5
NM	BIT	207.1
NM	SUB	209.2
NM	AVG	208.2
OH	AVG	204.7
OK	AVG	202.8
PA	AVG	204.7
TN	AVG	203.8
TN (north)		206.4
TN (south)		204.7
TX	BIT	202.8
TX	LIG	212.6
TX	AVG	207.7
UT	BIT	209.6
UT	SUB	212.8
UT	AVG	211.2
VA	AVG	206.4
WA	AVG	216.6
WV	AVG	211.5
WV (north)		204.7
WV (south)		206.4
WY	AVG	207.5
WY (N. Powder)		214.3

[15] Methane emissions from stationary combustion are primarily a function of the CH_4 content of the fuel and combustion efficiency.
[16] N_2O emissions from stationary combustion are closely related to air-fuel mixes and combustion temperatures, as well as the characteristics of any pollution control equipment that is employed.

State	Coal Type	CO_2 (lbs/MMBtu)
MT	LIG	219.3
MT	AVG	216.8
ND	AVG	219.3
WY (Other)		214.3
WY (S. Powder)	AVG	214.3

Source: http://www.eia.gov/forecasts/aeo/assumptions/pdf/coal.pdf

Exhibit 84 shows the coal upstream production emission factors by coal type.[17]

Exhibit 84: Coal Upstream Production Emission Factors By Coal Type

Coal Type	CO_2 (kg/ton)	CH_4 (kg/ton)	N_2O (kg/ton)
LIG	86.576	0.984	-
BIT	56.597	3.127	-
SUB	56.597	3.127	-
WC	86.576	0.984	-

Source: NREL (2008).

We used combustion and upstream production emission factors to estimate indirect and direct emission reduction factors per unit of electricity. Direct emission reductions refer to those emission reductions occurring on-site (i.e., combustion), and indirect emission reductions refer to those emission reductions occurring off-site (i.e., coal mining and other coal life-cycle stage emissions) from displaced coal. Exhibit 85 presents the direct and indirect emission reduction factors by USDA region and percent corn stover share by energy (i.e., co-firing rate).

Exhibit 85: Greenhouse Gas Benefits from Co-firing of Corn Stover for Electricity Generation for Direct (on-site) and Indirect Emission Sources by USDA Region and Co-firing Rate

Co-firing Rate	USDA Region	Indirect Emission Reductions (MT CO_2 /MWe)	Indirect Emission Reductions (MT CH_4 /MWe)	Direct Emission Reductions (MT CO_2/ MWe)	Direct Emission Reductions (MT CH_4 /MWe)	Direct Emission Reductions (MT N_2O/ MWe)
10%	Appalachia	114.5	6.2	4,398.6	0.0	0.1
10%	Corn Belt	148.7	8.2	4,887.3	0.1	0.1
10%	Delta	220.2	8.7	5,360.0	0.1	0.1
10%	Lake States	147.5	8.2	4,541.7	0.1	0.1

[17] Cradle to coal mine, including mining, transport, and cleaning, does not include coal combustion.

Co-firing Rate	USDA Region	Indirect Emission Reductions (MT CO_2 /MWe)	Indirect Emission Reductions (MT CH_4 /MWe)	Direct Emission Reductions (MT CO_2/ MWe)	Direct Emission Reductions (MT CH_4 /MWe)	Direct Emission Reductions (MT N_2O/ MWe)
10%	Mountain	200.5	10.9	6,251.5	0.1	0.1
10%	Northeast	107.6	4.4	3,336.0	0.0	0.1
10%	Northern Plains	288.5	9.5	6,264.3	0.1	0.1
10%	Pacific	177.6	9.8	5,498.5	0.1	0.1
10%	Southeast	83.0	4.6	3,185.5	0.0	0.1
10%	Southern Plains	321.4	10.4	6,843.4	0.1	0.1
20%	Appalachia	137.0	6.2	4,484.5	0.0	0.1
20%	Corn Belt	148.5	8.2	4,853.6	0.1	0.1
20%	Delta	222.4	8.6	5,320.6	0.1	0.1
20%	Lake States	144.3	8.0	4,464.1	0.0	0.1
20%	Mountain	252.5	11.1	6,322.0	0.1	0.1
20%	Northeast	152.4	4.5	3,432.9	0.0	0.1
20%	Northern Plains	275.2	9.6	6,198.4	0.1	0.1
20%	Pacific	221.0	10.5	6,179.7	0.1	0.1
20%	Southeast	90.3	4.5	3,118.3	0.0	0.1
20%	Southern Plains	345.9	10.4	6,873.6	0.1	0.1

On a per unit of electricity basis, the emission reduction factor values for combustion dominate the other life-cycle emissions. However, the emission reduction factor values vary by co-firing rate and USDA region. This variability is a result of different types of coal (e.g., lignite, bituminous) being used by different power plants with different electricity capacities across the various states comprising the USDA regions.

6.2.2. Adoption Potential

The adoption potential for each USDA region (in units of Mega Watts (MW) electricity) and option is based on the amount of corn stover available from each USDA region and the share of power plant electricity capacity available for co-firing in each USDA region. For example, the amount of corn stover estimated for the South Plains in 2020 is 2,799,677 dry Mg. Given that the corn stover required to achieve 10 percent co-firing at all of the existing coal plants in the Southern Plains is 5,067,440 dry Mg (for 1,099 MWe), the available amount of corn stover can achieve 55 percent or 607 MWe. Finally, given that 50 percent of the available corn stover is allocated to each of the options, the adoption potential for 10 percent co-firing in the Southern Plains is 304 MWe.

