# Climate Change and Missouri Agriculture

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# Climate Change and Missouri Agriculture

A report prepared for the Missouri Soybean Association

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# Executive Summary

The five-year moving average annual temperature in Missouri has been above the long-term (1985 to 2019) average for 22 of the last 25 years. The warming trend is observed primarily in the spring and fall. During the summer, daytime maximum temperatures have not risen, but nighttime low temperatures have. Missouri average annual rainfall also has been increasing since the 1950's. The increased rainfall tends to occur from March to May. The number of daily rainfall events exceeding three inches has also risen from a long-term average of 17.2 per year to an average of 23.3 per year during the last 20 years. The 10-year moving average for dew point temperatures in Missouri has been higher than the long-term average for the last 30 years.

Various changes in climatic conditions will affect the ability of farmers to productively and profitably produce crops. Research indicates that increased atmospheric $CO_2$ concentration will likely favor weeds and increase herbicide resistance problems. Increased temperatures are forecasted to reduce Missouri corn and soybean yields in the next few years. Increased extreme rainfall events during the spring make planting more difficult and increase erosion. The adverse effects of climate change on agriculture will necessitate continued investment in agricultural research.

Climate mitigation policy alternatives and market activities will affect farmers. Currently agriculture is considered a major emitter of greenhouse gases (GHG) and calls to reduce emissions associated with agriculture are persistent. Total GHG emissions from agriculture are increasing, but at a decreasing rate. Presenting a compelling story of how U.S. farmers are contributing to mitigation efforts will be politically important and allow them to participate in marketing the ecosystem benefits of emergent agricultural practices.

Yield-scaled emissions, defined as GHG emissions per unit of production, are decreasing. USDA and EPA data show that GHG emissions per unit of total agricultural production have decreased 15% between 1990 to 2018. Increases in emissions have been the result of increased production of crops and livestock. Decreases in yield-scaled GHG emissions have been the result of improved production practices and increased yields. Research concludes that yield gains in agriculture from 1961 to 2005 have reduced *net* GHG emissions by 161 billion metric tons of carbon – 34% of the total GHG emissions attributable to human activity between 1850 and 2005.

The protocols of trade are being developed for markets that compensate businesses capturing GHG or reducing GHG emissions. Businesses who want to market products as climate friendly are leading the efforts by compensating farmers who can prove emission reductions. Opportunities exist to participate in these developing markets and to develop the rules that will be used in future markets.

Using research-based estimates of GHG emissions from agricultural practices and verifiable estimates of Missouri crop acres using those practices, GHG emission reductions of at least 2,963,114 tons $CO_2e$ are occurring annually. This is equivalent to the emissions from the energy use of over 25% of all Missouri registered automobiles or the all the housing units in Kansas City, St. Charles and Springfield combined.

# Overview

Climate change has the potential to impact Missouri agriculture. A changing climate may affect which crops are grown, their yield and how they are managed, particularly with respect to weeds and pests.

Efforts to reduce climate change also have the potential to impact Missouri agriculture. As greenhouse gas levels increase in the atmosphere, efforts to reduce or slow their increase become weighty. Caps may be put on various sectors of the economy, including agriculture, that emit greenhouse gases (GHG). Markets may develop that compensate entities that reduce or capture GHG rather than allowing them to escape or remain in the atmosphere.

As concern over climate change increases, it will be important for Missouri agriculture to be able to communicate its contribution to mitigation efforts. Food, feed, fuel and fiber must be produced. But increased production releases more GHGs into the environment. The question becomes how to optimize the production of agricultural commodities with an eye to minimizing GHG emissions – or maximizing GHG reductions.

This report focuses as directly as possible on climate change with respect to Missouri agriculture. It does this by seeking the best information specific to Missouri, or the Midwest U.S. Research that addresses the entire U.S. agricultural system is also presented when Missouri and Midwest research is unavailable.

# Midwest Climate Change Forecasts

The U.S. Global Change Research Project delivered the *Fourth National Climate Assessment* in 2018 – a report that it is mandated to provide to Congress every four years or less. The Assessment garners attention for its forecasts of climate conditions and their likely impacts on the nation.

The *Assessment's* chapter on the Midwest projects that increasing growing season temperatures will contribute to decreased agricultural productivity while increased humidity in the spring will contribute to increased soil erosion and reduced planting season workdays. Their assessment considers increased rainfall over the last 30 years from April to June to be the most impactful climate trend for Midwest crop production (Angel et al. 2018).

While uncertain about the severity and prevalence of droughts into the future, they forecast increased precipitation to result in greater erosion and flooding of farmland. Daily maximum summer temperatures in the Midwest have not trended upward over the past several decades as they have in other regions of the world. However, Midwestern daily minimum temperatures have increased.

The *Assessment's* chapter on the Midwest, using the Representative Concentration Pathways 8.5 (RCP8.5; see a later section for an explanation of RCP), projects that the Midwest will experience the greatest warm-season temperature increases in the U.S. The frost-free season is expected to increase as much as 30 days by the end of the century.

# Missouri Climate Trends

This section focuses on historical indications of climate change in Missouri. It reinforces the many of the forecasts for the Midwest U.S. found in the *Assessment.*

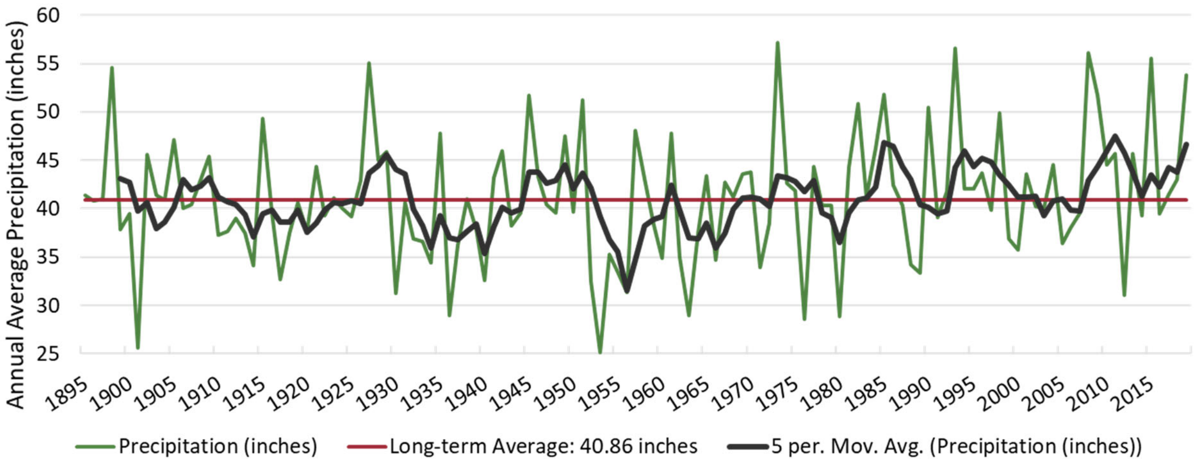
The graphs below and their analysis are not statistically validated for degree of confidence but paint a picture consistent with what climatologists are observing on a regional and national scale. All figures below are from Guinan (2020).

## Precipitation

An unprecedented wet period in Missouri began in the early 1980's. This increased rainfall tends to occur during March, April and May – causing planting challenges and increased erosion challenges. This wet period is evidenced by an increased annual precipitation trend and an increase in the number of heavy (≥ 1 inch) and extreme (≥ 3 inch) daily precipitation events.

The long-term annual precipitation in Missouri is 41 inches/year. The five-year moving average annual precipitation in Missouri has been above the long-term normal for all but three of the last 25 years.

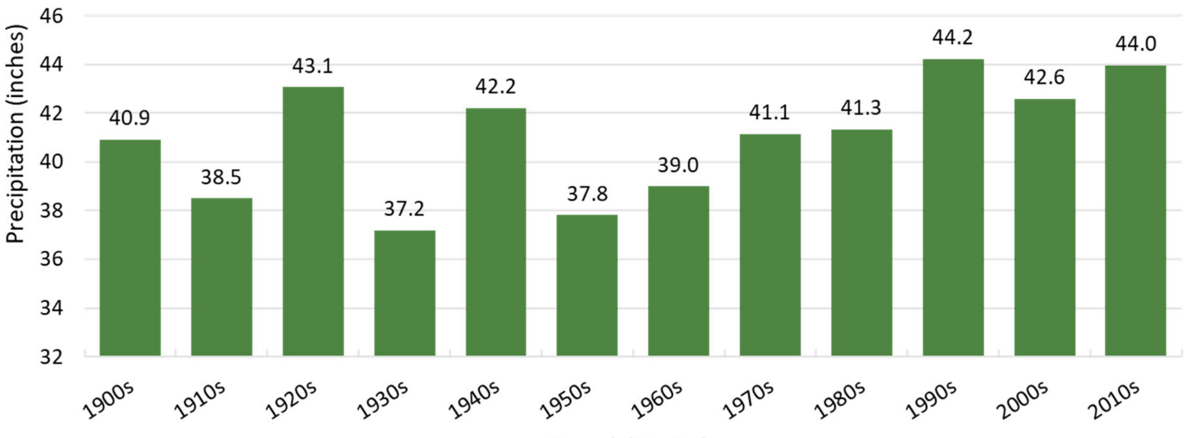
*Exhibit 1. Missouri Average Annual Precipitation.*



Source: NOAA/Missouri Climate Center

The average annual precipitation in Missouri by decade also shows a fairly consistent rise in precipitation since the 1950s.

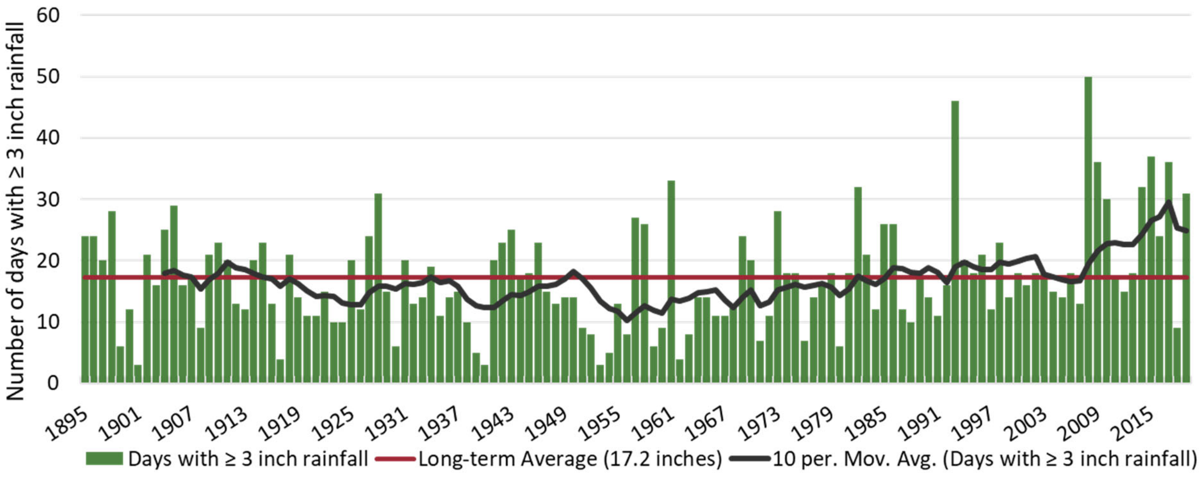
*Exhibit 2. Missouri Average Annual Precipitation by Decade.*



Source: NOAA/Missouri Climate Center

The annual number of extreme rainfall events (defined as >3 inches per day) in Missouri has been trending up since the 1950s. The historical average is 17.2 extreme rainfall events per year but during the last 20 years has averaged 23.3 per year. Extreme rainfall events create runoff from fields that negatively impact soil and water quality and may hinder subsoil moisture supply regeneration.

*Exhibit 3. Number of days with ≥ 3-inch rainfall in Missouri.*

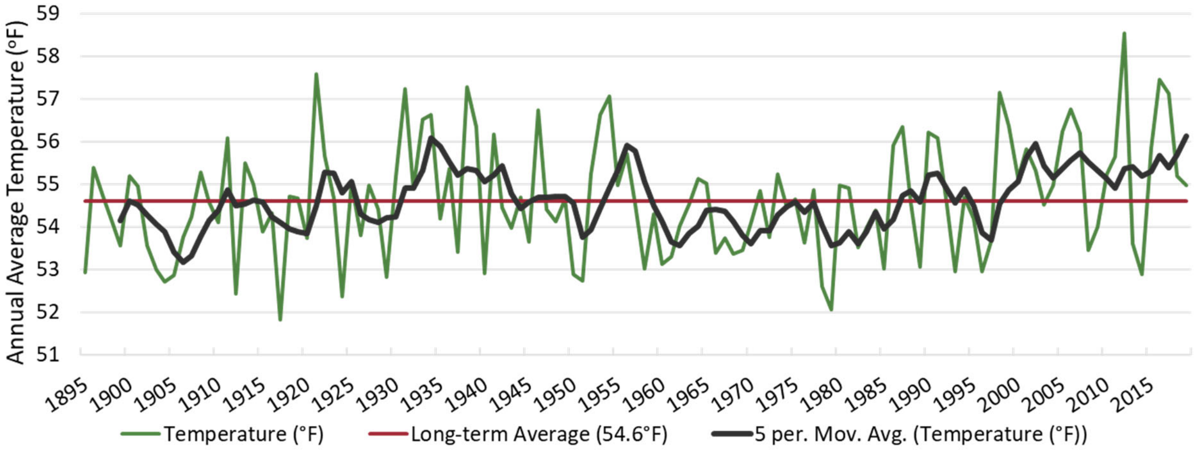


Source: NOAA/Missouri Climate Center

## Temperatures changes

The five-year moving average annual temperature in Missouri has been above the long-term average (1895 to 2019) of 54.6°F for 22 of the last 25 years. Missouri's most recent warm annual temperature trend began in the late 1990's. Since 1998, 17 out of the past 22 years (77%) have been above normal. The average 2012 temperature of 58.5°F was the warmest year on record.

*Exhibit 4. Missouri Average Annual Temperature.*

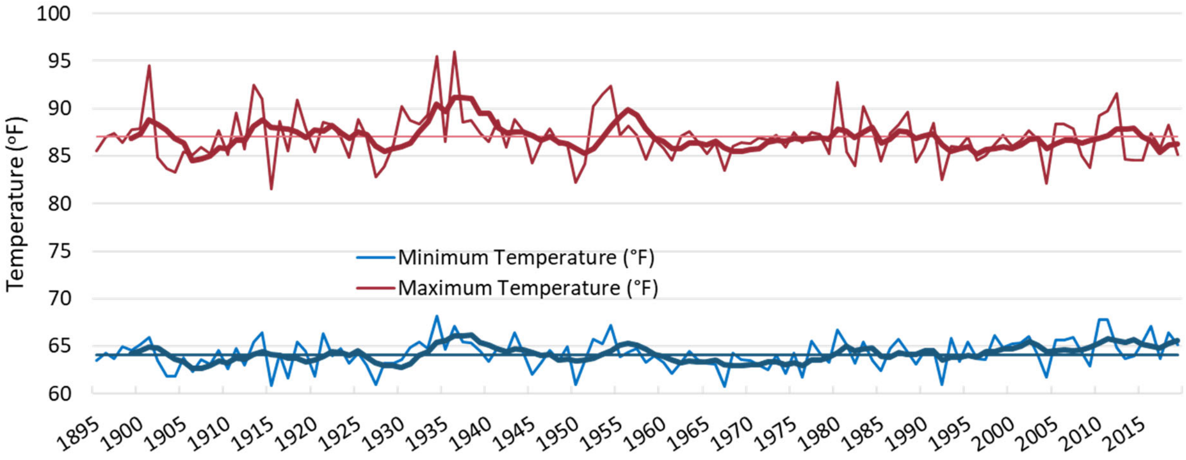


Source: NOAA/Missouri Climate Center

Seasonally, Missouri winters and springs have experienced the greatest warming trend. Twenty-one of the past 31 winters (68%) and 17 out of the past 22 springs (77%) have been above long-term average temperature. Some may dismiss the rise in temperature over the last several decades because the number of days with temperatures above 90°F has trended downward since the 1930s. A rise in temperature is not simply a year-round increase in daily high temperatures but is observed mostly as a rise in night time low temperatures during the months of June, July and August. The five-year moving average minimum (nighttime) temperatures during June/July/August have been above the long-term average for most of the last 30 years. The five-year moving average maximum (daytime) temperatures during June/July/August have been below the long-term average for most of the last 30 years.

