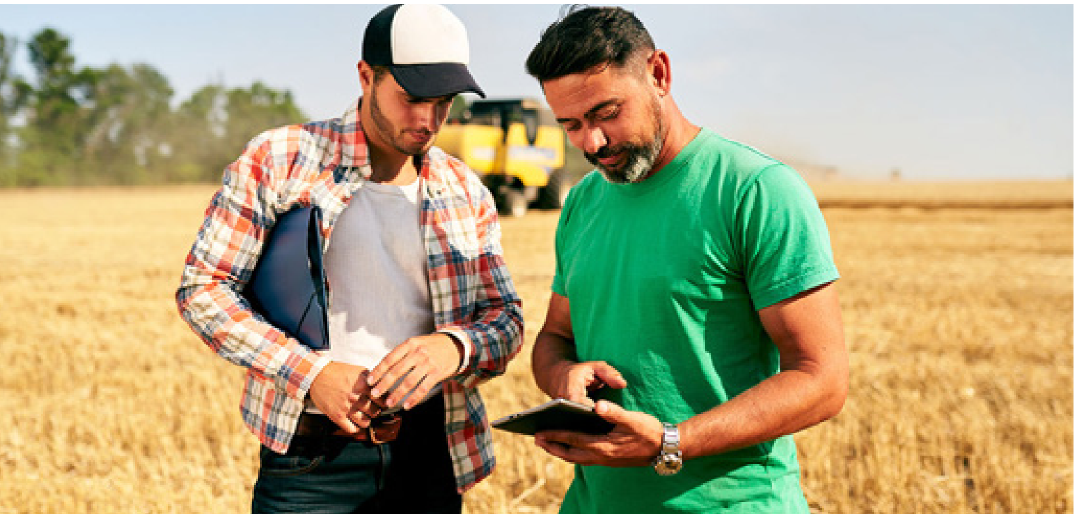
Field to Market®

Environmental Outcomes from On-Farm Agricultural Production in the United States

FOURTH EDITION | DECEMBER 2021







CONTRIBUTORS

Allison Thomson, Eric Coronel, and Kelly Young, Field to Market.

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SUMMARY

- This report summarizes progress towards sustainable agriculture in the United States by analyzing national trends in environmental indicators for 11 crops from 1980-2020.
- While substantial progress has been made since 1980 in reducing soil erosion, reducing greenhouse gas emissions and improving efficiency of energy, water and land use, progress in the most recent 15 years has generally been slower and some declines in resource use efficiency are observed.
- Engagement of the broader agricultural community to overcome systemic barriers and achieve a widespread transition to sustainable agriculture will be necessary to enable and scale verifiable progress towards environmental goals.
- The report findings will be used by Field to Market to identify opportunities for member-led efforts to achieve continuous improvement in environmental outcomes through partnerships and collective action by the value chain.