Corn stover availability was estimated based on the future projected harvested area of corn provided by Monsanto multiplied by the corn stover yield per harvested area taken from the literature—1.4 dry Mg/acre/year (3.4 dry Mg/ha/year; Wang et al., 2014).[18]

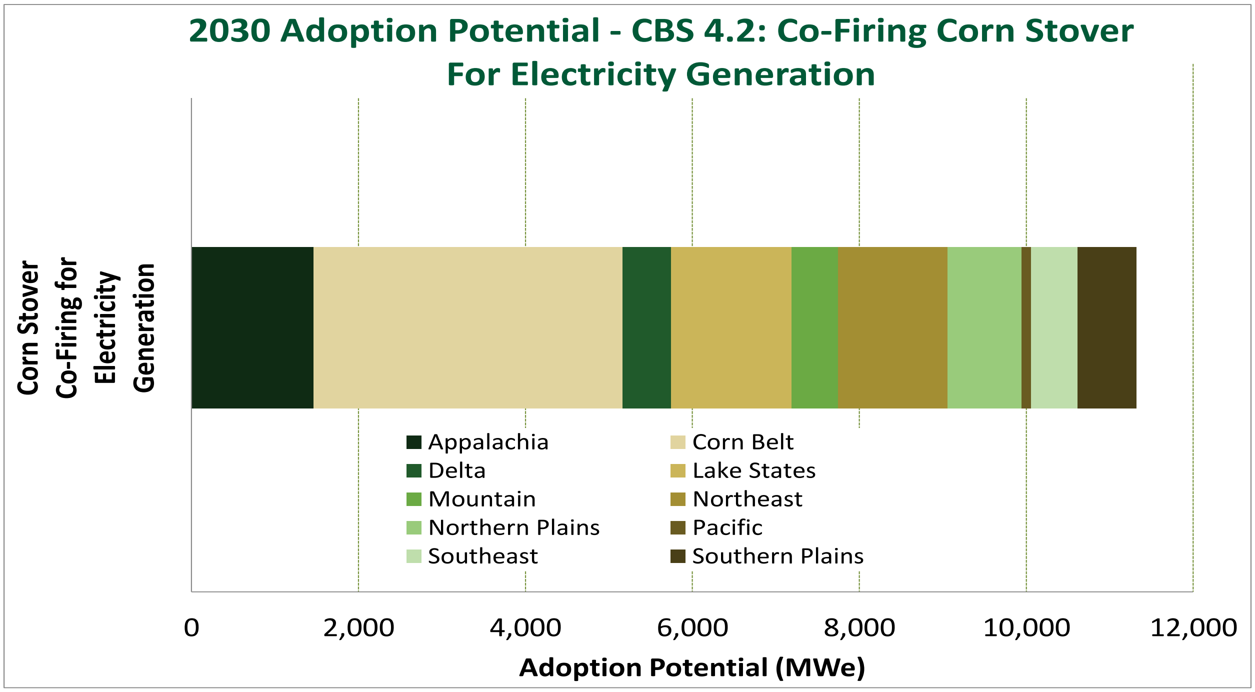
ICF International (2016) Exhibit Annex-7 presents the projected harvested corn area and corn stover yield by USDA region. ICF International (2016) Exhibit Annex-8 presents the projected corn stover by USDA region.

When calculating the estimated adoption potentials, we assumed that the available corn stover in a particular USDA region is co-fired for electricity generation either up to the maximum amount of available corn stover or the maximum available co-firing capacity for the existing power plants (whichever is limiting). We allocated 50% of the stover to each of two options: (1) retrofitting a coal only power plant to co-fire 10 percent corn stover share by energy, and (2) retrofitting coal only power plant to co-fire 20 percent corn stover share by energy. For example, for the Corn Belt region, 11,307,405 dry Mg corn stover is required to achieve a 10 percent co-firing rate across all of the existing power plants, and in 2020, 51,640,727 dry Mg corn stover is projected to be available (i.e., corn stover availability is greater than the potential demand). However, for the Southeast region, 3,235,020 dry Mg corn stover is required to achieve a 10 percent co-firing rate across all of the existing power plants, and in 2020, only 1,245,024 dry Mg corn stover is projected to be available (i.e., corn stover availability is less than potential demand).

Exhibit 86 presents the adoption potentials for 10 percent and 20 percent co-firing by USDA region (see also ICF International, 2016, Exhibit Annex-9). As seen in Exhibit 86, the adoption potential is significantly higher in those regions with larger areas of corn and higher capacity of existing power plants (e.g., Corn Belt).

[18] According to Wang et al. (2014) only a fraction of the available stover in cornfields can be harvested to maintain and replenish soil organic carbon and prevent erosion.

Exhibit 86: Adoption Potential for Co-firing of Corn Stover for Electricity Generation



6.2.3. Mitigation Potential for 2020, 2030, 2040, and 2050

Based on the emission reductions associated with co-firing corn stover for electricity generation, national mitigation potential was estimated for the two options: (1) retrofitting a coal only power plant to co-fire 10 percent corn stover share by energy, and (2) retrofitting coal only power plant to co-fire 20 percent corn stover share by energy. Exhibit 87 shows the national mitigation potential for co-firing corn stover for electricity generation direct and indirect emission reductions. Emission reductions are primarily direct, on-site emission reductions associated with off-setting coal (i.e., fossil fuel) combustion with corn stover (i.e., biogenic) combustion. The key findings include:

- For co-firing corn stover for electricity generation all of the net emission reductions result from coal displacement in the energy sector and include fugitive emission reductions and stationary combustion reductions.
- The life-cycle emissions from corn stover collection, fertilizer, handling and storage, and transportation are de minimis compared to the emission reductions from coal displacement.
- The adoption potential for each USDA region (in units of MW electricity) and option is based on the amount of corn stover available from each USDA region and the share of power plant electricity capacity available for co-firing in each USDA region.
- There is not sufficient power plant electricity capacity in some USDA regions to co-fire all of the available corn stover (see Exhibit 88).