Warmer nighttime temperatures have implications for agriculture because during the summer both growing crops and livestock rest from the daytime heat. Increased nighttime respiration stresses both plants and animals, making them less productive.

*Exhibit 5. Missouri average minimum and maximum temperature (°F) during June/July/August.*



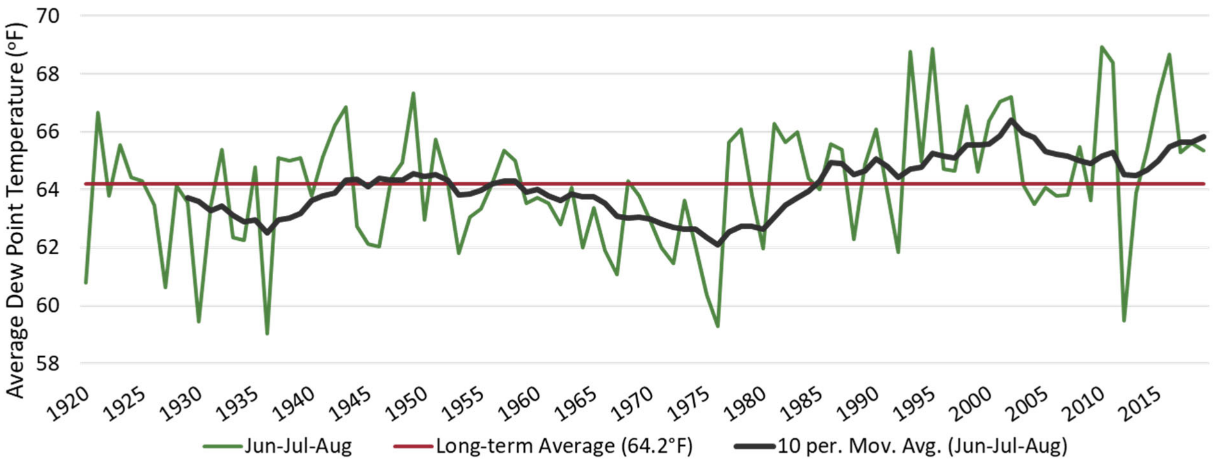
Source: NOAA/Missouri Climate Center

The median day of the last spring frost during the last 20 years is about 6 days earlier than its long-term median; the first fall frost is about 5 days later than its long-term median. Together this makes the growing season 11 days longer than historically experienced. While a longer growing season can be favorable, it also allows weeds to germinate earlier and migrate from lower latitudes into Missouri.

## Humidity/Dew Point

The 10-year moving average for dew point temperatures in Missouri has been higher than the long-term average for the last 30 years. Higher dew points are important to agriculture because they favor insects and pathogens that attack growing plants and stored grain.

*Exhibit 6. Average dew point temperature (°F) for Columbia, Missouri, during June/July/August.*



Source: NOAA/Missouri Climate Center

## GHG Emissions

Much of the discussion of GHG emissions references carbon dioxide ($CO_2$). However, $CO_2$ is not the only GHG. Agriculture is not a significant emitter of $CO_2$ but does emit other important GHGs, particularly methane ($CH_4$) and nitrous oxide ($N_2O$). When discussing the opportunity to sequester or reduce GHG emissions, $CO_2$, $CH_4$ and $N_2O$ are all important GHGs to consider.

But for measurement purposes, a carbon dioxide equivalent ($CO_2e$) puts all GHG gases into a common unit. One ton of $CO_2$ in the atmosphere equals one ton of $CO_2e$. One ton of $CH_4$ equals 23 tons $CO_2e$. One ton of $N_2O$ equals 298 tons $CO_2e$.

Two critical metrics for discussing the impact of agriculture on GHG emissions are total emissions and yield-scaled emissions.

Total emissions are reported by the U.S. Environmental Protection Agency (EPA) and are of the most importance to climate scientists researching and forecasting climate change. The total concentration of GHGs in the environment is considered a major driver of climate change. Total emissions from agriculture have increased over the last 30 years.

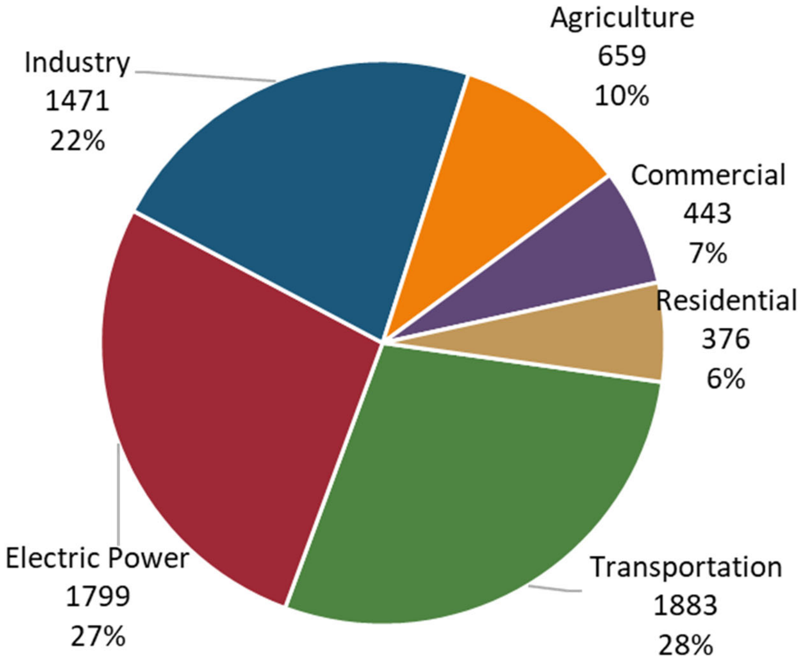
A second metric is yield-scaled emissions. Yield-scaled emissions convert the total emissions into emissions per unit of output (e.g. tons nitrous oxide per ton of corn). A growing population requires sustainable agricultural production that fosters human health and flourishing. Yield-scaled emissions take into account production efficiency – quantifying the efforts of the agricultural sector to meet the demands of the world while minimizing contributions to total GHG concentrations. Yield-scaled emissions have decreased over the last 30 years.

## U.S. Agriculture

The U.S. Environmental Protection Agency (EPA) annually publishes the *Inventory of GHG Emissions and Sinks* for the U.S. The entire U.S. economy is estimated to emit 5,424.9 million metric tons[1] carbon dioxide equivalents (tons $CO_2e$) in 2018.

While many sectors of the economy are required to report their actual, measured GHG emissions to the EPA, most agricultural businesses do not. The EPA uses models to estimate agricultural emissions. Agriculture is estimated to have emitted 659 million tons of $CO_2e$, or 10% of total U.S. GHG emissions in 2018.

*Exhibit 7. 2018 Total U.S. GHG emissions by sector (million metric tons $CO_2e$).*



Source: U.S. EPA Inventory of GHG Emissions

From 1990 to 2018, agricultural emissions have increased 11%, from 554.4 to 618.5 million metric tons $CO_2e$. Emissions from crop production have increased 6.1%; and from livestock, 20.2%. Emissions from fuel use in agriculture have decreased 10.5%. The EPA notes that methodological changes in how emissions are estimated increased the emissions estimate by 60 million metric tons $CO_2e$ in 2017, or approximately 10% (EPA, 2020).

From a climate change perspective, total emissions are the critical metric and U.S. emissions have increased over time. The increased emissions from agriculture are one factor in their being named as key categories for improvement by the EPA.

Given that sufficient food and fiber are necessary for an increasing world population, yield-scaled emissions are important. The emissions per unit of agricultural output have been decreasing. USDA reports that total agricultural output increased by 31% from 1990 to 2017. GHG emissions per unit of total agricultural production have decreased 15% over the past 30 years. Increases in emissions have been the result of increased production of crops and livestock. The decrease in GHG emissions per unit of output have been the result of increased efficiencies.

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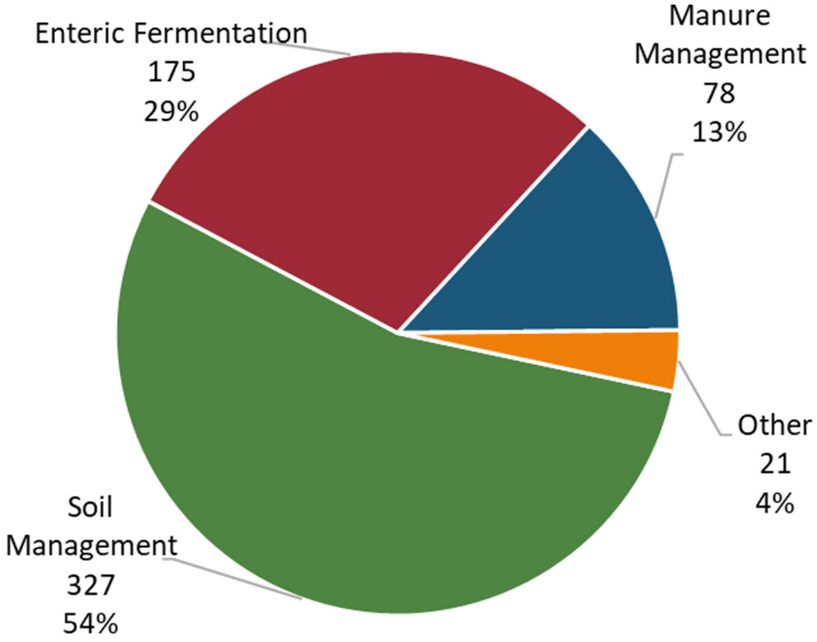
[1] Metric tons are used when measuring quantity of GHG emissions. In this report, when referencing GHG emissions, the term "ton" should be understood to be a metric ton, or 1000 kg. All other quantities are expressed in English units.

Within the agricultural sector, approximately one-half of GHG emissions are from soil management and one-half from livestock production. This report focuses primarily on the GHG emissions and mitigation potential from soil management.

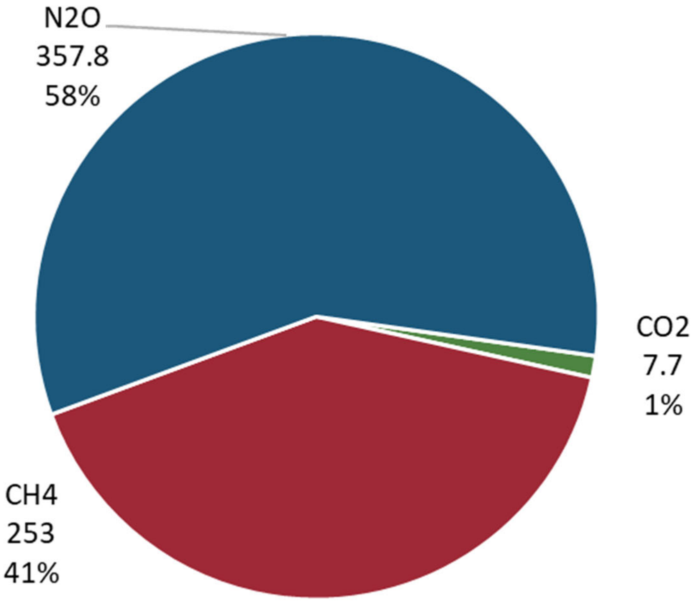
*Exhibit 8.2018 U.S agricultural GHG emissions by source (million metric tons $CO_2$e).*



Source: U.S. EPA Inventory of GHG Emissions

Agriculture emits three types of GHGs involved in climate change: carbon dioxide ($CO_2$), nitrous oxide ($N_2O$) and methane ($CH_4$). Soil management is responsible for most of the $N_2O$ emissions. Manure management also emits some $N_2O$. Enteric fermentation and manure management are responsible for most of the $CH_4$emissions. Rice production is also a source of $CH_4$ emissions. Fuel combustion, emitting $CO_2$ is a relatively minor source of GHG associated with agriculture.

*Exhibit 9. 2018 U.S. agricultural GHG emissions by type.*



Source: U.S. EPA Inventory of GHG Emissions

The prevalence of $N_2O$ and $CH_4$ emissions from agriculture indicates that crop cultivation and livestock production offer the greatest opportunity for efficiencies to reduce emissions. The EPA estimates that both agricultural $CO_2$ and $CH_4$ emissions increased 16% from 1990 to 2018; agricultural $N_2O$ emissions increased 8.4% from 1990 to 2018. Almost all $N_2O$ emissions are from crop/soil management. The total emissions and the upward trend of emissions of each gas is important to the climate scientists. However, rom a yield-scaled impact, the 8.4% increase in $N_2O$ emissions was accompanied by an estimated 31% increase in crop productivity. $N_2O$ emissions have decreased 17% per unit of crop produced.

The importance of yield-scaled emissions is demonstrated by Burney et al. (2010). They estimate $CO_2e$ releases due to agriculture from 1965 to 2005 under different scenarios and conclude that without yield increases "additional 1111 Mha [2745 million acres] of cropland would have been needed to maintain per capita production at 1961 levels." They further estimate that yield gains in agriculture from 1961 to 2005 have reduced *net* GHG emissions by 161 billion metric tons of carbon – corresponding to 34% of the total GHG emissions attributable to human activity between 1850 and 2005.

## Missouri Agriculture

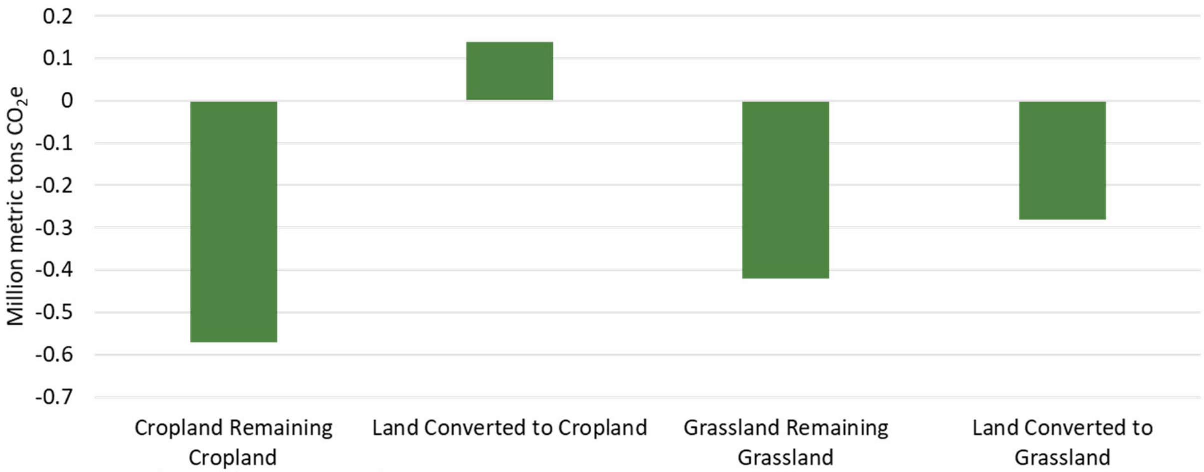
The EPA does not estimate GHG emissions by state, except for special situations.

