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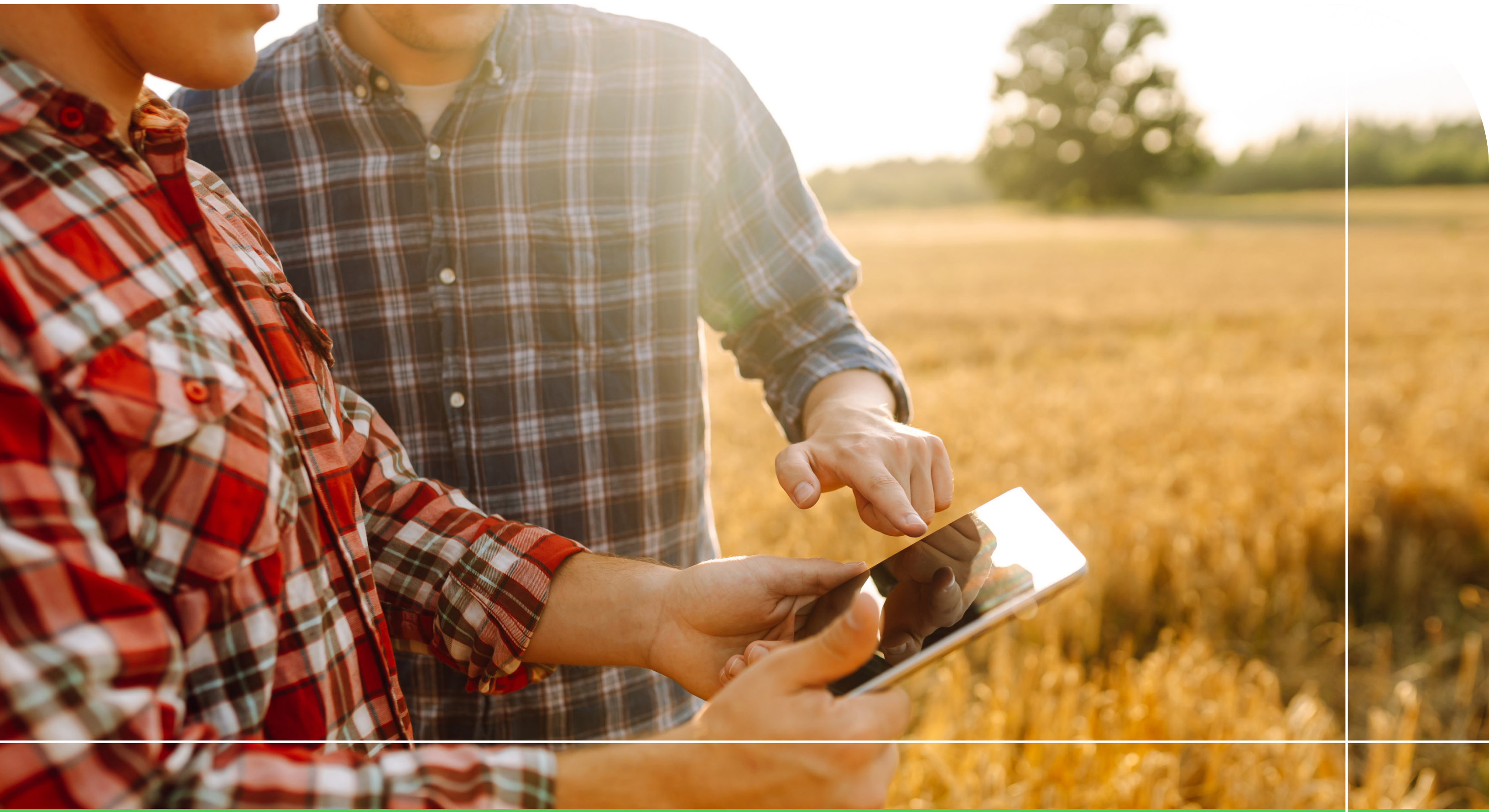

November 2024 | Interpretive Summary of Full Report

Potential for U.S. Agriculture to Be Greenhouse Gas Negative

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In 2020, U.S. Farmers & Ranchers in Action (USFRA) established an independent scientific working group to analyze the potential for U.S. agriculture to collectively reduce greenhouse gas (GHG) emissions, including the potential to achieve a state of negative emissions, or emitting fewer total GHGs than are sequestered.

Building on a 2019 report by the National Academy of Sciences, Engineering and Medicine titled "Science Breakthroughs to Advance Food and Agricultural Research by 2030," the independent authoring group established by USFRA, consisting of 26 leading research scientists, identified current practices and emerging technologies with the most potential for reducing emissions. Their findings are based on a comprehensive analysis of scientific literature, computer simulations, and life cycle analysis estimates.

At USFRA's request and with support from the Foundation for Food & Agriculture Research, the National Academy of Sciences appointed a six-person committee to review the report, assessing its clarity, organizational effectiveness, and scientific rigor.

The final report, "Potential for U.S. Agriculture to Be Greenhouse Gas Negative," outlines how combining reduced GHG emissions from some agricultural activities with increased carbon sequestration in others could achieve GHG-negative agriculture. It also describes the research needed to help accomplish this.

We commend the members of the independent authoring group and National Academy of Sciences review committee for their commitment and substantial volunteer efforts throughout this multiyear endeavor.

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Executive Summary

Carbon is the foundation for agricultural products beginning with the conversion of carbon dioxide into sugar through the process of photosynthesis and ultimately converted into compounds that are harvested through grains, fruit, vegetables, nuts, and fiber and animals convert into meat, milk, eggs, or wool. Carbon dioxide is released back to the atmosphere through processes associated with agricultural production along with methane from enteric fermentation in ruminants and nitrous oxide from nitrogen fertilizer use (Figure E1). These three comprise the greenhouse gases (GHG) that impact the environment. Currently, GHGs from agriculture represent about 10% of total emissions from all economic sectors in the United States[1]. One of the goals is to reduce these emissions. This report explores U.S. agriculture's opportunities in GHG reduction for the benefit of producers, society and the environment.