Exhibit 87: Mitigation Potential for Co-firing Corn Stover for Electricity Generation

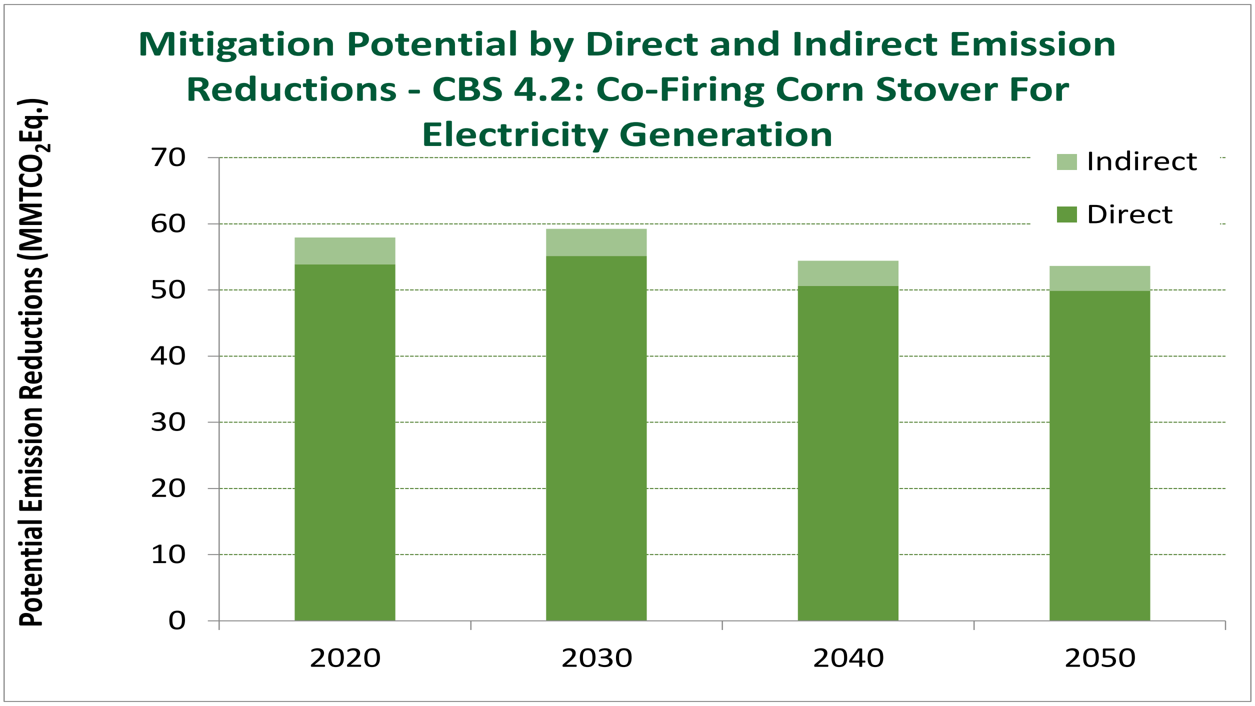
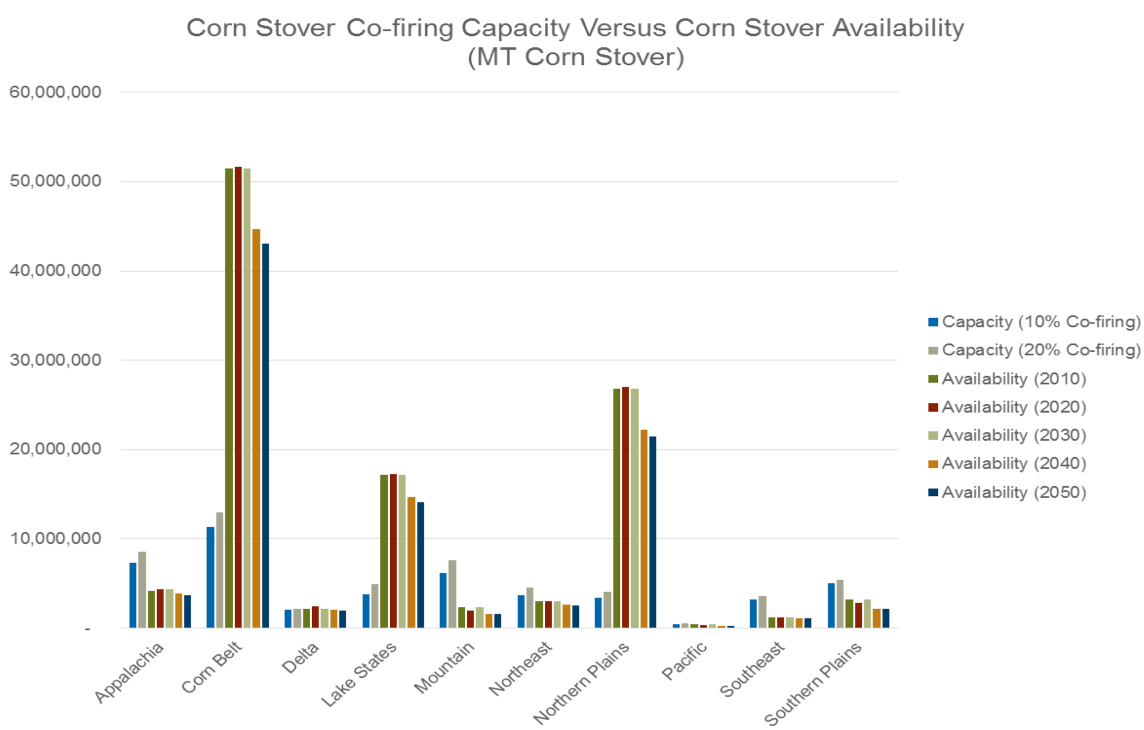


Exhibit 88: Corn Stover Co-firing Capacity versus Corn Stover Availability by USDA Region



6.2.4. Sensitivity Analysis and Risk Factors

6.2.4.1. Sensitivity Analysis

Exhibit 89 indicates the upper and lower bounds and the source of the values for selected input variables. Exhibit 90 presents the national mitigation potential for each change in variable.

Exhibit 89: Uncertainty Estimates for Input Variables

Variable		Units	Value Used in Base Case	Lower Bound	Upper Bound
Indirect Emission Reductions	CO_2-eq	kg/kg coal	Various[a]	60%[b]	167%[b]
Direct Emission Reductions	CO_2	lbs/mmBtu	Various[c]	99%[d]	101%[d]
Direct Emission Reductions	CH_4	g/GJ coal	1.0	50%	150%
Direct Emission Reductions	N_2O	g/GJ coal	1.5	10%	1,000%

[a] Varies by coal type.
[b] Based on ICF analysis using GHG Protocol Pedigree Matrix method.
[c] Varies by mining state and coal type.
[d] Based on uncertainty bounds from IPCC (2006).