The USDA (2016) publication *U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2013* provides estimates of GHG emissions for livestock and rice production in Missouri but not for crop production. They estimate that $CH_4$ emissions by enteric fermentation in Missouri was 5.64 million metric tons $CO_2e$ in 2013, almost exclusively from beef cattle. They estimated total GHG emissions from managed waste to be 1.33 million metric tons $CO_2e$ in 2013 with 72% coming from swine production and 14% coming from dairy cattle. The forested area of Missouri in 2013 (15,451,500 acres) was estimated to contain 1,645 million metric tons $CO_2e$ in non-soil stock (mostly aboveground biomass with some belowground biomass and dead wood) and 1,116 million metric tons $CO_2e$ in soil organic carbon stock.

The concept of land use and land use change (LULUC) is also of particular interest to agriculture. Life Cycle Analysis research on the impact of agricultural products (especially meats and biofuels) looks not just at the GHG emissions of the producers of the commodity used in those products. They frequently include the concept of LULUC to include indirect effects such as deforestation in the U.S., or even other countries, deemed necessary to accommodate changes in agricultural production.

Overall Missouri Land Use and Land Use Changes in 2013 was estimated to have sequestered 1.13 million metric tons $CO_2e$ (USDA, 2016). Only land converted to cropland was considered a net emitter of

*Exhibit 10. Missouri GHG flux due to land use and land use changes in 2013.*



Source: U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2013

GHG. All other Missouri land uses, including cropland remaining cropland, and land use changes were estimated to have sequestered, or captured, GHG.

# Forecasted Impact of Climate Change

## U.S. Corn Belt agriculture

Climate scientists forecast temperature and precipitation changes for the Midwest U.S. as atmospheric $CO_2$ concentrations increase. Various chapters of the *Fourth National Climate Assessment* contain references to the impact of climate change on agricultural production. In the chapter on *Agriculture and Rural Communities*, Gowda et al. (2018) state that "food and forage production will decline…and expand the distribution and incidence of pests and diseases for crop and livestock." The chapter on the *Midwest* states that "Projected changes in precipitation, coupled with rising extreme temperatures before mid-century, will reduce Midwest agricultural productivity to levels of the 1980s without major technological advances (Angel et al., 2018)."

The caveat of "without major technological advances" is critical to understanding the literature on climate change impacts. The most often quoted estimate of climate change, called the Representative Concentration Pathway 8.5 (RCP8.5) assumes that emissions will continue at their current pace and no technological changes in agricultural production efficiency occur. The historical record shows that the quantity of GHGs in the environment continues to increase – but at a slower rate – and agricultural production efficiency is continually reducing the yield-scaled impact of production on GHG emissions.

Gordon et al. (2015) using RCP8.5 conclude that the increasing temperature will make the largest impact on Midwest agriculture. This emphasis on future temperature differs from the historical impact of April to June precipitation changes which are considered to be the most impactful historical climate feature on Midwest crop production (Angel et al., 2018). Gordon et al. (2015) estimate that rising temperatures in the Midwest will be from warmer winters rather than hotter summers. By the year 2100 they forecast the Midwest will experience 22 to 77 days per year with temperatures over 95°F – compared to 3 days with temperatures over 95°F for the last 30 years. The result in agricultural production is that beginning in 2020 and continuing to 2059 southern states such as Missouri will have reduced corn and soybean yields while northern states such as Minnesota will have increased yields. By the year 2100, even Minnesota will experience decreased crop yields. Midwest wheat yields are forecasted to increase.

The impact of temperature on yield is not the only climate change impact expected on crop production. Another expected result of climate change with production and economic impacts is increased crop/weed interaction due to rising atmospheric $CO_2$ concentration.

Scientists often group plants by the way they utilize $CO_2$ for photosynthesis. The two groups most often discussed are $C_3$ and $C_4$ plants. Soybeans, rice, wheat and fescue are important $C_3$ crops. Corn and sorghum are important $C_4$ crops. Generally, $C_3$ crops such as soybeans and wheat use $CO_2$ more efficiently and may have increased yields in an environment with elevated levels of $CO_2$.

Waterhemp, giant ragweed, and marestail are important $C_3$ weeds. Palmer amaranth, Johnson grass, barnyard grass, and giant foxtail are important $C_4$ weeds.

Crops and weeds alike will respond to the environmental conditions brought on by climate change. Exhibit 11 lists crop and weed responses to several high $CO_2$ levels, increased temperatures, and prolonged drought – all associated with climate change.

*Exhibit 11. Response of crops and weeds under elevated $CO_2$, increased temperature and prolonged drought periods.*

| | Plant Response | Result | $CO_2$ | Temperature | Drought |
|---|---|---|---|---|---|
| **Crop Plants** | Root Mass | Root/Shoot Ratio | + | | |
| | Leaf Area | Inception of PAR[1] | + | | |
| | Leaf Development | Leaf Area | | - | |
| | Flowering | Vegetative Stage | | - | |
| | Harvesting | Yield | | - | - |
| | Fruit Production | Yield | | - | |
| | Vernalization | Vegetative Stage | | - | |
| | Stomata Conductance | Rate of Photosynthesis | | - | - |
| | Stomata Closure | Water Use Efficiency | | + | + |
| | $CO_2/O_2$ | Rate of Photosynthesis | | | - |
| | Respiration Rate | Biomass Production | | + | |
| | Seed Formation Period | Yield | | - | |
| | Biomass Production | Yield | + | - | - |
| | Node Number | Biomass, Height | | | - |
| **Weeds** | Stomata Closure | Water Use Efficiency | + | | |
| | Maturity Rate | Vegetative Stage | + | | |
| | Root Biomass | Root/Shoot Ratio | + | | |
| | Distribution | | | + | |
| | Vernalization | Vegetative Stage | | - | |
| | Biomass | | | + | |
| | Seed Germination | Distribution | | + | |
| | Rhizomes | Distribution | | + | |
| | Seed Longevity | | | | + |

+ and - signs indicate positive and negative effects, respectively

[1] PAR = photosynthetically active radiation

Source: Korres, et al. (2016), Table 8

Climate change is also expected to change weed ecology in several ways. Increasing temperatures are likely to expand the geographic range of southern weeds, while limiting the range of northern weeds (ex. Canada thistle, proso millet) (Korres et al., 2016 cited Ziska and Runion, 2007). Midsouth weeds that are associated with greater corn and soybean yield loss are expected to spread into the Midwest (Korres et al., 2016; Walthal et al., 2012). Weeds that respond to higher $CO_2$ levels with increased biomass are expected to increase reproductive output (Korres et al., 2016; Korres and Froud-Williams, 2002) and become more abundant. Increased $CO_2$ results in increased leaf thickness, reduced stomatal number and conductance, reduced transpiration and herbicide uptake of soil-applied herbicides, decreased window of susceptibility with shortened seedling stage length, and in the case of perennial weeds stimulated rhizome and tuber growth. All of these have important implications for weed/crop interactions and herbicide efficacy (Ziska et al., 1999). Herbicide use and expenses are forecasted to rise along with temperatures and $CO_2$ levels (Karl et al., 2009; Korres, et al., 2016).

It has been demonstrated that for several combinations of $C_3$ and $C_4$ crops and weeds, $C_3$ crops tend to outcompete $C_4$ weeds under high $CO_2$ conditions. Weeds tend to outcompete crops in all other combinations ($C_3$ weeds vs $C_3$ crops, $C_3$ weeds vs $C_4$ crops, $C_4$ weeds vs $C_4$ crops) (Korres et al., 2016). Increased $CO_2$ levels increase photosynthesis, with the response much stronger in $C_3$ than $C_4$ plants (Ainsworth and Long, 2005; Ziska et al., 1999,). However, increased temperatures could favor C4 plants (Duke and Mooney, 1999; Korres et al., 2016). Ziska et al. (1999) found that elevated $CO_2$ levels resulted in increased photosynthesis, increased growth, increased height, and reduced stomatal conductance in a $C_3$ weed (lambs quarters), while there was no effect seen in a $C_4$ weed (redroot pigweed).

*Exhibit 12. Response of crops and weeds grown under competition under high $CO_2$ concentrations.*

| **Weed and Crop classification** | **Species** | **High $CO_2$ Favors** | **Research Environment** |
|---|---|---|---|
| **$C_4$ weed vs. $C_3$ Crops** | | | |
| | *Sorghum halepense* vs.*Festica pratensis* | Crop | Greenhouse |
| | *Sorghum halepense* vs. Glycine max | Crop | Growth Chamber |
| | *Amaranthus retroflexus* vs. *Glycine max* | Crop | Field |
| | *Echinochloa glabrescens* vs. *Oryza sativa* | Crop | Greenhouse |
| | *Paspalum dilatatum vs. various grasses* | Crop | Growth Chamber |
| | Various grasses vs. *Medicago sativa* | Crop | Field |
| **$C_3$ weeds vs. $C_3$ crops** | | | |
| | *Chenopodium album* vs. *Beta vulgaris* | Crop | Growth Chamber |
| | *Taraxacum officinale* vs. *Medicago sativa* | Weed | Field |
| | *Plantago lanceolata vs. pasture* | Weed | Growth Chamber |
| | *Taraxacum and plantago vs. pasture* | Weed | Field |
| | *Cirisum arvensis* vs. *Glycine max* | Weed | Field |
| | *Chenopodium album* vs. *Glycine max* | Weed | Field |
| **$C_4$ weed vs. $C_4$ crop** | | | |
| | *Amaranthus retroflexus* vs. *Sorghum bicolor* | Weed | Field |
| **$C_3$ weeds vs. $C_4$ crops** | | | |
| | *Xanthium strumarium* vs. *Sorghum Bicolor* | Weed | Greenhouse |
| | *Abutilon theophrasti* vs. *Sorghum bicolor* | Weed | Field |

Source: Korres, et al. (2016), Table 5

Ramesh et al. (2017) expect rising temperatures and increasing drought periods to favor $C_4$ plants over $C_3$ plants. They hypothesized that commercial rates of glyphosate may be ineffective to control lambs quarters, and by extension other $C_3$ weeds that respond similarly, under increased $CO_2$ levels. Korres et al. (2016) report glyphosate efficacy changes of additional $C_3$ and $C_4$ weeds under higher $CO_2$ levels. In general, $C_3$ plants develop glyphosate tolerance more consistently, whereas $C_4$ plants response is more variable (Fernando et al. 2016).

*Exhibit 13. Effects of increased $CO_2$ concentration on glyphosate efficiency for various weeds.*

| Common name | Latin name | P/S pathway | Efficacy change |
|---|---|---|---|
| **Canada thistle** | *Cirsium arvense* (L.) Scop | C3 | Reduced |
| **Dallisgrass** | *Paspalum dilatatum* Pior. | C4 | Reduced |
| **Lambsquarters** | *Chenopodium album* L. | C3 | Reduced |
| **Lovegrass** | *Eragrostis curvula* (Schrad.) Nees | C4 | Reduced |
| **Quackgrass** | *Elytrigia repens* (L.) Gould | C3 | Reduced |
| **Redroot pigweed** | *Amaranthus retroflexus* L. | C4 | None |
| **Rhodes grass** | *Chloris gayana* Kunth | C4 | Reduced |
| **Smut grass** | *Sporobolus indicus* (L.) R. Br. | C4 | None |

Source: Korres et al. (2016), Table 7.

## Missouri

Several studies forecast the likely impacts of climate change on crop production. Gordon et al. (2015) using RCP8.5 and assuming no technological changes, forecast that Missouri will be the hardest hit of Midwestern states. They forecast Missouri to experience 46 to 115 days above 95°F by 2100.

Exhibit 14 below summarizes the “most likely” forecasts of Gordon et al. (2015) for Missouri crop yields. They also forecast the 1 in 20 probability (most dire) crop yields in their paper but the authors have chosen to not discuss them in this paper. Wheat yields are forecasted to increase over the remainder of the century. Soybean yields could possibly increase through 2059 but afterwards are forecast to certainly decrease – as much as 75%. Corn yields are expected to decrease almost the entire period after 2020, with production almost sure to cease by the middle of the century. In the absence of technological advances, Missouri will become a wheat state.

*Exhibit 14. Forecasted Missouri crop yield changes due to climate change.*

| | Percent change in yields likely to occur in Missouri | | | |
|---|---|---|---|---|
| **Time Frame** | **All Crops** | **Corn** | **Soybeans** | **Wheat** |
| **2020 to 2039** | +8.1 to -13.5 | +4.7 to -24.4 | +9.9 to -12.7 | +6.5 to +1.5 |
| **2040 to 2059** | +3.7 to -31.9 | -9.4 to -49.1 | +7.3 to -30.4 | +15.2 to +4.9 |
| **2080 to 2099** | -5.7 to -72.8 | -37.4 to -90.0 | -0.3 to -75.8 | +44.6 to +15.8 |

Source: Gordon et al. (2015)

Eric Oseland, MU Weed science PhD candidate, says a common $C_3$ weed of concern in Missouri would be ragweed which needs to be sprayed when small. If it grows faster because of increased $CO_2$ levels, it would shorten the window for effective herbicide application and reduce crop yields. However, he sees herbicide resistance rather than increased weed competition as a greater threat to weed control in row crop production. As $CO_2$ levels rise in the environment, current research is conducted in the higher $CO_2$ environment. In other words, research takes into account incremental increases in $CO_2$ levels and new weed control practices take into account those changes.

## Questioning the Business as Usual Scenarios

Olmstead and Rhode (2008) in their book *Creating Abundance: Biological Innovation and American Agricultural Development* document the movement of crop producing regions in the U.S. Their analysis of the data provides interesting principles for how crops may respond to temperature and rainfall changes due to climate change. First, they document that wheat and corn varieties grown in the early

1900s were dramatically different from varieties grown in the early 1800s. At one point, they state "the efficiency of the transformation process is always being shocked by evolving environmental forces…."

Of most importance to the Midwest U.S. agriculture is their analysis of wheat and corn production from the 1800s to the mid-1900s. The conclusion of the wheat chapter summarizes that in the 1800's the most informed individual on wheat production in the U.S. concluded that "the commercial wheat belt would be forever limited to Ohio, Pennsylvania and western New York." People did not envision the new wheat varieties that would make the high plains states of Kansas to North Dakota the major wheat production region. Interestingly, these wheat varieties were developed by producers experimenting over time, not by companies doing genetic manipulation.

In their chapter on corn, a hybrid crop managed very differently than wheat, they documented the same migration of growing region due to biological innovation. Their table 13.4, reproduced in part below, illustrates how over a 70-year period corn and wheat production moved into very different climate conditions due to biological innovation. Corn and wheat production both moved to drier, warmer regions.