The carbon cycle in modern agriculture is complex (Figure E1). Agriculture is a dynamic and complex system; however, there are five major areas that offer opportunities to reduce the carbon footprint of agriculture. These are:

- Soil carbon management
- Nitrogen fertilizer management
- Animal production and management
- Crop production and the yield gap
- Efficient energy use in agriculture

1 USEPA (2022), Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020, available at: https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-chapter-executive-summary.pdf

Within each of these broad categories, there are a number of currently available practices and emerging technologies that can positively impact emissions while improving both production and profitability. For example, within soil carbon management, the goal is to increase sequestration; however, this can be the result of a suite of regenerative agricultural practices, (e.g., reducing tillage intensity, increasing crop diversity, adding cover crops, maintaining continuous cover over the soil surface, and integrating livestock and manures to the cropping system). The impact of these practices is not confined to increasing soil carbon sequestration; but it extends to expanding nutrient and soil water availability for the crop. The combination of those effects increases crop productivity, reduces the yield gap and decreases the energy requirement for crop production when less tillage is used in the production system. Nitrogen fertilizer management is aimed toward decreasing nitrous oxide emissions through practices that enhance nitrogen use efficiency like the 4Rs (right place right time, right form, and right amount); but it is also linked to changes in soil carbon management which affects the soil water dynamics. Soil water, along with the amount of nitrogen present in the soil, is a major factor affecting nitrous oxide emissions. Nitrous oxide is 300 times more impactful than carbon dioxide; so, a slight reduction in emissions significantly impacts agriculture's overall emission profile. The opportunity areas for nitrogen fertilizer management are based on interactions among carbon, water and nitrogen.

Similar interactions extend to animal production and management because these systems are comprised of feed production and animal feeding, housing and manure management. Crop production management systems that reduce the carbon footprint of grain transfers into and utilization of high-quality animal feeds affect methane release which is 30 times carbon dioxide impact. These interactions reduce ruminant emissions. Improved animal housing reduces the energy requirement and use of carbon-based sources of energy.

Present Day Agricultural Carbon Cycle

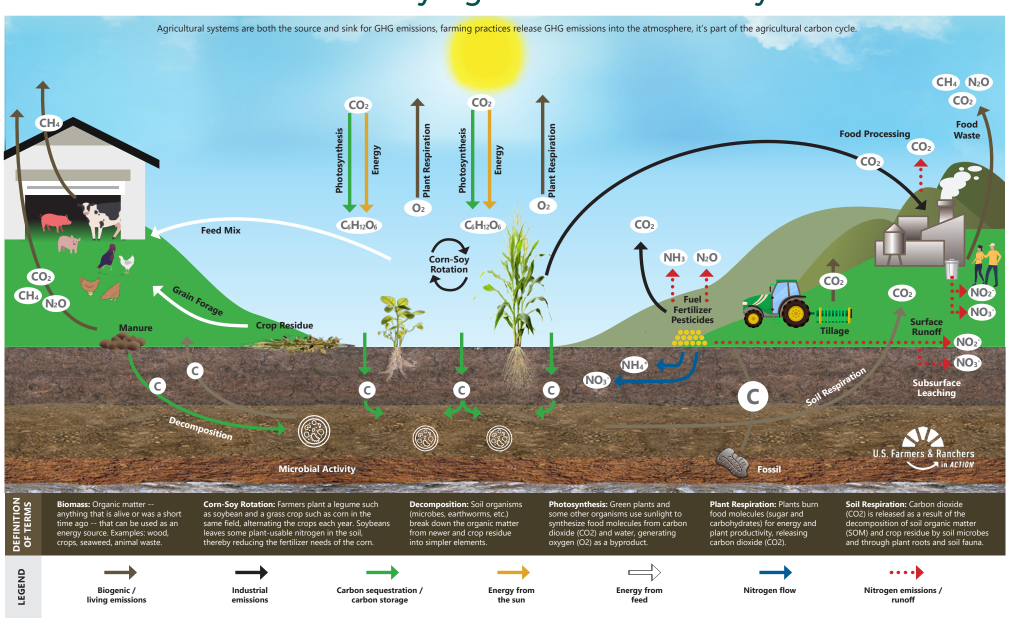


Figure E1

The carbon balance and GHG emissions are a result of the way all components of the system are managed.

A team of scientists identified the current practices and emerging technologies with the most potential for reducing GHGs based on their comprehensive analysis of scientific literature, computer simulations, and life cycle analysis estimates. These are shown (Figure E2) using two scenarios: 1) a medium impact if 50% of farm operations (as a percentage of total U.S. farm land area) adopted the practices, and 2) an aggressive impact if 75% (as a percentage of total U.S. farm land area) utilized the practices. Implementation of these five opportunity areas can have a large impact on agriculture's GHG footprint.

A future agriculture will look different than today (Figure E3). Achieving this goal will require an assessment of individual farms and production systems to determine the most effective strategies along with the technical and financial support to implement practice changes. On-farm research and demonstration of these practice changes are needed to ensure efficacy and impact on profitability and sustainability.

Agriculture will benefit from understanding the dynamic relationship between GHG emissions and the practices and technologies with the most reduction potential and direct benefit to producers. Adopting deployable practices and emerging technologies provides opportunities that would benefit all aspects in agricultural production.

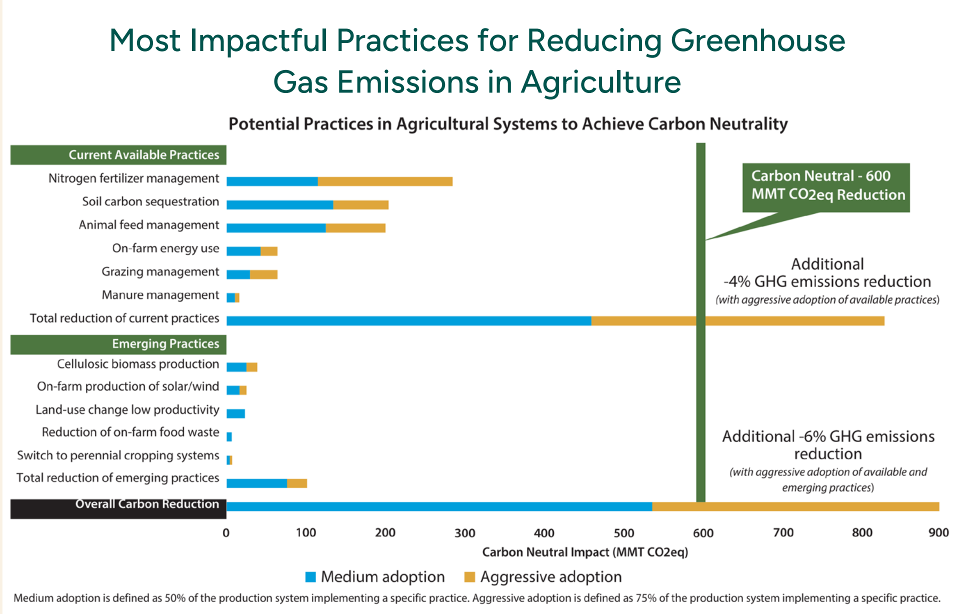


Figure E2 Potential carbon impact of current and emerging practices at the medium and aggressive levels of adoption in agricultural systems compared to overall target of 600 MMT CO_2-eq.