Exhibit 90: Resulting 2030 Mitigation Potential Based on Change in Variable (Metric Tons of CO_2-eq)

Variable		Using Lower Bound Value	Using Upper Bound Value
Baseline Value		**59,253,559**	
Indirect Emission Reductions	CO_2-eq	57,589,069	62,037,507
Direct Emission Reductions	CO_2	58,705,275	59,801,842
Direct Emission Reductions	CH_4	59,245,989	59,261,128
Direct Emission Reductions	N_2O	59,009,928	86,052,876

6.2.4.2. Technical, Economic, and Policy Risk Factors

Various technical, economic, and policy risk factors are evident for this CBS including:

Emission Reductions: The life-cycle emission reductions results for the co-firing of corn stover are influenced by both the choice of life-cycle accounting boundaries as well as the life-cycle methodology choices (e.g., allocation of corn farming energy between corn grain and corn stover). Therefore, different choices would likely result in different emission reduction estimates.

Abatement Potential: The adoption is based on the assumption that the maximum amount of available corn stover is used or the maximum available co-firing capacity for the existing power plants is met for each USDA region—i.e., the study models maximum abatement potential. As a result, the study does not consider any logistical constraints—e.g., the ability of a farmer/contractor to harvest the available corn stover, the feasibility of transporting all of the available corn stover to a retrofitted power plant, and whether sufficient plants exist to process the corn stover—and does not consider alternative uses for the available corn stover (e.g., treated stover feed).

6.2.5. References

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7. Summary of National Mitigation Potential

This section summarizes key findings. We present the mitigation potential by USDA region for each crop based strategy and then we summarize the national results by CBS and crop type. Although our report does not address costs of adoption, it is important to recognize that the costs for mitigation and co-benefits of the crop-based strategies differ by practice, region, climate, and other site-specific conditions. The costs for mitigation are typically expressed in dollars per ton of CO_2-eq mitigated and will differ by farm. An ICF published report for U.S. Department of Agriculture indicates a wide range of break-even prices for crop management options (expressed in dollars per ton of CO_2-eq mitigated)[19]. For example, use of inhibitors (without an increase in crop yield) ranges from $63/ton CO_2-eq to well over $100/ton CO_2-eq and use of variable rate technology ranges from a negative break-even prices (i.e., option is cost-effective) to over $100/ton CO_2-eq mitigated. Similarly, the break-even price for transitioning to reduced tillage or no tillage practices ranges from $16/ton CO_2-eq mitigation to over $100/ton CO_2-eq. A recent paper also summarizes the difference in costs and co-benefits of several mitigation strategies (Paustian et al., 2016). Consequently, the rate of adoption of the crop based strategies depends on the costs and will vary by region and practice.

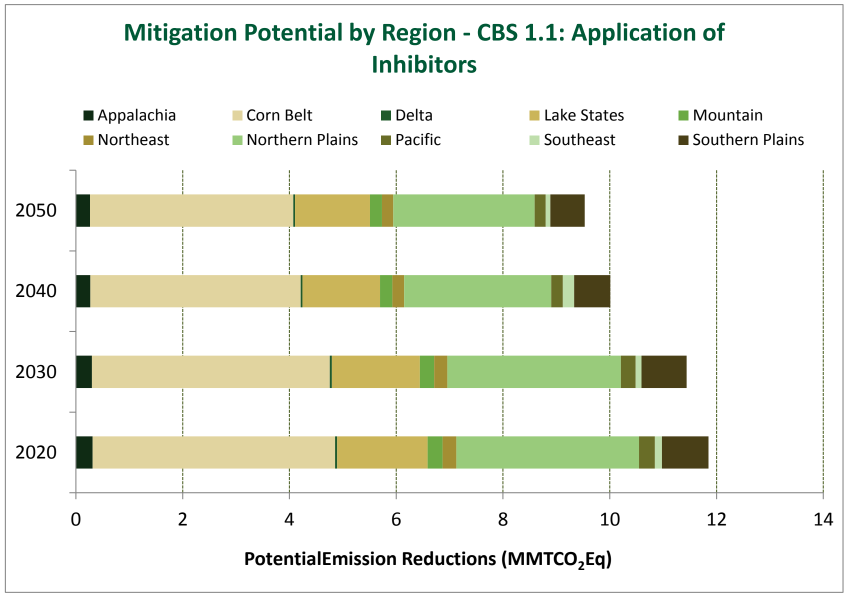
7.1. Summary of Mitigation Potential by USDA Region

Exhibit 91 and Exhibit 92 present the mitigation potential by USDA region for CBSs 1 and 2, respectively. Exhibit 93 and Exhibit 94 present the mitigation potential by USDA region for CBSs 3 and 4, respectively. As previously mentioned in the chapters for each CBS, we assumed adoption for all farms that are not currently undertaking the CBS (i.e., mitigation potential represents untapped mitigation potential).

[19] As defined in ICF International (February 2013), a break-even price is the payment level (or carbon price) at which a farm will view the economic benefits and the economic costs associated with adoption as exactly equal. Conceptually, a positive break-even price represents the minimum incentive level needed to make adoption economically rational. A negative break-even price suggests the following: (1) no additional incentive should be required to make adoption cost-effective; or (2) there are non-pecuniary factors (such as risk or required learning curve) that discourage adoption (ICF International, February 2013, page 1.3).

Exhibit 91: Summary of Mitigation Potential for N and C Management by USDA Region for CBS 1

- As yield increases, acreage declines, consequently, the emission reduction potential declines over time.
- The highest mitigation potential is in the Corn Belt and Northern Plains due to the relatively high number of acres in those regions.
- Acres of corn have the highest mitigation and adoption potential due to the high number of acres relative to other crops.
- Mitigation potential from inhibitors is almost evenly split between direct (on-farm) and indirect (off-farm) emissions.



- As yield increases, acreage declines, consequently, the emission reduction potential declines over time;
- The highest mitigation potentials are in the Corn Belt and Northern Plains due to the relatively high number of cropland in these regions
- The majority of the mitigation potential from variable rate technology and swath control is due to the potential decreases in indirect (off-farm) emissions.