*Exhibit 15. Changing geographic distribution of corn and wheat production in the U.S.*

| **Climate Indicator** | | | **Corn** | | **Wheat** | |
|---|---|---|---|---|---|---|
| | | **Percentile** | **Year 1840** | **Year 1910** | **Year 1840** | **Year 1910** |
| **Annual Precipitation (inches)** | Driest | 10 | 36.9 | 26.5 | 33.2 | 16.6 |
| | | 25 | 39.6 | 31.9 | 36.0 | 19.3 |
| | Median | 50 | 43.9 | 36.2 | 39.0 | 26.2 |
| | | 75 | 49.4 | 40.7 | 42.5 | 36.4 |
| | Wettest | 90 | 53.3 | 47.4 | 47.0 | 40.9 |
| **Annual Temperature (°F)** | Coldest | 10 | 50.9 | 47.2 | 47.8 | 40.1 |
| | | 25 | 53.3 | 49.7 | 49.7 | 43.6 |
| | Median | 50 | 56.3 | 52.5 | 52.6 | 50.4 |
| | | 75 | 60.0 | 56.4 | 55.3 | 54.1 |
| | Warmest | 90 | 63.3 | 61.6 | 58.7 | 56.7 |

Source: Adapted from Olmstead and Rhode (2008).

For example, the first row indicates that the 10% of corn grown in the driest region received 10.4 inches less precipitation from 1840 to 1910; 16.6 inches less rain fell in the region growing the driest 10% of wheat production. The median, a more likely indicator of impact, shows that the average corn production region received 7.7 fewer inches of rain over the 60-year period. The changes shown in this table were fostered by genetic and managerial changes allowing movement of corn and wheat production into new regions rather than the result of climate change.

From an economic perspective Olmstead and Rhode note that different crops moved into different regions based on economic factors. Wheat moved from the east to the west because it became cheaper to grow wheat in the west, freeing up land in the east for other crops. Corn moved further north and the south increased acreages of cotton, a more profitable crop.

A second perspective of the impact of "business as usual" climate change forecasts can be obtained from *The Wizard and the Prophet: Two Remarkable Scientists and Their Dueling Visions to Shape Tomorrow's World* by Charles Mann (2018). The book covers the philosophies and works of William Vogt and Norman Borlaug.

William Vogt had a Malthusian outlook and considered the world to be near it's carrying capacity in the mid-1900s. He forecast famine due to the inability to produce enough food for the world's growing population. Not seeing the ability to simultaneously preserve the environment and produce food, he emphasized population control as the solution to the problem.

Norman Borlaug lived at the same time as Vogt but focused on increasing agricultural production, emphasizing agricultural research in breeding and pest management. Under programs he introduced, Pakistan and India nearly doubled their wheat yields between 1965 and 1970.

Borlaug's perspective has proven effective for over 50 years while Vogt's prediction has not materialized 70 years after he forecasted it. The return to agricultural research has been instrumental in feeding a growing population while preserving the environment.

The importance here is the focus on "business as usual" or "agricultural research" allowing food and feed crops to be grown under many conditions. Vogt assumed business as usual and foresaw famine. Borlaug used technology to solve problems, resulting in increased production and overcoming famine.

Zhang et al. (2011) studying North China Plain corn and wheat production showed that evapotranspiration increases (presumably due to improved cultivars) resulted in increased yields and water use efficiency increased over time. This paper is illustrative of the ability of agriculture to adopt to slow changing conditions.

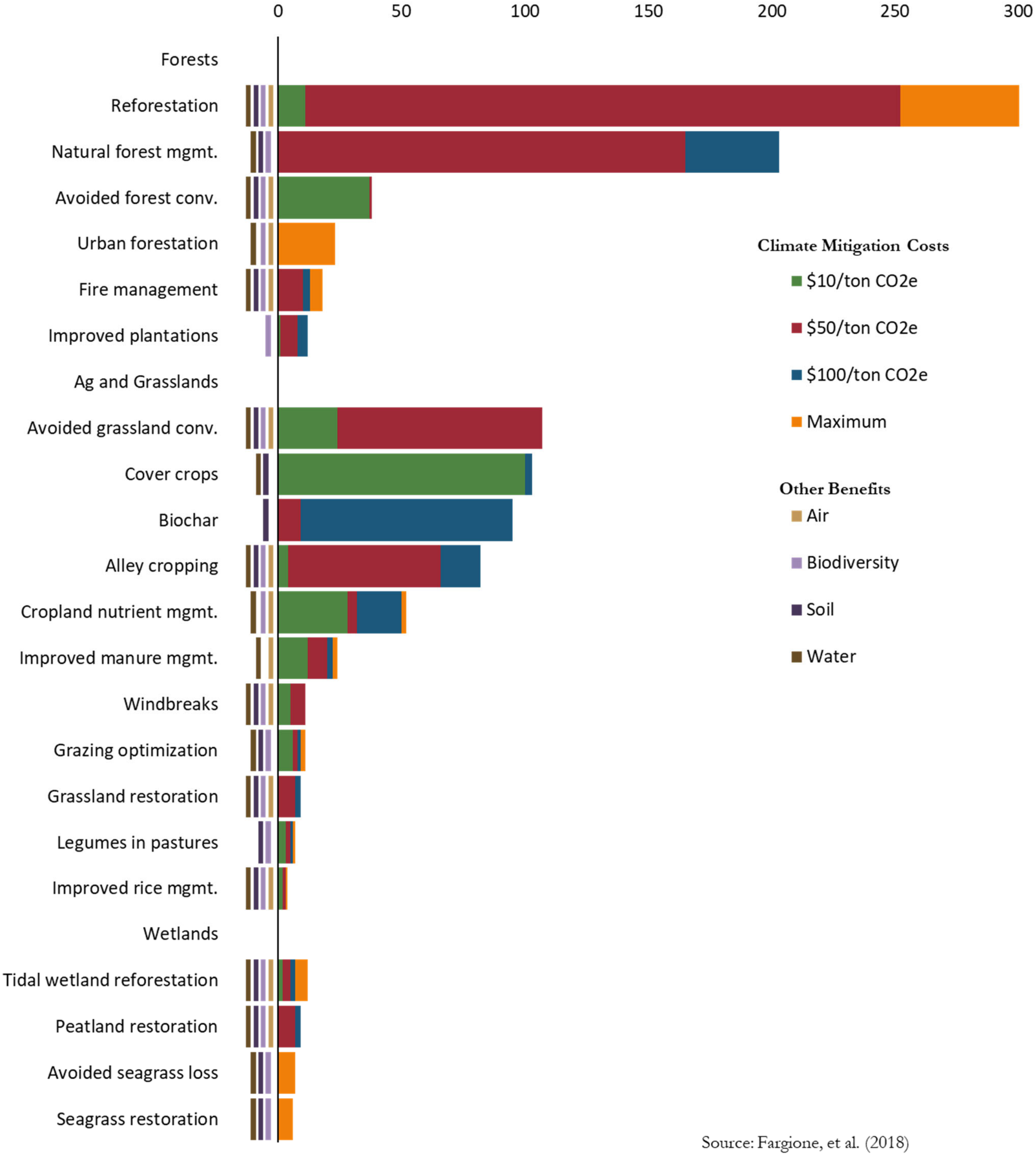
## GHG Mitigation Potential in Agriculture: Literature Review and Application

Agriculture producers facing climate change have the opportunity to mitigate GHG emissions and possibly benefit from carbon sequestration/capture technologies. Exhibit 16 (created from Fargione et al., 2018) indicates the potential for carbon conservation and uptake in the United States. They estimate that U.S. land management has the potential to capture 1.2 billion tons of $CO_2e$/year, equal to 21% of annual net GHG emissions in the U.S. The largest opportunities are in forest management, followed by agriculture and grassland management followed by wetland management.

Exhibit 16 quantifies the mitigation potential for various activities and estimates how much of that activity would be met by farmers if they received \$10/ton $CO_2e$/year, \$50/ton $CO_2e$/year and \$100/ton $CO_2e$/year. In the agriculture and grassland management section, a large percent of the mitigation potential of cover crops, nutrient and manure management could be met at the \$10/ton $CO_2e$/year. At \$50/ton $CO_2e$/year, more nutrient management practices and cropping changes are likely to be adopted.

Another feature of this graph by Fargione et al. (2018) is that it notes that the practices which reduce GHG emissions also have other ecosystem benefits. These benefits are noted as colored bars on the left side of the y axis. Frequently, these other benefits are the driver of the government and private programs that foster these practices. By compensating landowners for GHG reductions, these programs are likely to be more desirable to land managers.

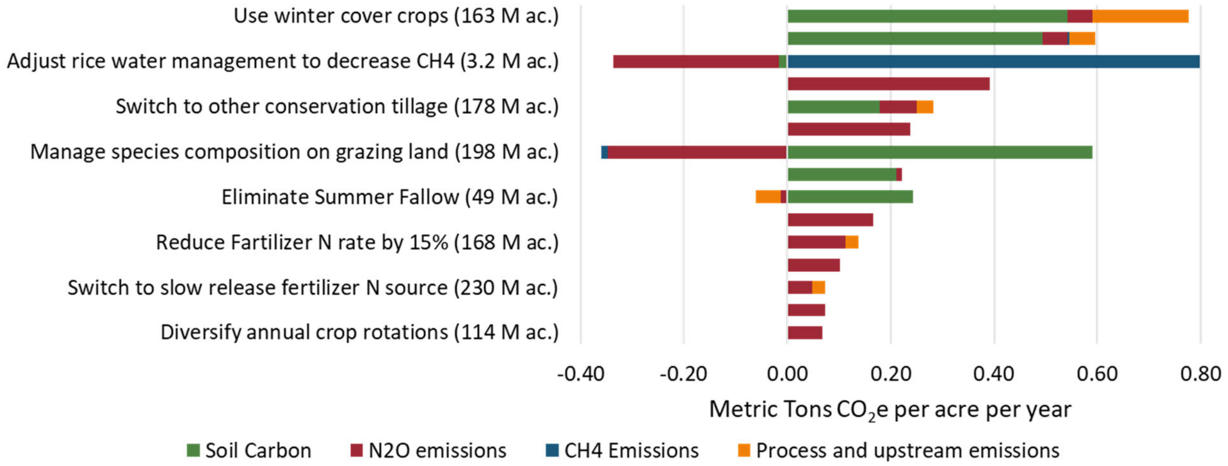
*Exhibit 16. Climate mitigation potential in 2025 (Tg $CO_2e$/year).*



Source: Fargione, et al. (2018)

Eagle et al. (2012) in a synthesis of literature, provide estimates of the ability of agricultural land management to mitigate GHG in the environment. Their summary graph (Exhibit 17) orders their estimates of GHG sequestration potential *per acre*, the number of acres that could be involved and reports the GHGs that could be reduced. Those management activities that sequester soil carbon deal predominately with cropping and tillage decisions. Those that improve $N_2O$ emissions deal mostly with improved nitrogen fertilizer management. Rice water management could reduce $CH_4$ emissions. Process and upstream emissions are emissions resulting from the production of inputs (especially fertilizer and fuel) and their use.

*Exhibit 17. Impact of various sequestration activities.*



Source: Fargione, et al. (2018)

The greatest potential for storing carbon and reducing $N_2O$ emissions in soils comes from planting winter cover crops. The second greatest potential is by switching from conventional tillage to no-till. Various changes in rice production and nitrogen fertilizer management can also reduce GHG emissions. Activities that yield high GHG emission reductions but are used infrequently include (not shown in the graph below) switching to short-rotation woody crops, restoring wetlands, planting herbaceous buffers, converting cropland to pasture, and replacing annual with perennial crops.

Fargione et al. (2018) label their work on climate mitigation by agriculture as Natural Climate Solutions. Several other terms are being used to describe efforts to encourage farmers to mitigate climate change. The World Bank (2020) defines Climate Smart Agriculture as “an integrated approach to managing landscapes” that achieves three outcomes: 1) increase productivity, 2) enhance resilience and 3) reduce GHG emissions.

The U.S. Farmers and Ranchers Alliance provides an aspirational picture of Climate Smart Agriculture. They contend that the technology currently available in agriculture has the capacity to reduce agricultural GHG emissions by 50%. With additional innovation and investment, agriculture can become a net negative emitter of GHG, or actually capture more than they emit.

The USDA has the Building Blocks for Climate-Smart Agriculture and Forestry Initiative. Baranski et al. (2018) details the extent to which practices that reduce GHG emissions have been used in the U.S. and their potential for future mitigation. They document that production has become more efficient, but acres harvested have also increased. Total environmental impact has increased while environmental impact per unit of production has decreased.

In addition to Climate Smart Agriculture, the French Four Per Thousand Initiative (4PT) promotes the goal of increasing carbon stock an average of 0.4% annually on most of the world’s managed soils (Chambers, Lal and Paustian, 2016). U.S. researchers have suggested several modifications to the French proposal that would make it more likely to succeed in the US. In short, some are taking seriously the aspirational goal of agriculture playing a significant role in *reducing* GHG concentrations in the atmosphere.

The Technical Working Group on Agricultural Greenhouse Gases (T-AGG, 2020) reports GHG reductions from adopting various farming activities. They suggest that no-till has the most potential to capture GHGs but suggest more novel ideas such as setting aside cropland and diversifying crop rotations.

McNunn et al. (2020) provides a more robust estimate of GHG fluxes from different management practices on corn and soybean production at the field level in 11 states (including Missouri). Their generalized accounting approach improves estimates of GHG inventories for different U.S. regions and has application to estimating GHG emissions associated with various agricultural supply chains. They conclude that the adoption of no-till likely provides the highest reduction in GHG emissions of any single activity. Cover crops and improved nitrogen fertilizer management also offer significant GHG benefits. Combining several activities increases emissions reductions but is not additive.

The EPA inventory of GHG emissions (2020, table 5-18) lists specific sources (and therefore management practices) of $N_2O$ emissions. Activities which affect the release of $N_2O$ from agricultural soils in Missouri include: synthetic N fertilization, livestock manure (labeled Organic Amendment), retention of crop residues, irrigation, tillage practices, and cover crops. On cropland, synthetic fertilizer and mineralization and asymbiotic fixation are the activities responsible for the largest amount of $N_2O$ emissions. Corn and wheat production, with their reliance on N fertilization, are the crops most involved in emissions from synthetic fertilization. Soybean and alfalfa, as N fixing legumes, are the crops most involved in emissions from asymbiotic fixation.

Not all researchers and environmentalists consider agricultural efforts at GHG reductions reasonable and sustainable. Amundson and Biardeau (2018) question the potential to use carbon sequestration to mitigate climate change on the grounds that warming sets in motion a positive feedback loop with soil carbon. As soils warm, microbes in the soil release more carbon from the soil so that sequestration is hampered. They also note a large gap between the maximum physical potential and the maximum sequestration achievable in a complex society. The maximum biophysical potential is reduced by economic factors, political considerations and social concerns so that stating the maximum potential is of little use.