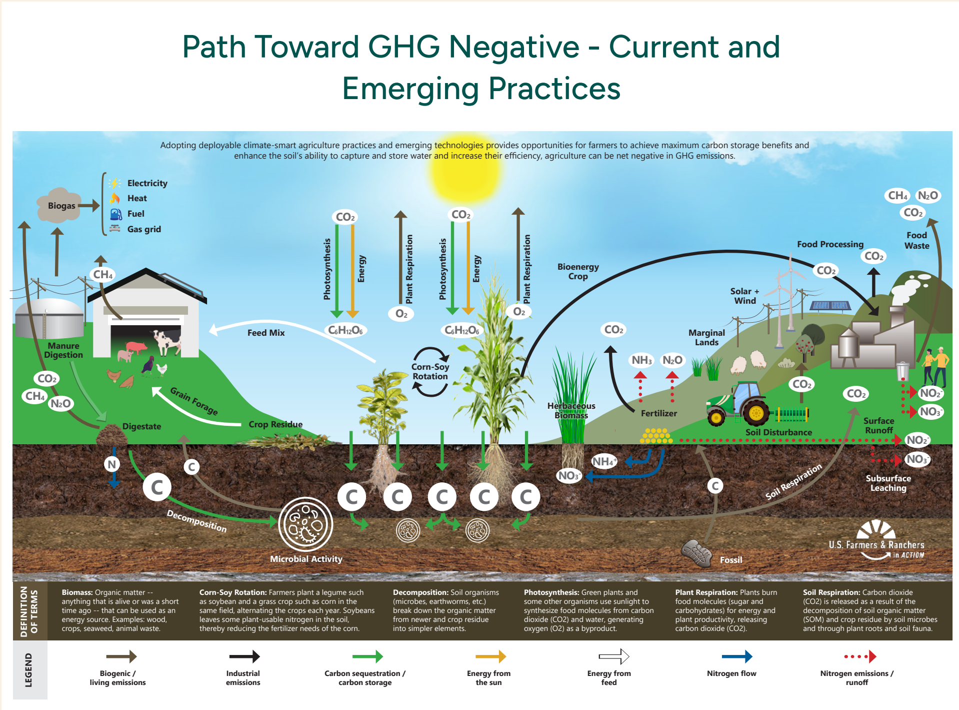


Figure E3 The agricultural carbon and GHG emission cycle with practices, that have been shown to change the carbon dynamics, would benefit all aspects in agricultural production.

The Research and the Challenge

This summary highlights the potential opportunities for moving U.S. agricultural production to a GHG negative status based on a report commissioned by USFRA and peer reviewed by the National Academy of Sciences (Rice et al., 2023). The potential for reduction of GHG emissions and sequestration of carbon from different practices was based on the best available science using a combination of life cycle analysis, computer simulations and compilation of estimates provided in the scientific literature.

The experts compiling these reports utilized the best available information to evaluate the current state of agricultural practices that could contribute towards a greenhouse gas neutral system. The full report includes medium and aggressive adoption of practices to provide an assessment of the potential for agriculture to reduce its carbon footprint without further financial or policy interventions.

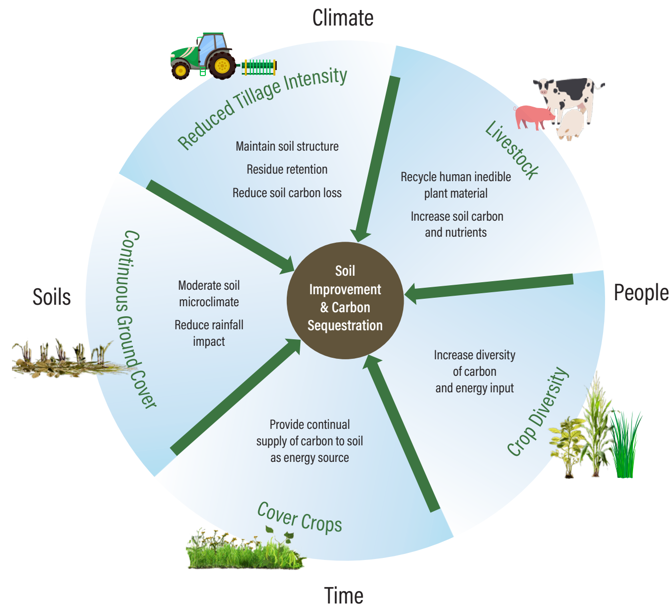
- **Medium adoption** is defined as 50% of the production system implementing a specific practice.
- **Aggressive adoption** is defined as 75% (or more) of the production system implementing a specific practice with no consideration of economic or technological factors.

Transitioning towards a GHG negative agricultural production system does not mean the elimination of carbon; but rather the most efficient utilization of carbon in production of food, feed, fuel, and fiber required to sustain society. Carbon is foundational in agricultural systems because it is the currency that forms the basis for all living organisms. An overview of the carbon cycle in agriculture shows the intricacies in how it is transformed throughout the production of goods and linked to all aspects of production including inputs related to the energy to produce the crop, production and distribution of fertilizers and pesticides, post-harvest storage, and transport of crops to processing facilities (Figure E1).

GHG negative agriculture demonstrates how decisions in the ag-food supply chain could reduce GHG emissions or carbon-equivalent (CO2-eq) footprint.

- Global GHG emissions were estimated at 68 gigaton (Gt) or 68,000 million metric tons (MMT) CO_2-eq in 2018 (Blandford and Hassapoyannes, 2018). Global emissions from agricultural production were estimated to be 14,000 MMT CO_2-eq (Hong et al., 2021).
- U.S. agriculture accounts for 10% of total GHG total emissions, according to the U.S. Environmental Protection Agency (USEPA, 2022). The total U.S. agriculture GHG emissions after land sequestration in 2020 was approximately 595 Tg CO_2e (approximately 0.6 Gt) (USEPA, 2021).