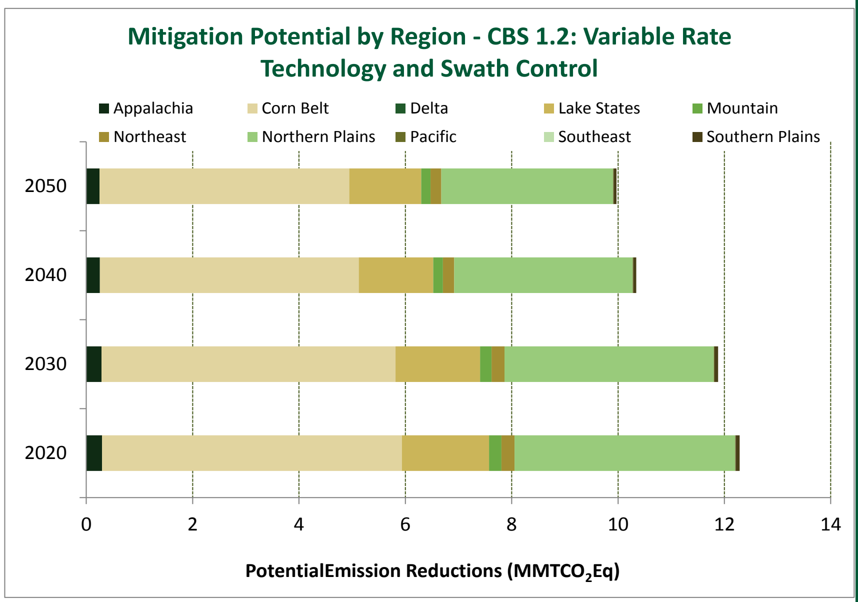
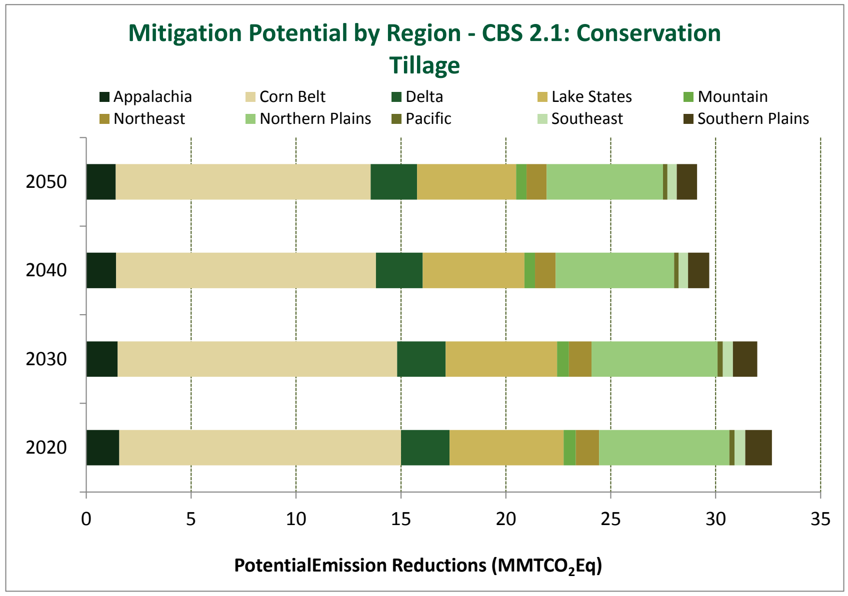


Exhibit 92: Summary of Mitigation Potential for N and C Management by USDA Region for CBS 2

- As yield increases, acreage declines; consequently, the emission reduction potential declines over time as acreage demands decline.
- Most mitigation potential for changes in tillage practices is for corn and soybean acreage.
- Regionally, the highest mitigation potential is for the Corn Belt and Northern Plains, primarily due to the adoption potential of corn and soybeans acres.
- Additionally, although barley acreage isn't as large as that of corn or soybeans in those regions, its large per-acre changes in fertilizer-related GHGs when switching from CT to NT are much higher than that of the other crops.



- As yield increases, acreage declines, consequently, the emission reduction potential declines over time;
- Currently there is low use (~ 2-3%) of cover crops in rotations with corn, wheat and soybean. Therefore, very high adoption potential exists as we assumed that 100% of these cash crops can be grown in rotation with cover crops.
- Cover crops have relatively high levels of carbon sequestration.
- The highest mitigation potentials are in the Corn Belt and Northern Plains due to the relatively high number of crop acreage in these regions.

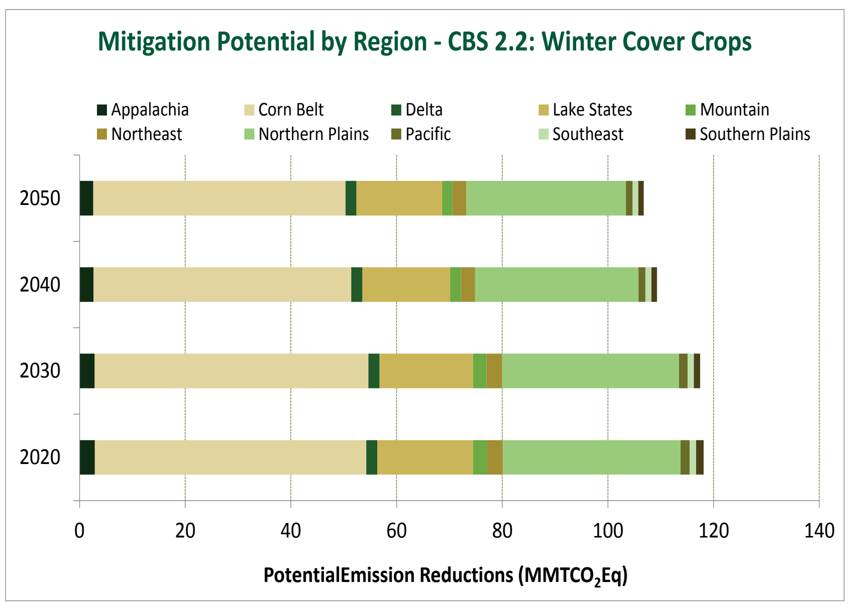
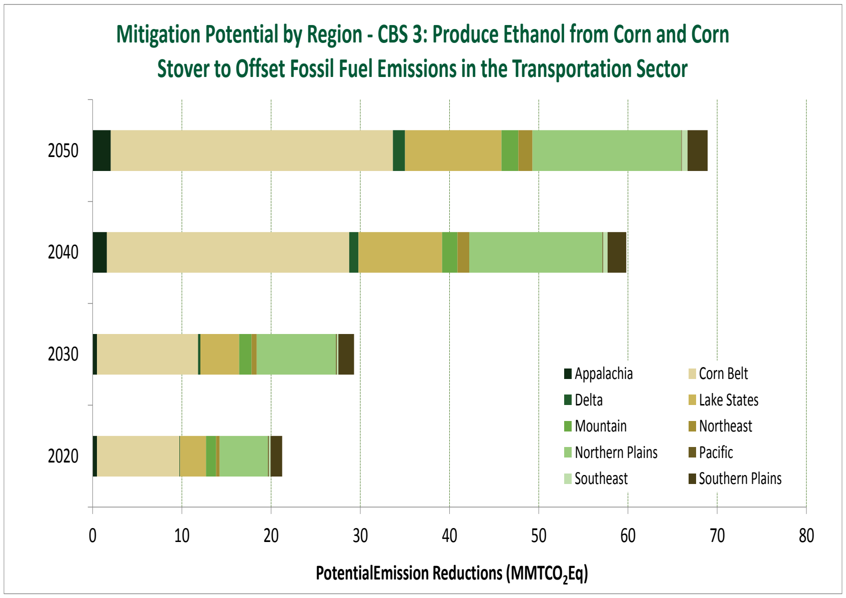