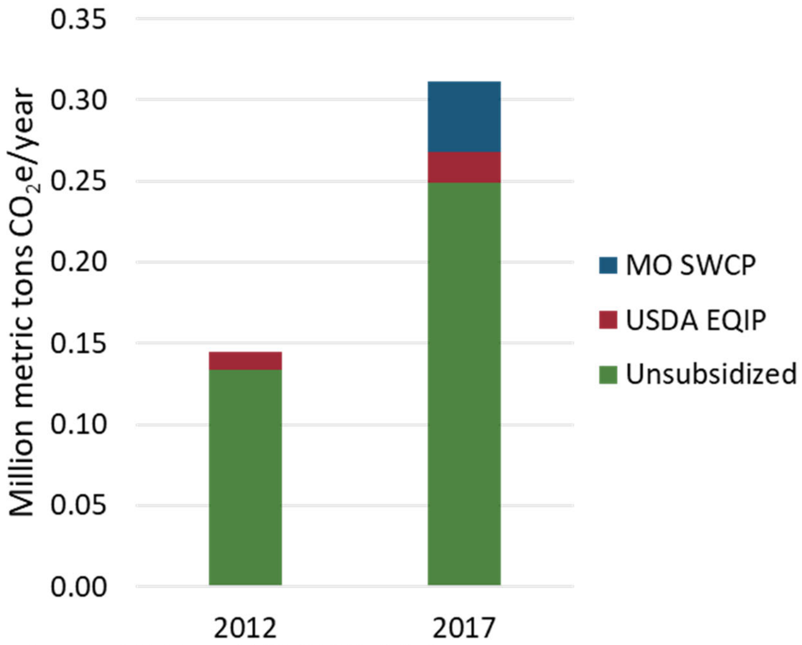
## Cover Crops

The latest data available on cover crop adoption in the corn belt indicates a rise from approximately 1% in 2010 to 4% in 2015 (Baranski et al., 2018). The 2012 and 2017 Censuses of Agriculture report cover crop acreage in MO increased from 390,114 acres in 2012 to 842,178 acres in 2017. Missouri ranks fourth in cover crop acres – following Texas, Iowa and Illinois.

In 2017 the USDA reported that they cost shared on 52,442 acres of cover crops. The Missouri Soil and Water Conservation Program (SWCP) cost shared on 117,175 acres of cover crops in 2017. Farmers without governmental financial assistance planted 672,561 acres to cover crops. Using the sequestration estimate of 0.37 tons $CO_2e$/acre/year (Swan et al., 2020; Biardeau et al., 2016) carbon sequestration in 2017 due to planting of cover crops in Missouri is estimated to be 311,606 tons $CO_2e$/year (see Exhibit 18).

Other estimates of the impact of planting cover crops have been made. Eagle et al.(2012) indicate that planting winter cover crops can sequester as much as 1.2 tons $CO_2$e/acre/year. They note that carbon sequestration is highest in warm winter locations. An average of research results yielded 0.5 tons $CO_2$e/acre/year. Savings on fertilizer from planting leguminous cover crops decrease process and upstream emissions while the additional fieldwork of planting and killing cover crops increases process emissions.

*Exhibit 18. Missouri cover crop GHG mitigation.*



Source: USDA and MO SWCP databases

McNunn et al. (2020) show a significant difference in $CO_2$e capture between rye cover (.31 tons $CO_2$e/acre/year), radish cover (0.35 tons $CO_2$e/acre/year) and clover cover (0.16 tons $CO_2$e/acre/year). Clover cover crop captures less $CO_2$e because it emits .06 tons $CO_2$e/acre/year in the form of $N_2O$ emissions. A visual estimate (from their figures, actual quantities not reported) of the GHG consequences of planting cover crops in Missouri range from emitting 0.65 tons $CO_2$e/acre/year to capturing 0.9 tons $CO_2$e/acre/year.

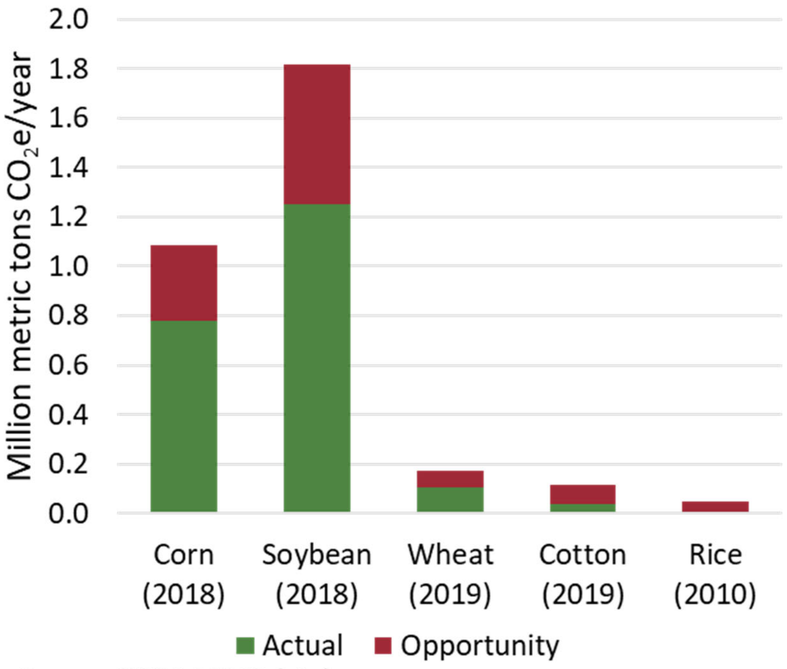
Moving from conventional till with fall nitrogen applications and no cover crops to the adoption of no-till, pre-plant and split nitrogen applications and rye cover planting was estimated to reduce GHG emissions by 1.1 tons $CO_2$e/acre/year (McNunn et al., 2020).

## Conservation Tillage

The USDA Agricultural Resource Management (ARMS) Survey estimates that in Missouri 72% of corn acres, 69% of soybean acres, 61% of wheat acres, 30% of cotton acres and 13% of rice acres are no-till planted acres. Overall, 46% of Missouri planted acres are no-tilled. Missouri ranks ninth in total no-till acres in the nation in the 2017 Census of Agriculture.

Using the USDA Comet net carbon sequestration estimate of 0.31 tons $CO_2$e/acre/year (0.42 tons $CO_2$e/acre/year from increased soil carbon - 0.11 tons $CO_2$e/acre/year from increased $N_2O$ emissions), Missouri sequesters over 2.1 million tons $CO_2$e annually. If all corn, soybean, wheat, cotton and rice production were no-till, another 1 million tons of CO2e would be sequestered annually. Exhibit 19 presents the actual and potential mitigation by crop grown in Missouri.

*Exhibit 19. Missouri no-till GHG mitigation.*



Source: USDA ARMS database

Estimates of captured carbon from no-till are varied. Eagle et al. (2012) estimate that switching from conventional tillage to no-till sequesters a total of 1.47 tons $CO_2$e/acre/year from increased soil carbon, and reduced $N_2O$, $CH_4$ and process emissions. Eagle et al. (2012) note that no-till sequestration estimates results are impacted by time, weather and soil characteristics. They specifically note that damp soils with high clay content and poor aeration (common in Missouri) increase $N_2O$ emissions after adoption of no-till.

McNunn et al. (2020) show a difference in $CO_2$e capture across the Missouri landscape. A visual estimate (from their figures, actual data not provided) of the carbon sequestration of adopting no-till in Missouri range from 1.7 tons $CO_2$e/acre/year in the bootheel region to 0.3 tons $CO_2$e/acre/year in hills of southcentral Missouri. If residue is removed, carbon sequestration will be reduced.

Neither T-AGG (2020) nor Biardeau et al. (2016) consider $N_2O$ emissions in their estimates of net carbon mitigation. T-AGG estimates sequestration of 0.83 tons $CO_2$e/acre/year for switching to no-till. Biardeau et al. (2016) estimate no-till to capture 0.42 tons $CO_2$e/acre/year from $CO_2$ reductions.

## Caveats

A controversy exists on the ability of no-till to deliver on its potential (Neufeldt et al., 2015; Six et al., 2004). Amundson and Biardeau (2018) assert that as temperatures rise, creating warmer soils, soil microbes will release more carbon from the soil so that sequestration is hampered. VandenBygaart (2016) questions many of the assumptions used. Specifically, he raises the question of whether no-till is continuous and whether non-continuous no-till has as much impact as asserted by agricultural interests. Kane (2015) also notes the carbon sequestered by no-till is released upon tillage and that the sequestered carbon is predominately near the surface. Fargione et al. (2018) do not include carbon sequestration from no-till in his estimate of agricultural climate mitigation potential because “the current state of knowledge does not enable a reliable estimate.”

Pittelkow et al (2015) in their discussion of conservation practices find that no-till can reduce yields 7.5% overall, but this effect can be minimized by simultaneously using cover crops or leaving crop residues and using crop rotation. ICF International (2013) also reports yield loss due to no-till but limits it to cool, wet climate conditions.

These expectations of reduced yields associated with no-till are not necessarily the case in Missouri. Adler and Nelson (n.d.) summarize an on-going 22-year Missouri study of corn-soybean-wheat production under different tillage systems. They report that from 1994 to 2016, most years' results indicate no significant differences in corn, soybean and wheat yields when no-till or reduced tillage. When corn yields were significantly different, five times reduced tillage yielded higher; one time no-till yielded higher. When soybean yields were significantly different, twice no-till yielded higher and once reduced till yielded higher. Reduced tillage always yielded higher wheat yields in the four years there was a significant difference. Another Missouri study by Nash, Nelson and Motavalli (2013) found that tillage interacted with nitrogen fertilizer management practices, timing of fertilizer application and weather. The highest yields occurred when injecting anhydrous ammonia into a no-till soil with nitrapyrin at pre-plant.

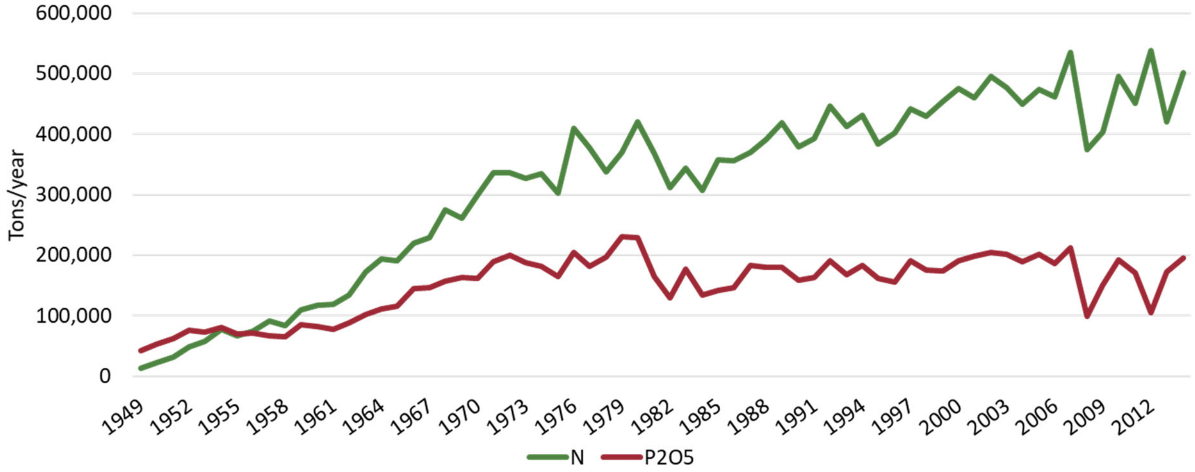
Lerch et al. (2013) studied the balance between the soil erosion benefits and the atrazine runoff from no-till on Missouri claypan soils. They found that incorporating atrazine with rotary till did not significantly increase erosion compared to no-till but did decrease atrazine concentrations in runoff.

## Nutrient Management

Nutrient management is expected to reduce the release of the $N_2O$. $N_2O$ emissions are converted to $CO_2e$ using the 100-year conversion factor of 298. In other words, every ton of $N_2O$ released into the environment warms the globe the same as 298 tons of $CO_2$ released into the environment.

The Missouri Fertilizer Tonnage Report shows total fertilizer use increasing in the state until about 2000 at which time it has leveled off.[2] This trend is consistent with the U.S. total fertilizer use (USDA). From an environmental perspective, this total nitrogen applied is expected to release more GHG gases in the form of $N_2O$. From a yield-scaled production perspective, fertilizer use increased 16% from 1994 to 2014 while crop output increased 31%. The emissions of $N_2O$ per unit of farm output decreased 9% in 20 years.

*Exhibit 20. Fertilizer shipped for use in Missouri.*



Source: Missouri Fertilizer Tonnage Report. http://aes.missouri.edu/pfcs/fert/mftr14.pdf

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[2] The last Missouri Fertilizer Tonnage Report available is for 2014.

Nutrient management to reduce GHG emissions from crop production tend to follow the 4Rs of nutrient stewardship (Fargione, 2018; ICF International, 2013). The 4Rs of nutrient management are the **r**ight fertilizer source applied at the **r**ight rate at the **r**ight time and in the **r**ight place (The Fertilizer Institute, 2020).

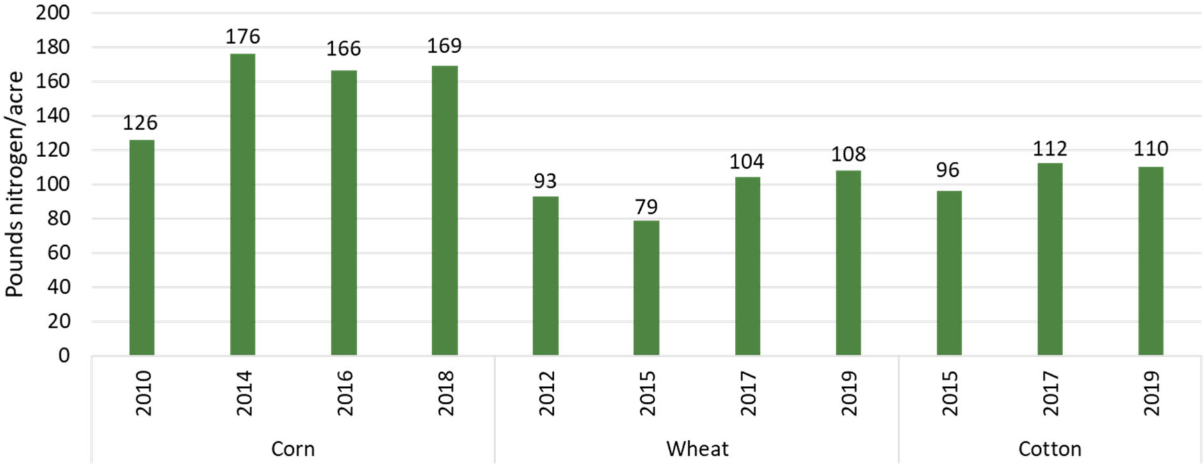
Reducing the total application of N fertilizer results from reducing the application rate and the precision placing of N fertilizer. Reducing the $N_2O$ emissions per unit of N applied results from improved timing of application and switching N fertilizer sources. Fargione et al. (2018 supplementary materials) found that "all practices together could reduce … overall field emissions to 67%" of a business as usual scenario.

## Reducing application rate

USDA ARMS data does not show a statistical difference in total nitrogen applied per acre for corn, wheat and cotton over time. No estimate of climate mitigation can be made for Missouri from reducing nitrogen application rate. Individual farmers reducing nitrogen rates might soon be able to market their reduced GHG emissions.

T-AGG (2020) estimate that if fertilizer use was reduced by 15% per acre in Missouri, it would reduce GHG emissions by 0.35 ton CO2e/acre (range .28 to .41). The potential mitigation from reducing nitrogen fertilizer rate by 15% on over 4 million acres planted to corn, wheat, cotton and rice in MO would be 1.4 million tons $CO_2$e/year.