Regenerative Agricultural Practices



Regenerative agricultural practices contribute towards carbon negative agricultural systems. Each factor contributes in a specific way that allows producers to adopt a range of practices best suited to their operations.

Figure 2 The agricultural carbon and GHG emission cycle with practices, that have been shown to change the carbon dynamics, would benefit all aspects in agricultural production.

While creating a "greenhouse gas negative" U.S. agricultural production system would have a limited impact on total global GHG emissions, it would serve as a strong model for the world community. Reducing global agriculture's net GHG by 50% (7,000 MMT CO2-eq) would impact worldwide emissions by more than 10%.

A GHG Negative Agriculture

The path toward a greenhouse gas negative agriculture is complex because the overall supply chain of food, feed and fiber is interrelated, yet affected by so many different variables like geography, weather, crop patterns, production, harvest practices, and more. Since agricultural production is comprised of many different systems — each with a variety of inputs — there are many opportunities to develop a path toward greenhouse gas negative systems.

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the dominant greenhouse gases associated with agriculture. Over the past three decades, these GHG emissions have been increasing (Table 1) with CO_2 up by 8.1% from 1990-2020, CH_4 up by 16.9% and N2O up by 1.8% (USEPA, 2022). The challenge for agriculture is to reverse the trend with the goal of reducing emissions while enhancing the capability of different production systems to efficiently generate food, feed, fiber, and fuel.

Greenhouse gas negative agriculture represents the total of all GHG expressed as carbon dioxide equivalents (CO_2-eq) to account for the difference in the global warming potential of the gases emitted from agriculture. For example, the global warming potential of CH_4 is estimated at 30 times CO_2 while N_2O is 298 times CO_2 over period of time. Globally, agriculture would need to sequester between 14,000 and 18,000 MMT CO_2-eq to become greenhouse gas negative. For the U.S., the change would be approximately 600 MMT CO_2-eq to offset emissions from all agricultural systems. To achieve this goal, there are practices that can be implemented ranging from carbon sequestration in the soil to adoption of precision nitrogen management practices. Agriculture has the opportunity and challenge to develop a path toward implementing practices that would achieve greenhouse gas neutrality.

Opportunity 1: Soil Carbon Management

OVERVIEW

Sequestration of carbon into the soil is one of the largest potential areas for agriculture to reduce its carbon footprint. Achieving this goal would require adoption of regenerative practices of reduced tillage, crop diversity, continual cover of the soil, cover crops, and integration of livestock in the cropping systems. The benefits are: 1) increased soil carbon and potential crop resilience to weather extremes, 2) decreased energy inputs into the system and 3) improved quality of the grain or forage produced. Increasing carbon storage in the soil could account for approximately 20-35% of the total emissions from agriculture. To achieve this level of adoption, producers would require on-farm demonstrations to show the impact of changing practices and technical assistance required to aid the transition.

Source	Emission (MMT CO_2-eq)	Potential Management Practices
CO_2		
Urea fertilization	5.3	Improved nitrogen fertilizer management
Liming	2.4	Improved soil management
CH_4		
Enteric fermentation	175	Improved feed efficiency
Manure management	60	Improved management
Rice Cultivation	16	Water and nitrogen management, cultivar selection
Agriculture residue burning	0.4	Remove burning
N_2O		
Agriculture soil management	316	Improved nitrogen fertilizer management
Manure management	20	Improved management

Table 1. This table shows the source of CO_2-eq emissions from different management practices and potential reductions. (Values extracted from USEPA, 2022)

Sequestration of carbon into soil has been discussed as a potential for agriculture in mitigating climate change. Soil is a large potential sink for carbon because the original levels of organic matter have been depleted over centuries of tillage. The carbon sequestration potential for a given soil depends upon the type, cropping history, climate, current production systems, and the associated management practices.

Increases in soil carbon are often accomplished through the regenerative agricultural practices of conservation and reduced tillage, cover crops, continual soil cover, crop diversity/rotation, maintenance of living roots, and integration of livestock into the production system. The impacts of these practices must be addressed within the context of each field's soil and climate regime (Figure 2).

Conservation and reduced tillage practices often result in decreased fuel consumption and increased soil carbon. Cover crops remove carbon from the atmosphere and store it in the soil as root mass and biomass integrated during tillage. Crop diversity, maintenance of living roots, continual cover, and livestock integration contribute to the soil becoming a more effective carbon reservoir. Soil carbon dynamics are governed by microbial activity.

Adoption of these practices provide:

- **Food** (carbon as the primary energy source for soil biology from roots and root exudates)
- **Water** (continual cover reduces soil water evaporation maintaining an environment conducive to microbial activity)
- **Air** (soil microbial systems associated with carbon and nutrient cycling are aerobic and promote air exchange)
- **Shelter** (decreases in tillage intensity reduces soil compaction resulting in a stable environment for microbial activity to flourish)

The exact amount of carbon stored within the soil profile is dependent upon the soil type and climate.

For example, fine-textured soils in cool, moist environments of the Midwest will accrue more carbon than the same practices in the warmer environments of the Southeast, which has coarser-textured soils. It has been estimated that adopting conservation practices at a moderate level across 2.47 million acres would remove 106 MMT CO_2-eq/year with an aggressive level up to 204 MMT CO_2-eq/year (Ellis et al., 2023).

Beyond soil carbon sequestration, a major adoption benefit of practices that impact greenhouse gas neutrality is plant-available soil water (the primary determinant in crop productivity). An increase in soil water availability associated with more infiltration of rainfall or irrigation water — coupled with better water-holding capacity and reduced soil water evaporation rates — can lead to improved crop productivity and yield stability over multiple years. Reducing the yield gap in crop systems can translate to more efficient use of carbon inputs, fuel, fertilizer, and pesticides.

Documentation of the effectiveness of the different regenerative practices requires monitoring soil carbon changes across fields and in the soil profile. Within the Soil Carbon Management area, there are currently available practices (e.g., reduced tillage and cover crops) with documented impacts on GHG emissions. Also, there are emerging or "frontier" technologies with potential (e.g., biochar as a soil amendment, genetic selection of crops with larger partitioning of carbon into the root system, or enhanced phenotypic screening of crops), but their impact for improved photosynthetic efficiency is undocumented.