Exhibit 93: Summary of Mitigation Potential for CBS 3

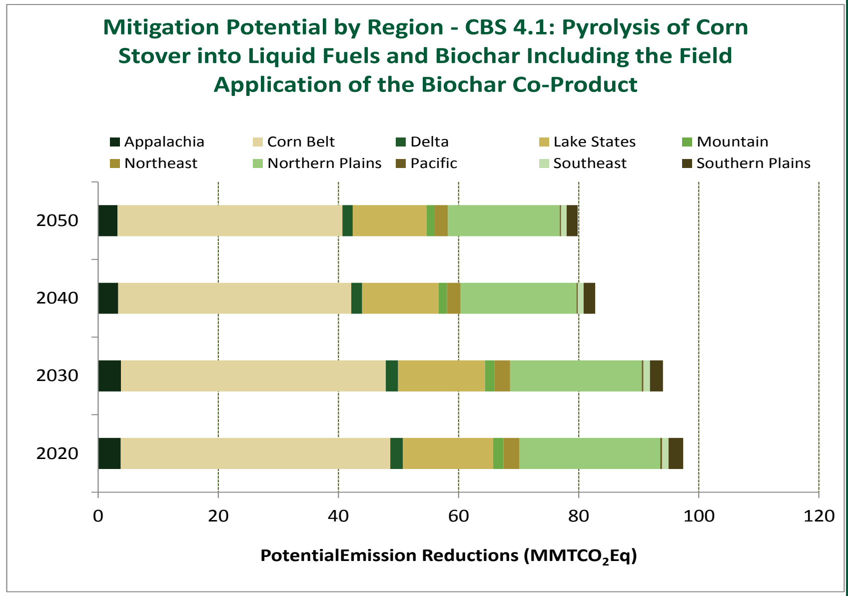
- Mitigation potential is higher in those regions with larger areas of corn.
- Excess corn is projected to provide an increasing share of the integrated ethanol—i.e., mitigation potential—in future decades.[20]
- Achieving this mitigation potential requires new integrated ethanol plants.
- No established corn grain is diverted from the market—i.e., the mitigation potential is based on new (i.e., excess) corn and left-over corn stover.[21]



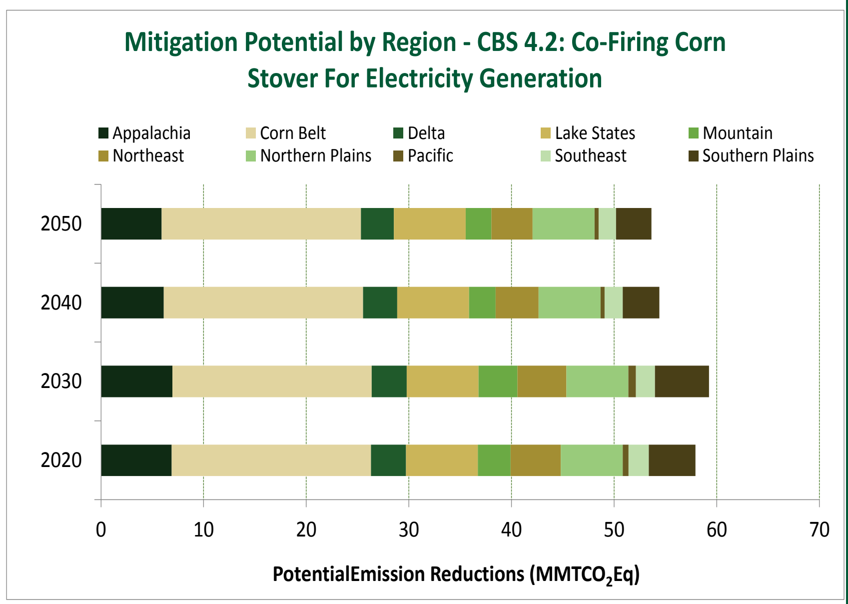
[20] Excess corn grain availability was estimated based on the difference between the maximum harvested area of corn and the future projected harvested area of corn in subsequent decades provided by Monsanto. The harvested area of corn is projected to be less in subsequent decades as future demand for corn is met through increases in corn yield rather than through increased corn area expansion. The excess corn grain was estimated from the difference in area multiplied by the corn yield per harvested area provided by Monsanto. As a result, the estimated excess corn grain represents the corn grain that could potentially be produced if the maximum harvested area of corn was maintained for corn production in future decades and not allowed to revert to other land uses.
[21] Corn stover availability was estimated based on the future projected harvested area of corn provided by Monsanto multiplied by the sustainable corn stover yield per harvested area taken from the literature.