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KEY FINDINGS

- Improvement in five environmental indicators – Land Use, Energy Use, Greenhouse Gas Emissions, Irrigation Water Use and Soil Erosion – varies by crop and over time. Despite concerted efforts by the value chain and aligned government programs, improvement in environmental outcomes from crop production in the U.S. over the past decade is limited.
- For major commodity crops, soil erosion was significantly reduced from around 1990 through 2005; however, since the early 2000s soil erosion has largely held steady. This reflects a flat trend for adoption of no-till and reduced-till practices recently and a relatively modest adoption of cover crops to date. Understanding why conservation tillage adoption has plateaued will be key to driving future improvements in soil conservation.
- Overall energy use efficiency from commodity crop production has improved over time; however, several major crops have shown increases in energy use over the past decade, resulting from increased use of fertilizer and crop chemical inputs.
- While greenhouse gas emissions have declined over time when considered on a per yield basis, they have held steady or increased on a per acre basis for several major crops driven by increasing nitrous oxide emissions. Reductions in greenhouse gas emissions per acre have only occurred for crops where nitrogen fertilizer use has declined.
- Overall, soils managed under the cropping systems considered in the Field to Market program have increased soil organic carbon stock throughout the last 25 years, according to a recent USDA report, with the greatest increase in 2005.
- Irrigation water use efficiency experienced significant fluctuations over time in response to weather conditions and shifting production regions, but most crops have improved over time.
- Significant improvement in soil erosion, energy use and greenhouse gas emissions in the 1990s and early 2000s demonstrates that when new technologies and incentives allow farmers to achieve greater efficiency, they will rapidly adopt new practices.
- Further progress through voluntary conservation efforts requires understanding and creating the enabling conditions that support widespread transition to sustainable practices, including providing farmers with financial incentives, technical assistance and peer learning opportunities.
- Significant opportunities for U.S. agriculture exist to contribute to climate change mitigation through reduction of greenhouse gas emissions, principally through achieving greater fertilizer use efficiency – which will reduce soil nitrous oxide emissions – and the use of renewable energy as well as energy efficiency improvements. Additional climate mitigation can be realized through reducing tillage and planting cover crops to increase soil carbon sequestration.
- Assessment of biodiversity and water quality trends highlights multiple environmental benefits from strategic placement of diverse, perennial vegetation, including native grasslands, within crop landscapes.
- Overall, these findings extend the trend of plateauing progress since the early 2000s that was noted in the third edition of the report (Field to Market, 2016). While the research to develop new technologies is critical to success, it is increasingly clear that social science research and community support to address the agronomic and financial risk related to changing productions systems is necessary to achieve sustained transformation of the agricultural system.

INTRODUCTION

Over the past two decades, agricultural stakeholders in the United States have collaborated on programs, tools and incentives to transition to sustainable farming systems which build thriving and healthy agriculture systems and improve environmental outcomes. Field to Market: The Alliance for Sustainable Agriculture was formed in 2006 from one such collaborative effort between farmers, agribusiness, brand and retail companies, environmental organizations and university and government partners to focus specifically on improving environmental outcomes from commodity crop production. As the largest share of cropland in the U.S. is devoted to commodity crops, transitioning these lands to sustainable systems can provide many environmental benefits across the country while helping to ensure resilience to climatic disruptions already occurring and anticipated to worsen over the next several decades.

U.S. croplands are some of the most productive agricultural areas on the planet and provide food, feed, fiber and fuel for domestic consumption and export. As a critical region for global food security, maintaining the productivity of U.S. cropland is key to achieving the UN Sustainable Development Goal (SDG) of Zero Hunger by ensuring adequate, nutritious food for a growing population (United Nations, 2015). At the same time, the harmful environmental impacts from the past centuries of farming on these lands have been considerable and are at odds with other SDGs including Clean Water, Life on Land, Life Below Water and Climate Action. Recent progress reports on the SDGs highlighted the important role of agricultural value chain stakeholders and partnerships in devising solutions to achieve Zero Hunger (SDG 2) (Veldhuizen et al., 2020) as well as the need to focus on the interconnections between the goals and to strive for achieving synergistic improvements (Messerli et al., 2019). Balancing these goals is the critical challenge facing agricultural producers and stakeholders over the coming decade.

Recent scientific reports have highlighted historical biodiversity losses in agricultural regions and found that the growth in agricultural land use since 1970 is unsustainable with respect to the natural systems impacted, including declines in soil health and pollinator diversity. These reports call for renewed efforts to protect and restore nature (Diaz et al., 2019). In addition, the most recent scientific consensus on climate science has confirmed that disruptive weather events over the past several years are attributable to global climate change caused by human activities. These weather disruptions are likely to increase in frequency and severity over the next several decades regardless of climate mitigation efforts (IPCC, 2021). While continued rising global temperatures and associated weather patterns can be avoided over the long term with immediate and concerted action to reduce emissions, it is clear that a certain amount of change is already unavoidable. Therefore, action by agricultural stakeholders is necessary for both climate mitigation and to enhance the resiliency of U.S. cropland to extreme weather events.