Opportunity 2:
Nitrogen Fertilizer Management

OVERVIEW

Application of nitrogen to crops represents one of the largest inputs of energy and GHG impacts from agriculture due to the release of nitrous oxide to the atmosphere. However, it may be one of the more easily adoptable changes in management because it requires a modification in the rate, form, time, or placement of the nitrogen fertilizer. The impact of these changes could range from 20 - 50% of the total agricultural emissions with the return to the producer being reduced fertilizer costs and increased nitrogen use efficiency. The tools exist to help producers more precisely apply nitrogen across a field. To show the direct benefit to producers, these systems must be put into place through financial incentives, demonstrations and technical assistance.

Nitrous oxide is one of the most climate impactful losses from agricultural systems and accounts for over 50% of the total GHG emissions.

Nitrous oxide has a warming potential approximately 300 times that of CO_2. This would suggest that practices reducing N_2O emissions would have a significant impact on moving toward a greenhouse gas neutral agricultural system. Understanding the N cycle and the factors affecting N_2O emissions provides a basis for quantifying the potential opportunities (Robertson and Basso, 2023).

Emerging technologies in nitrogen management include the use of biological nitrogen fixation on non-legume crops, production of green ammonia, and development of tools to more accurately predict crop nitrogen needs. These technologies have the potential to reduce the nitrogen footprint for agriculture and GHG emissions.

Soil Carbon Management Challenges

For the producer, the adoption of practices leading to enhanced soil carbon (either by reduced tillage, cover crops, expanding crop diversity, or integrating livestock) must be profitable or cause no uncompensated costs. Producers, who have implemented these practices, have observed increases in soil organic carbon, infiltration, soil water availability, and nutrient use efficiency. This has resulted in reduced risk in crop production and increased profitability.

Enhancing the soil through improved soil carbon, water, and nutrient cycling benefits both the crop and the environment. The primary challenge is to demonstrate the value of these practices and develop support systems to help producers understand how to transition their cropping practices to include regenerative methods. The second challenge is to demonstrate and quantify the effects of these practices on environmental and ecological parameters and reward producers for achieving those benefits.

Reducing Methane from Rice Cultivation Is an Integrated Solution

In cultivated agriculture, rice production is one of the largest areas of methane emissions. The solution represents the linkage among all aspects of production management. The exact amount of CH_4 emission reduction from changing water management, nitrogen management and cultivar selection have been identified. To achieve an effective emission reduction, that producers would adopt, all three factors — water, nitrogen and cultivar selection — must be considered as part of a profitable and sustainable production system. Emerging evidence shows that shifting rice production from flood to drip irrigation would decrease water and nitrogen use by two-thirds leading to large reductions in both CH_4 and N_2O emissions, decreased water use, and enhanced productivity.

Nitrogen Management Challenges

Reductions in nitrogen application rates are difficult because the plant response to nitrogen is inconsistent year-over-year. This uncertainty in plant response is due to weather variations, especially rainfall. As Basso et al (2019) demonstrated, every field produces crops differently and exhibits a consistent response to the amount of nitrogen applied. This level of uncertainty and the inability to accurately predict weather conditions throughout the year often results in over-application. Development of tools to quickly assess the nitrogen status of crops and having access to application equipment to meet plant needs would help to alleviate excess nitrogen from being applied. This could reduce N_2O emissions and nitrate-N leaching and improve the nitrogen footprint of U.S. agriculture.

Opportunity 3: Animal Production and Management

OVERVIEW

Animal production systems are linked to the release of enteric methane from ruminants and account for nearly half of agricultural GHG emissions. A wide range of opportunities exist within animal production systems to reduce emissions and are contingent on the type of production system. There are three areas of potential impact: feeding systems for ruminants, manure handling and feed production (not applicable to every dairy or livestock farm operation). For example, dairy systems have the potential for all three interventions, while grazing cattle is limited to changes in forage quality. Also, confined swine and poultry have the potential for manure handling and energy usage in buildings. The major barriers to producer adoption of these technologies is proving the effectiveness of the practice with no impact on production or excessive capital investment.

GHG emissions from animal production are, primarily, from feed production (Kebreab et al., 2023). Reducing GHGs in feed production also benefits the supply chain in animal production.

The next most significant GHG emissions are from ruminant digestive enteric methane production and manure management, which account for 43% of total U.S. agricultural emissions. Intensive feeding operations for beef and dairy account for most enteric and manure emissions (Kebreab et al., 2023). Enteric emissions from ruminant animals are the result of microbial fermentation of carbohydrates and amino acids in the rumen and the hindgut, allowing them to convert low-energy and value lignocellulosic biomass into high value protein and fat. Potentially viable solutions include: 1) changes in fiber digestibility, 2) increasing dietary lipid content or 3) using feed additives to inhibit methanogens.

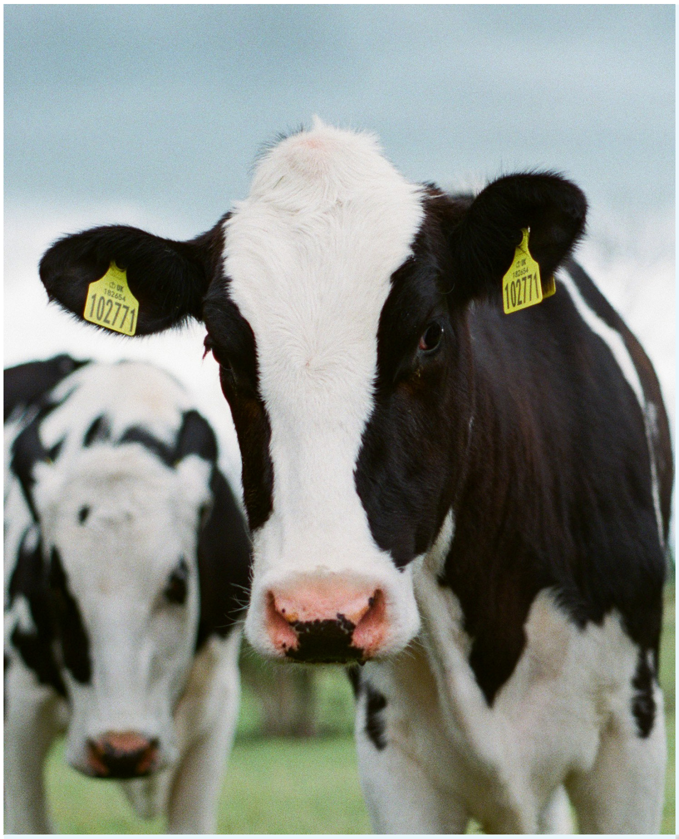
Results from different studies would suggest CH_4 emissions could be reduced by 20-40%; however, there is a trade-off with costs related to these changes and impacts on either meat or milk production. The primary challenge is to demonstrate the effectiveness of feed management practices at a scale in which producers have confidence in the results.