Exhibit 94: Summary of Mitigation Potential for CBS 4

- Mitigation potential is higher in those regions with larger areas of corn.
- Number of pyrolysis plants needed to process the available corn stover is large.
- Slow pyrolysis produces a larger yield of biochar—i.e., abatement potential—than fast pyrolysis.



- Mitigation potential is higher in those regions with larger areas of corn and higher capacity of existing power plants.
- Adoption potential for each USDA region (in units of MW electricity) and option is based on the amount of corn stover available from each USDA region and the share of power plant electricity capacity available for co-firing in each USDA region.
- There is not sufficient power plant electricity capacity in some USDA regions to co-fire all of the available corn stover.



7.2. Summary of Reduction Potential by CBS and Direct and Indirect Emission Reductions

Exhibit 95 presents the mitigation potential by CBS, year of adoption of the CBS, and by direct and indirect emission reductions. Exhibit 96 presents the total mitigation potential by CBS. And Exhibit 97 presents the mitigation potential by crop type. Findings for each CBS are summarized below.

- **CBS 1.1 Application of Inhibitors**: As indicated, direct and indirect emissions are comparable. Indirect emission reductions are relatively high due to emission reductions from reduced fertilizer production, application, and runoff. The emission reductions decline over time due to decreases in acreage due to increases in crop yields.
- **CBS 1.2 VRT and Swath Control**: Indirect emissions savings are considerably more than direct emission savings. The savings from reduced use of herbicides, pesticides, and seeds resulted in greater emission reductions from production and application of these inputs compared to direct emission reductions (i.e., on-site emission reductions).
- **CBS 2.1 Conservation Tillage**: A significant majority of the emission reduction potential for conservation tillage practices comes from changes in net direct emissions. The primary source of direct emissions savings is the increase in soil organic carbon sequestration associated with reducing tillage. The second-most significant source of direct emission reductions is the decline in diesel fuel from reducing on-site machinery use. Overall, the most significant indirect emissions savings are associated with the reduced upstream emissions from fertilizer production.
- **CBS 2.2 Winter Cover Crops:** Cover crops have the highest national mitigation potential. Most of the emission reductions are on-site from carbon sequestration. As indicated in Exhibit 96, the adoption of use of cover crop for all cropland currently not using cover crops, has the highest national mitigation potential across the CBSs.
- **CBS 3 Produce Ethanol from Corn and Corn Stover to Offset Fossil Fuel Emissions in the Transportation Sector:** Indirect emission savings are considerably more than direct emissions impacts. All of the net emission reductions occur when the integrated ethanol displaces gasoline in the transportation sector, and these downstream emission reductions more than offset the net direct emissions associated with integrated corn ethanol production.
- **CBS 4.1 Pyrolysis of Corn Stover into Liquid Fuels and Biochar Including the Field Application of the Biochar Co-Product:** Direct and indirect emission reductions are comparable. Indirect emission reductions result from the fuel production associated with fast pyrolysis displacing fossil fuel in the transportation sector. Direct emission reductions from the carbon sequestration and the beneficial agricultural effects associated with the field application of biochar more than offset the indirect emission impacts associated with biochar production (i.e., pyrolysis).

- **CBS 4.2 Co-Firing Corn Stover for Electricity Generation:** Direct emissions savings are considerably more than indirect emission savings. The direct emission reductions result from coal displacement in the energy sector, and the indirect emissions result from the fugitive emission reductions associated with the displaced coal. The indirect emissions impacts from corn stover collection, fertilizer, handling and storage, and transportation are de minimis compared to the direct emission reductions from coal displacement.

As indicated in Exhibit 96, the use of cover crops has the highest mitigation potential, followed by pyrolysis of corn stover into liquid fuels and biochar including the field application of the biochar co-product and co-firing corn stover for electricity generation. The mitigation potential for each CBS strategy is not additive as the adoption potential is based an independent assessment of the acreage of cropland (i.e., we did not evaluate a landowner implementing both CBSs 1 and 2 simultaneously, nor the allocation of agriculture residues amongst CBSs 3, 4.1, and 4.2 (each was evaluated independently).

As indicated in Exhibit 95, most of the mitigation potential is from corn and soybean crops. Soybean crop have relatively less opportunity for reductions from nutrient management as relatively less fertilizer is applied to soybean crops compared to other crop types. Wheat crops have relatively less opportunity for carbon sequestration from cover crops due to the relatively lower sequestration values for wheat than corn and soybean for most USDA regions.[22] The mitigation potential associated with sorghum, barley, and rapeseed is relatively low due the comparatively low number of acres compared to corn, soybeans, and wheat.

Exhibit 95: Mitigation Potential by Year of Adoption (Million Metric Tons of CO_2-eq)

CBS	2020	2030	2040	2050
Application of Inhibitors				
Direct	5.51	5.33	4.63	4.45
Indirect	6.34	6.10	5.38	5.08
Total	11.85	11.44	10.01	9.53
VRT and Swath Control				
Direct	2.19	2.13	1.85	1.79
Indirect	10.09	9.76	8.49	8.19
Total	12.29	11.88	10.34	9.97
Conservation Tillage				
Direct	31.33	30.65	28.47	27.92
Indirect	1.36	1.33	1.22	1.20
Total	32.68	31.98	29.69	29.11

[22] As mentioned in Chapter 4: CBS 2 Sustainable Tillage and Cover Crops, limited data exists on the carbon sequestration potential for cover crops, consequently, additional research is needed to validate the relative comparison of mitigation potential by crop type due to use of cover crops.