*Exhibit 21. Nitrogen fertilizer application rate in Missouri.*

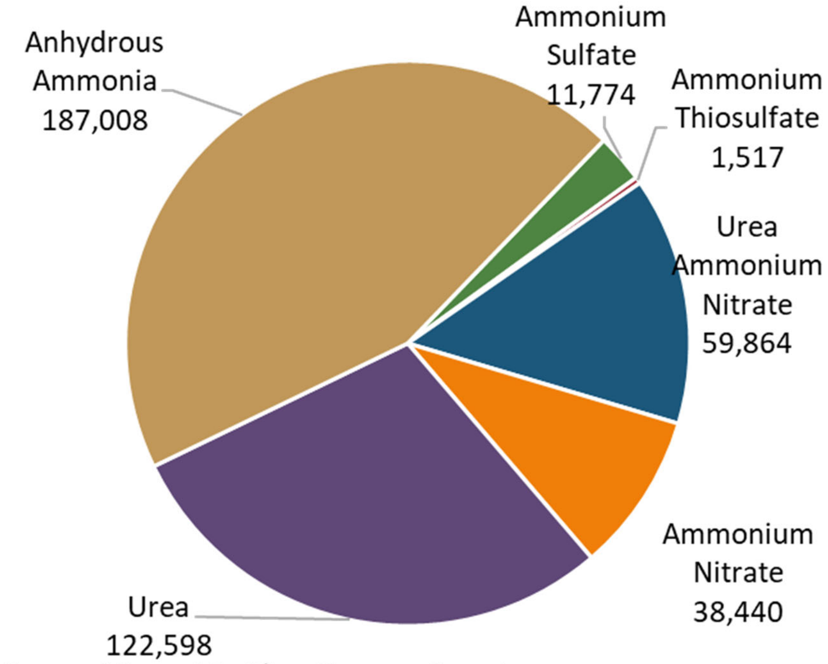


Source: USDA Agriculture Resource Management Survey

## Switching N fertilizer sources

The 2014 Missouri Fertilizer Tonnage Report shows that Missouri farmers used 228,059 tons of anhydrous ammonia, supplying 187,008 tons N (see Exhibit 22). For every U.S. ton N supplied by anhydrous ammonia switched to N supplied by urea, 2.6 metric tons less $CO_2$e would be emitted in the production of crops (Fargione et al., 2018 supplementary materials). Ceasing the use of anhydrous ammonia would reduce GHG emissions by 486,220 tons $CO_2$e/year.

*Exhibit 22. Tons of N applied in Missouri.*



Source: Missouri Fertilizer Tonnage Report.

Eagle et al. (2017) found that switching from anhydrous ammonia to urea resulted in 45% reduction in $N_2O$ emissions per bushel of corn produced.

Fargione et al. (2018) estimated that the marginal abatement cost of switching from anhydrous ammonia to urea would be $90 per ton $CO_2$e mitigated. This cost exceeds estimates of carbon market prices so farmers will not easily switch from anhydrous ammonia to urea applications, without other justifications.

## Enhanced efficiency fertilizers

The USDA (2016) reports that the use of enhanced efficiency fertilizers (EEF) reduces the amount of nitrogen lost to the environment. EEFs slow the process by which fertilizers are broken down forms which can be volatilized into the air, leached into water, and utilized by crops. At the national level EEF use in corn increased from 8.5% to 12.5% from 2005 to 2010. Though later ARMS surveys have been conducted, they no longer report EEF use. Data for MO shows use of EEF increased from 3% to 12% from 2005 to 2010.[3]

Assuming that 12% of 3.5 million acres of corn planted in Missouri in 2018 used EEF, 420,000 acres of corn received EEF. The use of nitrification inhibitors in Missouri reduces GHG emissions by 0.12 tons $CO_2$e/corn acre (ICF International, 2013), the emission reduction on the 420,000 corn acres using EEF would be 50,400 tons $CO_2$e/year.

ICF International (2013) estimates of the impact of nitrification and urease inhibitors for the corn belt ranged from 0.12 tons $CO_2$e/acre for corn, 0.08 to 0.09 tons $CO_2$e/acre for soybean, 0.05 to 0.12 for wheat tons $CO_2$e/acre and 0.00 to 0.06 tons $CO_2$e/acre for cotton. T-AGG (2020) estimates emission reductions of 0.05 tons $CO_2$e/acre.

Baranski et al. (2018) notes that EEFs reduce both GHG emissions per ton of fertilizer applied and the number of tons of fertilizer needed.

Eagle et al. (2017) found yield-scaled $N_2O$ emission reductions (the reduction of $N_2O$ emissions per unit of crop production) for switching from urea to SuperU was 26% and to polymer-coated urea was 15%.

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[3] MO specific estimates are provided by the USDA but not considered statistically unreliable.

They also estimate that “nitrification inhibitors and side-dress fertilizer N each reduce $N_2O$ losses by about 30%.” They note that higher July soil temperatures and higher levels of soil carbon increase $N_2O$ emissions.

In Missouri, Nash, Motavalli and Nelson (2011) report no $N_2O$ emission difference between polymer-coated urea and non-coated urea on a per acre basis. However, on a yield-scaled basis, polymer-coated urea emitted 0.12 kg $N_2O$/metric ton of corn grain less than non-coated urea.

### Fertilizer Timing

Baranski et al. (2018) report that 23% of corn fertilizer application in the corn belt occurs in the fall. This would indicate that 805,000 acres of Missouri corn had fall applied nitrogen. Assuming 0.17 tons $CO_2$e/acre reduction (McNunn et al., 2020) by switching from fall to pre-plant application on these 805,000 acres, reductions of emissions of 96,660 tons $CO_2$e/year could be realized.

McNunn et al. (2020) estimated that switching from fall only nitrogen fertilizer applications reduced GHG emissions from 0.03 to 0.17 tons $CO_2$e/acre/year, depending on whether spring only applications or fall and spring were adopted and whether sidedress applications were used. Eagle et al. (2017) found yield-scaled $N_2O$ emission reductions for switching from fall nitrogen applications to spring applications was less than 10% and not statistically significant.

### Fertilizer placement

In Missouri, Nash, Motavalli and Nelson (2012) report on claypan soils strip-till deep banding of urea emitted 0.2 kg $N_2O$/metric ton of corn grain than did no-till surface broadcasting of urea

## Manure Applications

Eagle et al. (2012) cite a 100-year Missouri study where the use of livestock manure increased $CO_2$e sequestration by 0.5 tons $CO_2$e/acre/year on wheat and 0.8 tons $CO_2$e/acre/year on corn ground. Their estimate from all literature is that manure use can sequester 0.1 to 2.1 tons $CO_2$e/acre/year.

## Precision Agriculture

Roberts et al. (2010) use Missouri specific research to conclude that using precision agriculture canopy reflectance technology to apply in-season nitrogen to corn can increase yield efficiency and nitrogen fertilizer recovery efficiency. Expected nitrogen savings of 8.9 to 44.6 pounds N/acre savings depend on soil types, reflectance readings and corn and fertilizer prices. Using the USDA ARMS estimate of 167 pounds N/corn acre, the expected nitrogen savings from precision agriculture ranges from 5% to 27%. Assuming the midpoint of savings (approximately 15%) is obtained, precision agriculture in Missouri could reduce GHG emissions by 0.35 tons $CO_2$e/acre/year (T-AGG, 2020).

Brandes et al. (2016) found that from 2 to 27% of low-yielding portions corn and soybean fields in Iowa, depending on crop and input prices, could be planted to low-input perennials while increasing overall profitability. This type of management using precision farming technology could capture carbon by planting perennials and reducing nitrogen application in the low performing portions of the field. No estimate of GHG reductions was given in this study. Fargione et al. (2018) also asserted that precision agriculture can be used to reduce fertilizer rates in parts of fields while maintaining yields but did not quantify the impact.

## Fuel use with tractor efficiency

Autoguidance technology is recognized as increasing field efficiency of machinery. Typically, machinery efficiency can range from 50% (planter with small boxes) to 85% (large swath equipment on large, rectangular fields). Overlap is one cause of machinery inefficiency. Overlap is managed with foam markers (8% overlap), lightbars (4% overlap) and autoguidance (1% overlap). The change in field efficiency from adopting autoguidance depends on 1) the initial technology (e.g. foam marker or lightbar), 2) the geometry of the field (e.g. rectangular vs irregular, large vs small) and 3) the swath width of the equipment used (e.g. 90 feet for sprayer to 20 feet for 8 row planter). Dhuyvetter, et al. (KSU, 2016) developed a model to evaluate the economic impact of autoguidance and section controls. Using the average of their spreadsheet example, autoguidance would increase field efficiency about 2%. This would lead to a 2% decrease in fuel use for field activities. (Depending on the distance travelled to fields, the actual fuel usage would be less).

While a 2% increase is progress in improving production efficiency, it has little impact on GHG mitigation. Agriculture emissions due to fuel combustion (tractors, trucks and irrigation) is 6% of all agricultural emissions.

## Fallow management

Missouri is not a state with purposeful fallow acres. However, planting problems in 2019 caused many acres to not be planted and termed fallow. Eagle et al (2012) estimate that the elimination of summer fallow can decrease $CO_2$e in the atmosphere by 0.18 tons $CO_2$e/acre/year. The use of winter cover crops captures 0.78 tons $CO_2$e/acre/year. Policies that allow prevented planted acres to be cover cropped can help sequester carbon.

## Crop Rotation

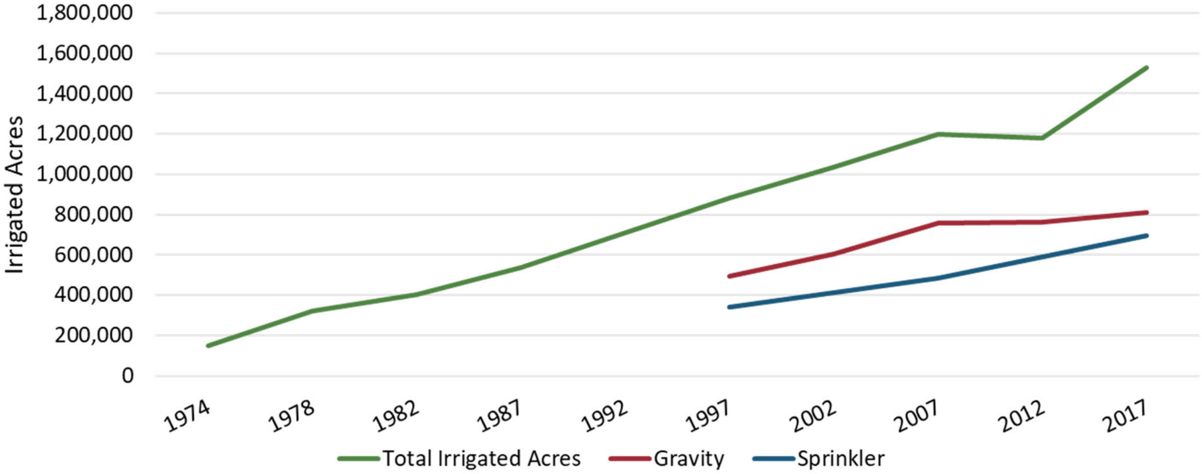
Eagle et al (2012) state “Field studies demonstrate that although certain rotations can sequester carbon, the soil C response to diversification is highly variable. Nearly 90 comparisons yielded an average soil C change near zero, although for rotations other than corn-soybean, diversification from a monocrop results in an average gain of about 0.1 t $CO_2$e ha-1 yr-1 [0.04 tons $CO_2$e/acre/year].” Missouri is a state that produces more soybeans than corn. There probably is little opportunity to reduce GHG emissions from crop rotation. Double crop soybeans (with wheat) may yield some $CO_2$e benefits but no mitigation estimate exists for that specific practice in the Midwest. Adding a perennial (alfalfa or grass hay) to an annual crop rotation can sequester 0.29 tons $CO_2$e/acre/year.

## Irrigation and water use

The USDA Census of Irrigation from 1998 to 2018 report quantity of water applied by either sprinkler or gravity irrigation systems. The difference shows that sprinkler irrigation consistently uses 0.3 acre-feet less water per irrigated acre. For every 1,000 acres switched from gravity to sprinkler, approximately 100 million gallons less water is needed for crop production. This reduction would save an unspecified quantity of fuel used for pumping.

Irrigation increases GHG emissions from fertilizer use and fuel combustion for pumping while increasing yields. From a yield-scaled perspective, irrigation reduces $CO_2$e emissions per unit of output. No estimate of GHG emissions due to irrigation is available for Missouri.

*Exhibit 23. Irrigated Acres in Missouri.*



Source: USDA Censuses of Irrigation

Mohammadi et al. (2013) using life cycle analysis research in Iran that shows that GHG emissions from soybean production could be reduced by 11 percent with changes in irrigation management (7%) and fertilizer management (4%).

## USDA and State Programs

USDA EQIP programs assist farmers in adopting environmentally beneficial farming practices. While GHG mitigation is a contributing factor to EQIP practices, it is not normally the major consideration. However, several practices have significant GHG ramifications and might be encouraged. Exhibit 24 summarizes USDA Comet estimates (Swan et al., 2020) of $CO_2e$ mitigation per acre from various NRCS practices. Conservation cover, critical area planting, field borders, riparian herbaceous cover and riparian forest buffer all mitigate more than one ton of $CO_2e$/acre/year.

The table also includes the acres enrolled in specific conservation practices in 2019 for both the USDA NRCS and Missouri Soil and Water Conservation Programs (SWCP). These acres are used to estimate the GHG sequestration of conservation programs. These conservation programs sequestered or captured 409,197 tons $CO_2e$ in 2019.

Many of these practices are performed by Missouri farmers without federal or state involvement but there is not data available to quantify the impact. The impacts noted in the table are the lower limit of GHG mitigation for those practices.

### Conservation Cover (Practice 327)

Conservation cover is the establishment and maintenance of perennial vegetative cover on land retired from agricultural production. In 2019, The USDA had active contracts on 31,555 acres. These are 5-year contracts. Often the farmers maintain the perennial vegetation after the life of the contract and therefore the sequestration in Missouri from conservation cover is expected to exceed the 39,759 tons $CO_2e$/year from the current contracts.

### Critical Area Planting (Practice 342)

Critical area planting is the establishment of permanent vegetative cover on highly erodible land. In 2019, Missouri farmers had active contracts on 12,440 acres with the USDA and the Missouri SWCP.

These are 10-year contracts. Often the farmers maintain the perennial vegetation after the life of the contract and therefore the sequestration in Missouri from conservation cover is expected to exceed the 15,674 tons $CO_2$e/year from the current contracts.