- **For dairy,** opportunities exist in changing feed and manure management to achieve carbon neutrality.
- **For beef** on pasture or rangeland, reductions would be limited to forage quality and management of the grazing areas.
- **In pork and poultry production** for confined animal feeding operations (CAFOs), the carbon footprint could be reduced through feed sources and energy demand for heating and ventilating buildings. Both animal species exhibit high efficiency in converting feed to meat or eggs. The emissions from these species are linked more to manure handling and storage than from production practices.

Across all animal species, after crop feedstock GHG reduction, manure management offers the greatest potential to a greenhouse gas neutral path (Montes et al., 2013). Storage of manure in lagoons results in anoxic and anaerobic conditions and CH_4 emissions.

Emissions could be reduced by:

1. Using anaerobic digesters to capture and reuse methane
2. Decreasing storage time in lagoons
3. Using aerobic lagoons to digest waste
4. Reducing water content through liquid-solid separation
5. Composting manure. Manure is an asset in regenerative agriculture as green fertilizer and soil amendment.



Journey to Carbon-Neutral Dairy Systems

Dairy production systems offer the potential to achieve carbon neutral systems in the areas of milk production, feed production and storage, animal feeding and nutrition, and manure handling. Utilization of regenerative agriculture practices, coupled with precise nitrogen management, will reduce the carbon footprint of the feed and forage produced and decrease energy use. Enhanced feed quality and additives will potentially reduce the enteric methane emissions from cows and the emission rate per unit of milk produced. Utilization of digesters for manure processing, along with methane capture as a fuel source, would further reduce the carbon footprint. These potential practices would significantly reduce the CO_2-eq from dairy systems.

A robust research approach is required to provide quantitative evidence of the GHG impact and incorporate an economic assessment of the practices compared to traditional systems. These studies would need to be conducted across a range of dairy systems and climate regions.

Beef Grazing Systems and Greenhouse Gas Neutral Approaches

Confined feedlot systems for beef production and approaches for carbon neutrality can employ the same tactics as dairy by evaluating feed production, feed quality or additives, and manure handling. For grazing animals and cow-calf operations, the largest emissions are from methane related to the quality of forage consumed. This is a more difficult system to tackle, but one which could pay large dividends in improving animal performance and reducing GHG emissions. This research area requires a large investment to conduct trials and measurement techniques to quantify changes in animal emissions at a scale in which producers will have confidence in the results.

Opportunity 4: Crop Production and the Yield Gap

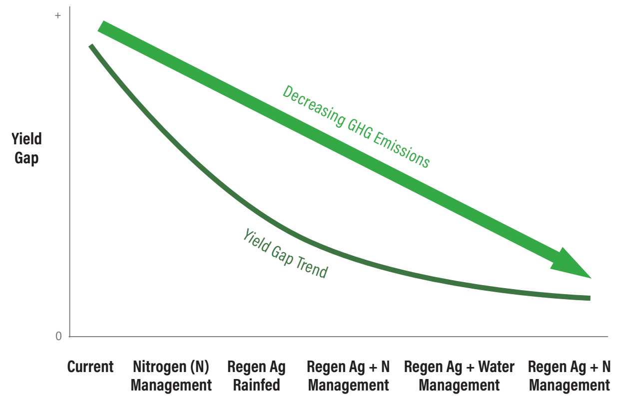
OVERVIEW

Crop production systems represent the integration of a series of inputs with a GHG impact. Improving production efficiencies can reduce the carbon footprint. This does not require a major change in the practices; but rather, an increased understanding of the factors limiting the realization of genetic potential. Any increase in production improves the crop's carbon return on investment. The tools exist to help producers evaluate their cropping systems and are applicable to all plants in the agricultural system from vegetables, fruit and nuts to grains and fiber. Further development and application of tools is needed to help producers evaluate their systems for production changes and technical assistance needed for long-term support of the application of these technologies.

The United States produces a wide variety of crops used for food, feed, fuel, and fiber. These require GHG-intensive inputs. Yield gap — expressed as the difference between field-level yields and the genetic potential of the crop — can be as high as 50%. Progress in closing the yield gap has occurred where modern agricultural practices optimize inputs for high yields. Even in high-yielding systems like the United States, gaps exist; consequently, there are opportunities to benefit from the increased efficiency of input use.

The basis for understanding the factors linked to closing the yield gap requires knowledge of the genetics X environment X management complex (Hatfield et al., 2023). For example, the application of 4R practices — right source, right rate, right time, and right place — for nitrogen management helps to decrease the yield gap by preventing nitrogen deficiencies in crops during critical growth periods. This leads to more efficient use of nitrogen fertilizer and an improved carbon footprint. Selection of crops with genetically enhanced photosynthetic efficiency increases the potential for improved yields with little or no additional input requirements. Any practice capable of reducing the yield gap will lead toward a more carbon neutral crop production system.

Closing The Yield Gap Can Reduce GHG Emissions



Yield gap is the difference between field-scale yields and the genetic potential of the crop. Closing the yield gap by adopting regenerative agricultural practices coupled with water and nitrogen management leads to reduced greenhouse gas emissions along with capturing more yield potential.

Figure 3 Yield gaps would decrease with increasing implementation or regenerative agricultural practices coupled with improved nitrogen and water practices.

Combined Practices Offer the Greatest Impact

A combination of practices in crop production demonstrates the potential impact toward carbon neutral farming systems and reduces the yield gap. Linking practices, that increase soil carbon sequestration with precision nitrogen management, will potentially lead toward a better realization of a crop's genetic potential. The combined effect of regenerating the soil for enhanced water and nutrient ability allows for more efficient utilization of applied nitrogen and other nutrients. The overall effect is a reduction in the carbon intensity of the crop produced. For producers, the challenge is to demonstrate the value of combined practices based on economic return. This is an area in which improved phenotyping of crops for enhanced light, nitrogen, and water use efficiency and enhanced root systems offer potential solutions to reducing the yield gap and carbon footprint.