CBS	2020	2030	2040	2050
Winter Cover Crops				
Direct	121.48	120.76	112.29	109.70
Indirect	-3.36	-3.31	-3.01	-2.93
Total	118.12	117.45	109.27	106.77
Produce Ethanol from Corn and Corn Stover				
Direct	-5.38	-7.42	-15.16	-17.47
Indirect	26.62	36.71	74.96	86.39
Total	21.24	29.29	59.80	68.92
Pyrolysis of Corn Stover into Liquid Fuels and Biochar				
Direct	50.51	48.76	42.91	41.40
Indirect	46.90	45.28	39.84	38.44
Total	97.41	94.04	82.75	79.84
Co-firing Corn Stover for Electricity Generation				
Direct	53.89	55.11	50.62	49.90
Indirect	4.04	4.14	3.79	3.74
Total	57.93	59.25	54.41	53.64

Exhibit 96: Summary of Emission Reduction Potential by CBS

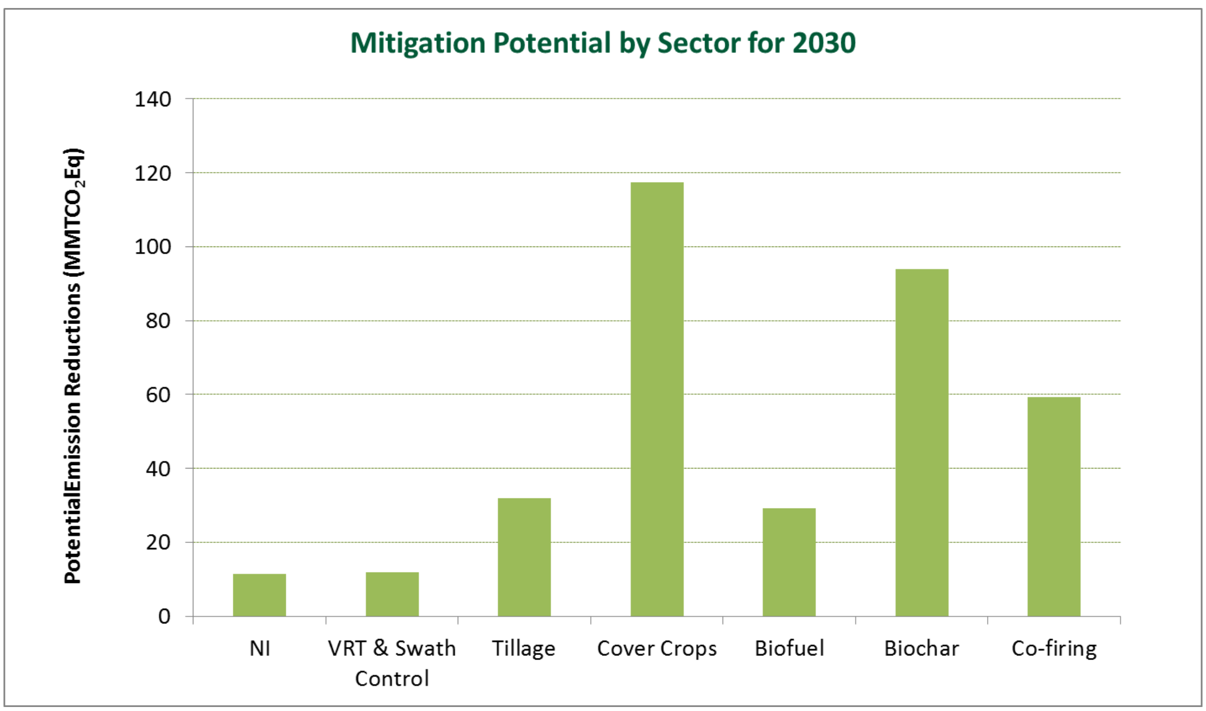
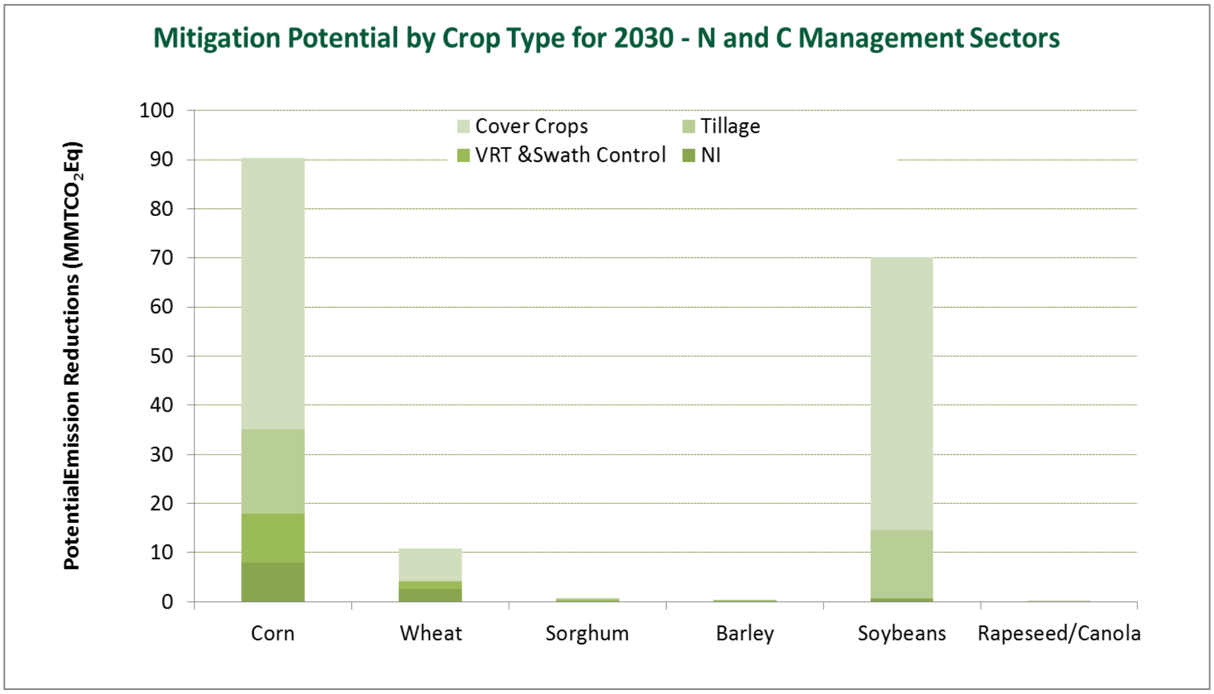


Exhibit 97: Summary of Emission Reduction Potential by Crop Type



7.3. References

ICF International. 2013. *Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States*, Prepared by ICF International USDA Contract No. AG-3142-P-10-0214. U.S. Department of Agriculture.

Paustian, K., J. Lehmann, S. Ogle, D. Reay, et al. 2016. Climate-smart soils. *Nature*, 532:49-57.