*Exhibit 24. GHG mitigation estimates for various NRCS and SWCP supported land management activities in Missouri.*

| | | $CO_2$e/acre/year from | | | Acres under contract. Missouri (2019) | | $CO_2$e/year |
|---|---|---|---|---|---|---|---|
| **Conservation Practice** | **Code** | **$CO_2$** | **$N_2O$** | **Total** | **USDA** | **SWCP** | **MO Total** |
| **Conservation Cover** | 327 | 0.98 | 0.28 | 1.26 | 31,555 | -- | 39,759 |
| **Conservation Crop Rotation** | 328 | 0.21 | 0.01 | 0.22 | 61,853 | -- | 13,608 |
| **Residue and Tillage Management, No-Till/Strip Till/Direct Seed** | 329 | 0.42 | -0.11 | 0.31 | 27,015 | 43 | 8,388 |
| **Cover Crop** | 340 | 0.32 | 0.05 | 0.37 | 359,122 | 160,793 | 192,369 |
| **Critical Area Planting** | 342 | 1.9 | 0 | 1.9 | 9,145 | 245 | 17,841 |
| **Residue and Tillage Management, Mulch Till** | 345 | 0.13 | 0.07 | 0.2 | 65,132 | -- | 13,026 |
| **Field Border** | 386 | 0.98 | 0.28 | 1.26 | 1,608 | 763 | 2,987 |
| **Riparian Forest Buffer** | 391 | 2.19 | 0.28 | 2.47 | 171 | 57 | 562 |
| **Grassed Waterway** | 412 | 0.98 | 0.28 | 1.26 | 9,404 | 3,036 | 15,674 |
| **Mulching** | 484 | 0.32 | 0 | 0.32 | 6,155 | | 1,970 |
| **Forage and Biomass Planting** | 512 | 0.27 | 0.1 | 0.37 | 3,887 | 68,241 | 26,687 |
| **Nutrient Management** | 590 | 1.75 | 0.11 | 1.86 | 29,284 | 11,751 | 76,325 |
| **Total** | | | | | 604,331 | 244,929 | 409,197 |

Source: estimates based on USDA Comet GHG mitigation estimates and USDA EQIP program data.

### Riparian Forest Buffers (Practice 391)

Two hundred twenty-eight acres are funded by USDA NRCS and the Missouri SWCP for planting of riparian forest buffers in 2019. The majority of riparian forest buffers were planted between 1997 and 2002. Since that time acreage enrolled in riparian forest buffers has almost ceased. The USDA Comet program estimates riparian forest buffers sequester 1.26 tons $CO_2$e/acre/year. The 228 Missouri acres in funded riparian forest buffers sequesters 562 tons $CO_2$e/year. This estimate does not include unfunded forest buffers for which no data could be found.

Eagle et al. (2012) cite a 13-year Missouri study where corn-soybean ground planted to a tree-grass buffer resulted in 0.63 tons $CO_2$e/acre/year sequestered.

### Grassed Waterways (Practice 412)

Grassed waterways are channels containing suitable vegetation to convey surface water while reducing erosion. In 2019, Missouri farmers had active contracts on 9,145 acres with the USDA and 245 with the Missouri SWCP. These are 5-year contracts. Often the farmers maintain the perennial vegetation after the life of the contract and therefore the sequestration in Missouri from conservation cover is expected to exceed the 17,841 tons $CO_2$e/year from the current contracts.

### Wetland Restoration

The Wetland Reserve Program has restored 134,000 acres of Missouri land to wetland status (USDA NRCS, 2020). Wetland are estimated to sequester a net of 1.6 tons $CO_2$e/acre/year – storing 2.6 tons

$CO_2e$/acre/year in the form of soil carbon and reducing .3 tons $CO_2e$/acre/year in process emissions while also releasing 1.4 tons $CO_2e$/acre/year in the form of $N_2O$. The 134,000 acres of WRP acres in Missouri are sequestering over 214,000 tons $CO_2e$/year.

## Crop specific notes

### Soybean

Because soybean do not require nitrogen fertilization and the greatest source of GHG releases from agriculture is tied to $N_2O$ emissions from fertilizer, soybean production is not a major contributor to GHG emissions. However, Cai et al. (2015) estimate that production of soybean results in emissions of 0.3 tons $CO_2e$/1000 acres/year from soybean's nitrogen fixation process. Five million acres of Missouri soybeans would release 1,617 tons $CO_2e$/year. While this emission is low, environmentalists note it as a source of GHG. Grasses are often preferred to legumes when the objective is reducing total GHG emissions.

### Rice Production Practices

Rice production estimates of GHG emissions are reported by state in the 2020 *EPA Inventory of GHG Emissions and Sinks*. MO rice production is estimated to have emitted 600,000 tons $CO_2e$/year on 19,425 acres in 1990 and 700,000 tons $CO_2e$/year on 25,090 acres in 2015 (EPA Inventory table 5-11 and 5-13).

## Miscellaneous Factors in GHG Mitigation

Using USDA ARMS data, Claassen and Morehart (2009) conclude that 1) landowners are more likely than renters to participate in programs, 2) landowners will participate by making land use changes (e.g. cropland to pasture) and 3) land use changes are more likely to create carbon offsets than are production practice changes (e.g. no-till adoption). He suggests that increasing rental agreements will be a hindrance to agricultural climate mitigation.

Baranski et al. (2018) reports conservation adoption data by farm size. The size aspect of production practices is of particular interest as MO has many small farms. They report that smaller farms (<250 acres) apply less nitrogen per acre of corn planted but more per acre of wheat planted. Small farms are also less likely than large farms to apply nitrogen fertilizer in the fall but are less likely to incorporate nitrogen fertilizer. Fall application releases more GHG than spring application but surface application also releases more GHG than incorporated fertilizer.

Small farms are less likely than large farms to use variable rate technology and auto steer, both expected to reduce GHG emissions.

Weber and McCann (2015) show that farmers more likely to use N inhibitors are: 1) younger, 2) in the Midwest states, and 3) also use conservation tillage, irrigation, VR N application, remote sensing and pretreated seed.

# Summary of GHG Mitigation from Current Agricultural Practices

A rough approximation of the GHG mitigation from current agricultural practices has been provided in each subsection in the preceding section. Exhibit 25 summarizes the lower bound of net $CO_2e$ discussed in those sections.

*Exhibit 25. Lower bound of GHG mitigation from Missouri farming activities.*

| **Practices** | **Estimated minimum $CO_2e$ from current practices in MO** |
|---|---|
| **Cover crops** | 311,606 |
| **Conservation tillage** | 2,178,268 |
| **Nutrient management practices** | |
| **Reducing Application rate** | + |
| **Switching N fertilizer sources** | + |
| **EEF** | 50,400 |
| **Fertilizer timing** | ++ |
| **Manure applications** | ++ |
| **Precision agriculture** | ++ |
| **Fuel use** | + |
| **Fallow management** | + |
| **Crop rotations** | + |
| **Irrigation and water use** | + |
| **NRCS practices**[a] | |
| **Conservation cover** | 39,759 |
| **Forage and biomass planting** | 26,687 |
| **Critical area planting** | 17,841 |
| **Grassed waterways** | 15,674 |
| **Wetlands (WRP)** | 214,400 |
| **Other NRCS and SWCP practices** | 108,479 |
| **Total estimate** | 2,926,114 |

[a] Estimates already included in the Cover Crops and Conservation tillage are not included in NRCS practices.
+ indicates a slight $CO_2e$ reduction is likely from MO farming practices.
++ indicates a medium $CO_2e$ reduction is likely from MO farming practices.

Missouri farmers can confidently assert that management practices adopted over the last 30 years are resulting in annual GHG emission reductions of 2,828,510 tons $CO_2e$. When estimates are provided, they are based on actual acreage in a practice and the estimate of GHG mitigation from that practice. When "+" and "++" are provided, there is no ability to provide an actual quantity but indications exist that GHG mitigation is occurring from those practices.

The EPA Greenhouse Gas Equivalencies Calculator indicates that the average car emits 5.1 tons $CO_2e$ annually and energy use in each house emits 9.5 tons $CO_2e$ annually (EPA, 2020). The 2,926,114 tons $CO_2e$ savings from agricultural practices would equal the emissions of 640,162 cars or 341,924 houses. For perspective, Missouri had 2.25 million registered automobiles in 2016. Agricultural emission reductions totals over 25% of all the registered cars in Missouri. Kansas City, St. Charles and Springfield have a combined total of 641,627 housing units. Agricultural emission reductions exceed the energy use of all homes in these three major Missouri cities.

## Outlook for GHG Mitigation by Agriculture

The different perspectives of climate scientists/environmentalists and producers has been addressed with different metrics (total emissions and yield-scaled emissions).

Bonnie, et al. (2020) evaluated several policies to foster GHG mitigation from five different perspectives (see Exhibit 26). Various agricultural stakeholders are likely to consider distinct GHG mitigation policies differently. Agricultural stakeholders may be able to expand some existing programs to develop GHG mitigation opportunities, but the transaction costs and mandates may be high hurdles. Forestry stakeholders have the potential for greater GHG mitigation but see challenges in developing flexible, low risk policies. Environmental and conservation groups express concern about the integrity of a market and the implications GHG mitigation policies may have on other environmental hot topics such as GMOs and chemical inputs. Different policies will also impact how much GHG mitigation occurs. Most policy options require substantial federal outlays, but some could be privately managed with little government cost.

Economics often enter into the decision of whether or not to pursue production practices that sequester GHGs. Most farmers consider the costs and benefits of new technologies. Internalized benefits (increased yields and output prices, labor concerns, reduced risk, etc.) need to exceed costs of the new technology to be voluntarily adopted. The challenge with GHG emission reductions is that currently they are an external benefit to society while the cost of achieving them is internal.

Estimating the cost of reducing GHG emissions is also a challenge. If the entire cost of sequestering GHGs is attributable to the activities needed to sequester the GHG, the cost per ton $CO_2e$ sequestered is often very high. The $CO_2e$ captured per acre are frequently less than one ton/acre so the cost per ton $CO_2e$ is greater than the cost per acre of reducing the emission. But GHG emission reductions often accompany other internal and external benefits. If these other benefits are also realized, the cost of sequestering carbon is reduced. Including the benefit of sequestering carbon into existing transactions can make those transactions more desirable.

ICF International (2013) estimates of changes in costs and revenues from changing production activities that result in reduced carbon emissions or increased carbon sequestration are summarized in Exhibit 27. For example, the switch from conventional to no-till production would reduce $CO_2e$ emissions while also reducing costs and yields. The result of switching to no-till is estimated to be a loss of net income to farmers. Assuming no other benefits to no-till, such as reduced erosion or conservation compliance, they use this loss of net income to estimate that corn farmers switching from conventional till to no-till would need to be paid $34 (in 2010 dollars) per ton $CO_2e$ sequestered to breakeven; soybean farmers need $77 per ton $CO_2e$ to switch to no-till. The table below presents some of the estimates of carbon payments Corn Belt farmers would need to receive to adopt various practices assuming all the net cost would be attributable to carbon sequestration.

*Exhibit 26. Policy Matrix. Positions and Effects of Specific Natural Climate Solution Policies.*

| | Agriculture Views | Forestry Views | Env./Conservation Group Views | GHG Delivery | Federal vs. Private Investment |
|---|---|---|---|---|---|
| **Compliance Offsets** | Mixed. Dairy/hogs, corn/soybeans can do well, wheat, cotton, rice not clear. Transaction costs can deter adoption, esp. for small farmers. | Risk is a challenge without price guarantee. Transaction costs can deter adoption, esp. for small landowners. | Concern about offset integrity; want long commitments from forestry and agricultural sequestration. | Transaction costs and risks (that practices will not result in qualifying offsets) may limit participation. | Privately funded; federal investments in streamlining/ technical assistance/aggregation/. Insurance products could address slow uptake, some participant concerns. |
| **Carbon Bank (De-risk,Guarantee Env. Integrity of Offsets)** | A new idea to many. Price guarantee helps most producers and should de-risk participation in markets. | Flexibility allows for variety of contracts to improve management practices with low risk. | Less concern about integrity. | Provides significant potential to generate GHG reductions. | Substantial federal cost. |
| **Use of Existing Farm Bill Incentive Programs** | Familiarity. Can use existing networks. | Forestry is still a smaller participant in programs. | May have some competing priorities without substantial new money. | Integrating GHGs into existing programs may be a challenge. | Substantial federal cost. |
| **Tax Incentives, Other Task Mechanisms** | Will likely work for some practices only, many producers have low tax liability which may limit effectiveness. | Large landowners need transferability; reforestation tax incentives may be opposed by forest landowners without bolstering timber markets. | General support. | For some practices, GHG delivery will be strong; challenge will be in measuring, monitoring. | Substantial federal cost. |
| **Crop Insurance** | Increased products for ag will garner support if crop insurance program preserved. | N/A | Support likely. | Powerful tool to affect millions of acres. | Possible government savings. |
| **Research, Tech Innovation, C Msmt** | Strong support for productivity, resilience research. | Strong support for productivity, markets research. | May be some concerns about GMO, high input ag. | Hard to measure but important contribution. | Substantial federal cost. |
| **Public Lands Mgmt** | Impacted western ranchers, farmers will strongly support. | Strong support. | Some environmentalists will resist management of public lands. | Large potential gains from reduced fire emissions. | Substantial federal cost. |
| **Increase Wildfire Suppression Expenditures** | Strong support for impacted landowners. | Strong support for impacted landowners. | Little resistance, though will want increase use of natural fires and prescribed fires. | Could be substantial. | Substantial federal cost. |
| **Bioenergy** | Biofuel mandates a must-have for corn, soybeans; tax incentives for renewable fuel and energy; livestock producers like biogas, fear rising feed prices from ethanol mandates. | Markets for low value wood very attractive to forest landowners; forest-dependent industries. | Resistance from many groups; some groups may support with measures to ensure bioenergy production done responsibly. | Could be substantial, particularly with carbon storage. | Mostly, privately funded (mandates on non-land sectors for renewable transportation fuel, voluntary decarbonization commitments); gov. support needed for infrastructure |
| **Beginning/Minority Farmers, Foresters** | General support. | General support. | Strongly support; in line with EJ goals; see beginning farmers as more environmentally conscious. | Probably not substantial. | Federal $ required; may be delivered favorable cost share treatment or other incentives, outreach will be key. |
| **Rural Investment Policies** | Support for agricultural productivity, bioenergy, resilience likely strong. | Support for wood markets very strong; western mills and forestry will strongly support forest restoration, fire management. | Some investments will raise concern, but if policies bring rural support, that may be persuasive. | Essential for executing natural climate solutions swiftly and on broad scale. | Substantial federal investment; could be mitigated through matching requirements from private industry. |

Source: Bonnie, et al. (2020)

*Exhibit 27. Estimated breakeven prices for various land activities to sequester one ton of $CO_2e$.*

| Activity | Crop | Breakeven prices for carbon (2010 \$/mt $CO_2e$) |
|---|---|---|
| **Reduce till to no-till** | Corn | \$43 |
| | Soybean | 77 |
| | Wheat | 37 |
| **Conventional till to no-till** | Corn | 34 |
| | Soybean | 32 |
| | Wheat | 57 |
| **Reduce fertilizer application 10%** | Corn | 32 to 174[a] |
| | Wheat | 2 to 17[a] |
| **Switch from fall to spring fertilizer application** | Corn | 167 |
| | Wheat | 179 |
| **Use nitrification inhibitors** | Corn | 60 to 63[b] |
| | Wheat | 93 to 150[b] |
| **GreenSeeker (Precision Agriculture)** | Corn | <0 to23[c] |
| | Wheat | <0 to 69[c] |

Source: ICF International (2013), Exhibit 2-37 modified.

[a] High breakeven prices use CO2e estimates from Ogle (2011); low breakeven price use CO2e estimates from Eagle et al. (2012).

[b] High breakeven prices use CO2e estimates from Ogle (2011); low breakeven prices uses CO2e estimates from Akiyama (2010).