Opportunity 5: Efficient Energy Use in Agriculture

OVERVIEW

Energy use in agricultural systems is often overlooked as a potential area for impacting GHG emissions. Most energy use is directly related to fossil fuels. Opportunities exist to replace fossil fuels with natural and renewable energy sources. Agriculture is energy intensive in all aspects of production and could provide a pathway for reducing the footprint by 10% of total emissions. Altering the form of energy sources or adopting new technologies (e.g., solar and wind, cellulosic energy, and shifting corn ethanol to herbaceous sources through land use change to remove low corn yielding areas) will require investments for development and implementation on the farm. The return on this investment would potentially impact the ability of producers to increase their energy efficiency of production and achieve multiple environmental goals of cleaner water and air and enhanced landscapes.

Agriculture is energy.

It is based on the capture of photochemical energy and conversion to biochemical energy in the form of many different products. The productivity levels of modern agriculture are the result of using fossil, electric and other energy sources. Modern agriculture is energy intensive in all aspects of cultivation, harvesting, transporting products, animal production, and distribution. This utilization of energy has increased productivity and decreased the amount of labor required to produce food, feed, fiber, and fuel.

Direct energy sources for agriculture include diesel fuel, gasoline, propane, natural gas, and electricity, as well as renewable energy like wind, solar and biofuel energy. A large amount of indirect energy is linked to products and equipment used to produce crops and animals. Direct energy use accounts for an estimated 60% of agriculture's energy consumption and indirect energy use is 40% (Matlock et al., 2023).

Agriculture's greatest energy demands come from fuel, fertilizer and irrigation requirements. Increasing crop productivity relative to energy inputs reduces the carbon footprint of the crop. For example, converting from intensive to conservation tillage reduces fuel usage without a yield penalty and increases carbon sequestration into the soil. Managing direct energy inputs into either crop or animal production systems provides one avenue of reducing the carbon footprint; however, producers need to be assured these practices have no negative impact on productivity or profitability.

A Path to Greenhouse Gas Neutral Agricultural Systems

Implementing the practices, summarized here, could result in a GHG neutral or GHG negative U.S. agriculture; thus, providing a roadmap for the world.

Nothing, however, is simple. Agricultural systems are particularly complex with interactions between carbon, water, nitrogen, and energy across a spatial and temporal framework. Because weather, soil, field, and regional conditions constantly change, effective solutions for greenhouse gas reduction could vary year-over-year and across each planting-to-harvest season (Figure E3).

The summary of potential GHG reduction and carbon sequestration methods described in the previous sections point to opportunities within different sectors of the agricultural system. Soil carbon sequestration, nitrogen management, animal feed and housing management, manure management, and on-farm energy use offer the greatest potential areas to achieve greenhouse gas neutrality in agriculture. Figure E2 shows the potential reduction in emissions from agriculture from implementation of different practices (Matlock et al., 2023).

Implementation of current technologies and practices at the medium level of adoption falls short of achieving greenhouse gas neutral systems; however, aggressive adoption provides the opportunity for agriculture to more than offset its carbon footprint. Emerging practices enhance the ability of agriculture to further reduce its carbon footprint. (See Appendix Table A1 for detailed values for each practice.)

Based on the current state of scientific literature and a detailed assessment of the results, there is a wide range in the impact of a specific practice to reduce GHG emissions and contribute to greenhouse gas neutral systems. The range of impact on the expected efficacy of different practices at the medium adoption level is shown in Figure E2 (page 4).

Increased investment in research should be directed toward those practices with the greatest impact and supported by a "practical systems approach" that provides producers with information about "how" a specific practice could impact their production system.

The barriers to achieving U.S. agricultures potential reduction levels are:

- Adoption
- Demonstration of impact across different parts of field and farming areas
- Policy to support practice adoption
- Technical support to assist producers in changing crop or animal production systems (Antle and Capalbo, 2023).

A more aggressive approach is needed to:

1. document the positive impact of practices on profitability and production resilience for seasonal weather changes and
2. develop tools to assist producers in transitioning to new practices. These include decision support systems to aid in evaluating the effectiveness of on-farm management (e.g., risk reduction and profit maximization) and new practices across growing seasons.

The potential of emerging technologies — artificial intelligence, machine learning and system-level computer simulation models that can assess production systems based on interactions among GHG emissions, production levels, environmental endpoints, economics, and carbon intensity — will continue to advance the evaluation of current and future scenarios across a wide range of settings.

These changes need to be at the farm-level where producers can see the effect on their operations rather than at aggregated scales where they can only see the general impact. For greenhouse gas neutrality to occur, the industry must understand that any change must be financially viable or profitable to the producer and fit within their management systems.

Frontier systems require investment into developing and implementing practices with a positive impact. For example, food waste is an emerging area of potential reduction, but the path toward implementing practices remains in the development stage (Nichols-Vinueza et al., 2023). Of primary importance in food waste is the loss before it leaves the farm gate. This could represent a large portion of the specialty crops (e.g., vegetables and fruit) with an estimate of nearly 14 million tons lost for various reasons (Nichols-Vinueza et al., 2023). While only a small part of agriculture's overall carbon footprint, reducing these losses could provide much-needed produce to communities.

Any investment in frontier and emerging practices would achieve environmental (carbon reduction) goals and demonstrate how agriculture benefits society by proactively investing in technologies with multiple benefits. These practices are a first step. As innovation and exploration advance, other potential practices may emerge. For example, biological fixation of nitrogen for all crops could offset nitrogen fertilizer inputs or genetic material, that is more resilient to stress and leads to more efficient production in adverse weather conditions.

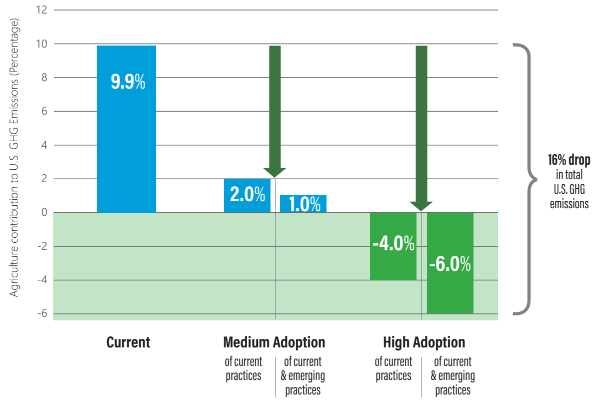
Developing greenhouse gas neutral-to-negative agricultural systems is a journey. It requires implementing practices with the potential of reducing GHG emissions while simultaneously increasing the profitability and resilience of the specific system. The value shown in Figure E2 and Appendix Table A1 for potential reductions are projections based on best-available information.