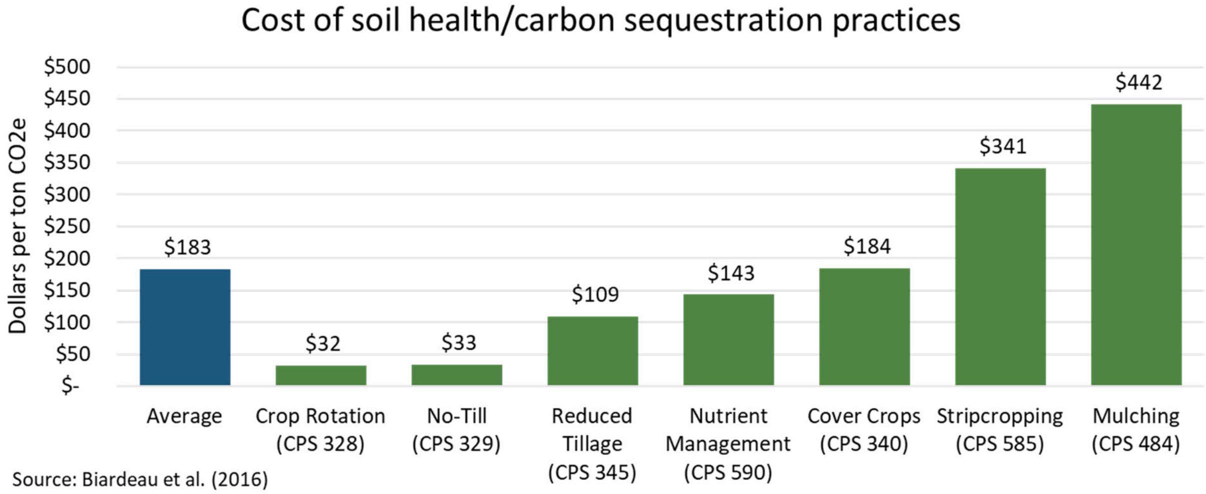
[c] Range is due to size of farm and estimate of CO2 emissions captured by the technology.

Fargione et al. (2018) provides the amount of GHG mitigation that could be done at various carbon prices. They peg the current market price of carbon at \$10/ton $CO_2e$ sequestered, the social cost of carbon at \$50/ton $CO_2e$ sequestered and the price needed to keep the 100-year average temperature from rising more than 2.5°C at \$100/ton $CO_2e$ sequestered. They estimate that cover crops hold the most promise for low cost management (103 million metric tons $CO_2e$/year at \$10/ton carbon). Next most promising is improved nutrient management (50 million metric tons $CO_2e$/year at \$10/ton carbon). A complete list of their results is shown in Exhibit 16.

Biardeau et al. (2016) estimate the carbon sequestration cost effectiveness of various land management decisions promoted by the USDA NRCS (see Exhibit 28). In their analysis they assume that the only benefit of the NRCS practice is carbon sequestration. They ignore the value of the benefits which have historically justified the NRCS practices. On average, it would take a \$183/ton $CO_2e$ payment for farmers to implement those practices for GHG mitigation purposes alone. Some practices such as no-till require a much lower payment while other practices such as strip-cropping would require a much higher payment. Their cost analysis also shows that breakeven prices for changes from conventional tillage to no-till are highest in the Corn Belt (\$104/acre) compared to the average for the U.S. (\$53/acre)

Biardeau et al. (2016) suggested their estimated \$183 cost/ton $CO_2e$ captured be viewed in light of the \$84 tax credit for energy efficient appliances and the \$732 production and tax credit and grants for renewable energy. They note the challenges of high transaction costs, scientific uncertainties, necessary technical assistance to succeed in GHG sequestration, lack of NRCS staff capacity and competing incentives between owners and renters hinder a ready solution for GHG mitigation programs.

*Exhibit 28. Estimated carbon sequestration cost estimates for various land management practices.*



Source: Biardeau et al. (2016)

They then conclude that the policies most likely to succeed would be to 1) adjust agricultural program implementation and 2) promote end market demand. Adjusting current program implementation would allow higher benefits to be recognized so farmers using them are more likely to get USDA assistance. Promoting end market demand would offer premiums to commodities that could be verified to have been produced with climate smart agricultural practices.

*Exhibit 29. Various GHG mitigation options and estimates of effectiveness and feasibility in the U.S.*

| | **Policy Effectiveness** | **Cost Effectiveness** | **Equity** | **Political Feasibility** | **Overall** |
|---|---|---|---|---|---|
| **Status Quo** | Low | Low | Low | High | **Low** |
| **Adjust Program Implementation** | Medium | High | High | Medium | **High** |
| **Increase Public-Private Partnerships** | Medium | Medium | Medium | Medium | **Medium** |
| **Promote End-Market Demand** | Medium | High | High | Medium | **High** |
| **Cap-and-Trade for Farmers** | Low | Low | Low | Low | **Low** |
| **NRCS as Carbon Bank/Broker** | Medium | Medium | High | Low | **Medium** |

Source: Biardeau et al. (2016)

Ggmoca et al. (2014) provided a summary of mitigation potential in a study of California GHG mitigation potential (see Exhibit 30). Farmland preservation ranked high because of high urbanization challenges and the political resolve to preserve a more natural setting. Efforts by farmers at reducing yield-scaled GHG emissions were ranked low to low-medium potential.

*Exhibit 30. Estimates of GHG mitigation potential in California.*

| Management Activity | Predominant Gases Involved | Biophysical Mitigation Potential (t $CO_2$ e $ha^{-1}$ $yr^{-1}$) | | | Relative Mitigation Potential |
|---|---|---|---|---|---|
| | | Min | Mean | Max | |
| **Farmland preservation** | $CO_2$, $N_2O$, $CH_4$ | -- | -- | -- | High |
| **Expansion of perennial crops** | $CO_2$, $N_2O$ | -- | -- | -- | Medium |
| **N fertilizer rate** | $N_2O$ | -- | -- | -- | Medium |
| **N fertilizer source** | $N_2O$ | -0.16 | 0.33 | 1.85 | Low-Medium |
| **N fertilizer timing and placement** | $N_2O$ | -- | -- | -- | Low-Medium |
| **N fertilizer efficiency enhancers** | $N_2O$ | -- | -- | -- | Low-Medium |
| **Irrigation practices** | $N_2O$ | 0.31 | 0.78 | 1.26 | Low-Medium |
| **Conservation tillage or no tillage** | $N_2O$ | -0.69 | 0.04 | 0.65 | Low |
| **Cover crops and organic amendments** | $N_2O$ | -1.69 | 0.03 | 0.89 | Low |
| **Rice management** | $CH_4$, $N_2O$ | -0.13 | 1.49 | 2.52 | Low-Medium |

Source: Ggmoca et al. (2014)

In a conversation with David Miller (formerly with Iowa Farm Bureau and instrumental in the Chicago Climate Exchange) on July 17, 2020, he indicated that carbon sequestration in soil was not likely to be a good solution due to its impermanence and resistance by many environmentalists. He also mentioned that any credit for soil carbon sequestration should be done on a regional basis through a USDA program rather than individual farmers contracting with a carbon market. It is too easy to cheat on individual fields, the science is not precise enough on individual fields and environmental conditions (drought, flooding, etc.) can greatly affect the carbon sequestered. But on a regional basis the USDA could quite confidently and with scientific rigor indicate that they have sequestered an amount of carbon from farms that have implemented certain practices. It could be similar to a CSP program where farmers would get paid for practices implemented rather than actual carbon sequestered. Given conservative enough estimates of the impact of different activities, the regional carbon sequestration would occur but not be guaranteed on any one farm.

## Representative Concentration Pathways (RCP) explanation

Our changing climate is thought to be a result of increasing greenhouse gases in the atmosphere. The level of $CO_2$ in the atmosphere was 280 parts per billion in the late 1700s but now is measured at over 400 parts per billion (EPA, 2020). $N_2O$, $CH_4$ and chlorofluorocarbon levels have also risen over time. GHG concentrations in the atmosphere are used in models to forecast future climatic conditions.

Climate change research and modelling is reported using Representative Concentration Pathways (RCP). The most commonly cited RCP is RCP8.5. The RCP 8.5 pathway forecasts a temperature increase of about 7.7˚F by 2100, relative to pre-industrial temperatures**.** It is frequently considered the base scenario or the "business as usual" scenario. RCP2.6 is the lowest pathway, forecasting a total warming of about 3.2˚F by 2100, and considered "the mitigation pathway." Several pathways exist between these two extremes.

Each RCP defines a model that assumes certain concentrations of carbon in the atmosphere at any date. The pathways are defined by the concentration of carbon in the atmosphere, not the volume of carbon emissions.

Disagreement exists on whether RCP8.5 represents a "business as usual" scenario, a "high emissions" scenario, or a "worst-case" scenario. Further, there are questions about whether RCP8.5 is consistent with the current trajectory of emissions and whether RCP8.5 represents a politically altered pathway.

The disagreement about RCP8.5 exists among scientists about whether RCP8.5 accurately represents the concentrations of atmospheric carbon that would be reached on the business as usual path. Some think it underestimates future concentrations of atmospheric carbon on the business-as-usual path while others think it overestimates carbon concentrations. The IPCC reports that "Scenarios without additional efforts to constrain emissions ('baseline scenarios') lead to pathways ranging between RCP6.0 and RCP8.5."

## Emergent GHG Mitigation Programs in Agriculture

Several private sector entities are developing the protocols and markets for rewarding farmers who reduce or mitigate GHG. A list of some of these entities follows with their website provided. This field is rapidly changing so both the list and the description of the mission of each entity should be confirmed.

### Ecosystem Services Market Consortium

The Ecosystem Services Market Consortium (https://ecosystemservicesmarket.org/) seeks to "advance ecosystem service markets  that incentive farmers and ranchers to improve soil health systems that benefit society." They seek to merge carbon sequestration with other ecosystem benefits such as water quality and quantity improvements and habitat enhancement.

### The U.S. Farmers and Ranchers Alliance

The U.S. Farmers and Ranchers Alliance promotes agricultural interests to society. They have developed a program to explain how farmers are reducing carbon in the atmosphere and promote the aspirational goal of agriculture helping the U.S. become carbon neutral (https://usfarmersandranchers.org/ag-environmental-impact/can-farming-solve-our-carbon-problem/).

### Indigo Ag

Indigo Ag is an aggrotech company seeking to use precision agriculture to increase yields and decrease GHG emissions from agriculture. Their website (https://www.indigoag.com/for-growers/indigo-carbon) claims that farmers have submitted over 20 million acres to participate in their carbon exchange. Indigo Ag works with farmers to adopt practices that reduce GHG emissions or sequester carbon and then finds businesses that are willing to pay for this type of ecosystem benefit.

### Bayer's Carbon Initiative

Bayer's Carbon Initiative will pay farmers for adopting climate smart practices that reduce GHG emissions or sequester carbon. Their website (https://media.bayer.com/baynews/baynews.nsf/id/Bayer-takes-steps-to-make-carbon-sequestration-a-farmers-newest-crop-opportunity) states that agriculture accounts for about 25% of GHG emissions worldwide (EPA estimates 10% in the U.S.). Their goal is to reduce yield-scaled emissions by 30% by 2030.

### Syngenta's Good Growth Plan

Syngenta's Good Growth Plan (https://www.syngenta.com/sustainability/good-growth-plan) is targeted at making agriculture more resilient and sustainable by striving for carbon neutral agriculture. Their website summarizes a survey they conducted that concludes that 87% of farmers experience some climate change impact and 63% have taken steps to reduce their GHG emissions.

### Alliances between input suppliers and commodity users

Alliances tend to focus on the possible benefits of precision agriculture adoption to mitigate GHG emissions.

Smithfield has had a long term goal of sourcing most of its grain used in hog feed from farmers who employ practices that reduce fertilizer loss. In 2020 Smithfield partnered with Granular (Corteva Agriscience). The partnership allows crop producers to obtain Granular's precision agriculture tools at a reduced cost with the expectation that the new tools will reduce GHG emissions from crop production used to feed hogs. At this point, this alliance is operational in the Ohio, North Carolina, South Carolina and Virginia.

Land O'Lakes is a network of farmer cooperatives marketing food products. Land O'Lakes announced that it will be using Microsoft's Azure to help farmers use data to make better decisions that increase efficiency and reduce GHG emissions. One aspect of this alliance is that Microsoft is advocating for better broadband internet access in rural communities and will be offering free public Wi-Fi at Land O'Lakes facilities in 19 states.

## Important Climate Change Research Entities

There are several public and private sector entities that attempt to quantify GHG emissions and reductions from agricultural practices. Below is a listing of the most common sources of GHG estimates.

### USDA NRCS

The USDA NRCS has developed estimates of GHG mitigation estimates for many conservation practices with an eye to incorporating GHG mitigation into their evaluation of funded practices. One tool they have funded is COMET Farm (http://comet-farm.com/Home) which allows users to obtain estimates of GHG mitigation from various land use decisions.

### U.S. Environmental Protection Agency

The USEPA annually publishes an *Inventory of Greenhouse Gas Emissions and Sinks* (https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks). This inventory is used to establish GHG mitigation priorities.

### DayCent: Daily Century Model

The Colorado State University Natural Resource Ecology Laboratory has developed a model called DayCent (https://www2.nrel.colostate.edu/projects/daycent/) that is used extensively for GHG estimates. The EPA uses DayCent for its estimates of soil management $N_2O$ emissions. It is a daily time-step biogeochemical model that uses climatological inputs (temperature, precipitation, etc.) and land use and management descriptors to estimate flows of carbon and nitrogen.

## U.S. Climate Resilience Toolkit

The U.S. Climate Resilience Toolkit aggregates climate information from across many government agencies into a single location for the purpose of helping users to understand and build climate resilience. The National Oceanic and Atmospheric Administration (NOAA) manages the site. It's site on Midwest agriculture (https://toolkit.climate.gov/regions/midwest/agriculture) contains case studies and links to tools such as the Useful to Usable Crop Decision Dashboard.

## Argonne National Laboratory

U.S. Department of Energy Argonne National Laboratory studies GHG emissions for many sectors of the economy, including agriculture. They have published estimates of GHG emissions for biofuels, fertilizers and agricultural practices, such as cover crops. Their primary model, Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET; https://greet.es.anl.gov/index.php) is considered the gold standard for life cycle assessment (LCA) studies.

## University of Arkansas

The University of Arkansas Center for Agriculture and Rural Sustainability (https://cars.uark.edu/) has expertise in agricultural LCA studies. They have well researched and respected LCA studies on cotton and are in the process of LCA studies on corn and dairy production.

## Duke University

The Duke University Nicholas Institute for Environmental Policy Solutions has a Technical Working Group on Agricultural Greenhouse Gases (T-AGG). Most of their work on GHG emissions in agriculture occurred before 2015 but recently have published several research summaries on climate change and agriculture (https://nicholasinstitute.duke.edu/publications).

## Winrock International

Winrock International Watershed Ecosystem Service Tool (https://www.winrock.org/westool/greenhouse-gas-emissions-from-land-use-and-land-use-change/) is used by many studies for estimates of GHG emissions from land use and land use change, particularly deforestation. Their estimates are particularly important in LCA studies whose boundaries extend beyond the actual land on which a commodity is produced and is considered to affect land use in other countries.

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