Much remains to be done in each commodity to realize this potential. Detailed research is needed to provide quantitative information for a range of climates, soils, production systems, and scale of operations. And, it must be evaluated for impact and barriers that limit adoption including financial, technological, and sociological constraints.

As a first step, agricultural producers must be able to determine how their operations can benefit in the greenhouse gas neutral journey. This must happen before benefits from other environmental and social goals can be evaluated. Practices that add value and provide understanding will move producers forward on the adoption curve.

The path toward greenhouse gas neutrality is complex because it involves changes in both crop and animal production systems. Producers know their systems and must be part of the on-farm implementation and assessment process to ensure changes are impactful and long-lasting. Sustainable, long-term change will require policy that supports and rewards producers for their efforts (Antle and Capalbo, 2023).

Agriculture has the Potential to Reduce its Footprint to -6% of Total GHG Emissions



Medium adoption of current practices to improve Nitrogen management, soil carbon sequestration, animal feed and on-farm energy use has the potential to reduce 80% of the current agriculture GHG emissions. With the addition of frontier and emerging technologies including cellulosic biomass production, solar and wind energy production, advance cropping systems, agriculture can reduce emissions to -6% of total U.S. GHG emissions, that's a 16% drop in total.

Figure E6 U.S. agriculture's contribution to GHG emissions could decrease to 1%-2% with medium adoption of available practices. It could be further reduced to -4% to -6% with aggressive adoption of available practices.

The magnitude of these changes can be seen in Figure E6. A medium adoption rate of current available and emerging practices can reduce 80-90% of U.S. agriculture's GHG emissions. Soil carbon sequestration, nitrogen fertilizer and animal management systems account for 81% of potential reductions with on-farm energy use adding another 9% (Figure E2). The other areas contribute the remaining 10% of potential reductions with no single practice having a large impact.

Impact levels from these areas suggest that concentrating on efforts in soil management, N fertilizer management, animal management systems, and on-farm energy use would pay dividends for the producer and environment. It highlights the potential for agriculture to demonstrate its ability to achieve GHG neutrality.

The high level of adoption of current practices would further reduce the impact on agriculture to -4% of current emissions and -6% with the implementation of frontier and emerging technologies (Fig. E6). There is an increase in the impact of soil carbon sequestration, nitrogen fertilizer management, animal management systems, and on-farm energy use to 90% of the reduction potential.

Focusing on these specific areas would contribute significantly to U.S. agriculture's GHG neutrality goals and serve as an example for achieving without negatively affecting production targets, food security or environment.

Implications for Producers

Opportunities exist for producers to take advantage of practice changes that would benefit GHG neutrality and increase the efficiency of their operations. (e.g., Increasing soil carbon improves water storage, climate resilience, forage and grain quality, and animal performance.) Practices benefiting the individual producer have a larger environmental impact on water quality and ecological health.

For example, the carbon market is one avenue for rewarding producers for carbon sequestration in soil. These markets, however, neither consider all practices leading to greenhouse gas neutrality nor reward producers for ecosystem services. The restrictions on enrollment and data requirements to document the impact of practices are barriers to widespread adoption.

Producers have the potential to implement practices on their own farms that benefit economic return, resilience and climate-smart agriculture. Being able to assist producers in their transition phase to effectively implement any change in a climate-smart or greenhouse gas neutral practice will be critical to environmental and economic impacts of any practice. These are not unsurmountable obstacles, but they require a combination of robust scientific and economic policy to provide the information needed to facilitate change.

Moving Forward to a Greenhouse Gas Neutral Agriculture

Developing greenhouse gas neutral agricultural systems is a journey that requires implementing practices with the potential of reducing GHG emissions while simultaneously increasing the profitability and resilience of the specific system. The values shown in Figure E2 for potential reductions are projections based on available information from the scientific community. Much remains to be done in each commodity to realize this potential. Fortunately, for many of the commodities (e.g., dairy, beef, pork, corn, soybeans, and eggs) life cycle assessments have been completed to provide an assessment of the carbon footprint in typical production systems. These can help to guide the most critical steps to be addressed in the carbon neutral journey.

To develop this journey and realize the potential of these practices, a systems approach at field and farm levels is required to quantify the tradeoffs related to different practices. This determines the scale at which producers would evaluate and implement changes. Detailed research is needed in each of the areas to provide quantitative information across a range of climates, soils, production systems, and scale of operations. This needs to be evaluated for both impact and barriers that would limit adoption including financial, technological, and sociological constraints.

As the first step in the greenhouse gas neutral journey, agricultural producers must be able to determine how their operations can benefit. This must happen before benefits from other environmental and social goals can be evaluated. Practices that add value and provide understanding will move producers forward on the adoption curve.

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Appendix

Potential GHG Reduction

Opportunity Area	Potential Reduction (MMT CO_2-eq)	Fraction of Agricultural Emissions	Limitation
Current available practices			
Nitrogen fertilization management	115-284	0.19-0.47	Techniques for on-field precision application
Soil carbon sequestration	135-204	0.22-0.34	Adoption and monitoring techniques to document benefit
Animal management (feeding systems)	125-200	0.21-0.33	Demonstration of the impact of improved feed additives
On-farm energy use	43-64	0.07-0.11	Replacement of fossil fuels with renewable energy sources
Animal management (grazing)	30-64	0.05-0.10	Implementation of enhanced grazing management
Manure management	11-16	0.02-0.03	Implementation of improved management methods
Total reduction current practices	**459-832**	**0.76-1.40**	
Frontier and Emerging Practices			
Cellulosic Biomass	25.7-38.9	0.04-0.07	Incentives for production and conversion technologies
Land change from corn grown in low productivity soils to herbaceous biomass crops for ethanol production	23	0.04	Incentives to promote conversion Identify areas of low productivity soils or convert CRP ground into biomass production areas with conservation guidelines
On-farm Solar and Wind	16.8-25.4	0.03-0.04	Continued expansion on farms
On-farm food waste	6.8	0.01	Demonstration on efficient compost and reduce of harvest losses
Perennial cropping systems on marginal lands	4-7	0.007-0.01	Incentives to remove marginal land and convert to perennial cropping systems
Total Emerging Practices	**76.3-101.1**	**0.13-0.17**	
Total of all Practices	**535.3-933.1**	**0.89-1.56**	

Table A1. Carbon reduction potential ranges from medium to aggressive adroption rates and their portion of agricultural emissions and limitations to their adoption vary for different opportunity area.

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