These findings provide additional urgency and motivation for agriculture stakeholders to contribute solutions to these global challenges by working together to achieve widespread adoption of sustainable agricultural systems. Since 2009, Field to Market has tracked progress towards this improvement in five key environmental indicators through three editions of the National Indicators Report (Field to Market, 2009, 2012, 2016). Field to Market has also released two additional reports assessing trends in pesticide use (Field to Market, 2020a) and farm economics (Field to Market, 2020b). This fourth edition of the National Indicators Report extends the analysis from 1980 to 2020 to examine how trends in Land Use, Energy Use, Greenhouse Gas Emissions, Irrigation Water Use and Soil Erosion have evolved over the past four decades.

Since the third edition of the National Indicators Report was released, the findings have been used by several U.S. commodity organizations to set continuous improvement goals and develop protocols for industry wide improvements. These goals and commitments set by the American Soybean Association, National Cotton Council, USA Rice Federation and the National Corn Growers Association reflect a growing awareness that improvements are needed to meet the environmental goals of customers while building public confidence in agriculture's sustainable use of land and other natural resources.

Field to Market established a standardized approach – the Continuous Improvement Accelerator – to enable the private sector to partner around common goals, engage with technical experts and farmers in a given region, and design projects to support farmers adopting practices to improve key environmental outcomes. A key element of this approach is using the Fieldprint® Platform to measure and track improvements towards achieving environmental goals (Field to Market, 2020b). Partnerships set goals for regions and projects that align with the overarching Field to Market goals (see box) and reflect local and regional environmental concerns and agronomic conditions. In 2020, this framework was in use by over 70 partnerships across 4.5 million acres spanning 34 states.

Recent results from surveys and the 2017 USDA Census of Agriculture demonstrate continued adoption of conservation practices that are key to sustainable systems. However, long term data indicate that conversion to reduced- and no-tillage systems has slowed in recent years, only expanding from 104 million acres to 112 million acres between 2012 and 2017 (National Agricultural Statistics Service, 2019). Increase in cover crop acreage has been more significant over that time period, however the total extent of cover crop adoption remains relatively low at 5.1% of harvested cropland for all crops in 2017 (Wallander et al., 2021). An assessment by the USDA Economic Research Service documented the success of private and public sector financial incentives for increasing conservation practice adoption, indicating significant room for further adoption through expansion of such programs (Wallander et al., 2021). It is incumbent on the agricultural industry and stakeholders to identify and eliminate barriers to adoption and make conservation practices the best choice for farmers throughout the country.

While this engagement, and that of other organizations with sustainable agriculture goals is promising, it is impossible to determine progress at a national scale by focusing only on individual efforts and case studies. To understand whether these efforts are having a broader impact discernable throughout the agricultural system requires examining national trends using statistically robust data sets. This fourth edition of the National Indicators Report provides a progress report and reality check to help ground and direct future efforts.

FIELD TO MARKET GOALS STATEMENT

Field to Market is working to meet the challenge of producing enough food, feed, fiber and fuel for a rapidly growing population while conserving natural resources and improving the ability of future generations to meet their own needs. The organization and its members are committed to supporting resilient ecosystems and farmer economic vitality as fundamental components of agricultural sustainability. Field to Market will convene diverse stakeholders to support multi-sector collaboration, while providing useful measurement tools and educational resources for growers and the value chain that track and create opportunities for continuous improvement at scale. Our efforts are guided by the following interdependent goals:

Biodiversity – Supporting diverse species and ecosystems by conserving and enhancing habitats across U.S. agricultural landscapes.

Energy Use – Increasing energy use efficiency on U.S. cropland.

Greenhouse Gases – Reducing greenhouse gas emissions from U.S. cropland per unit of output, and sustained contribution to reducing the overall greenhouse gas emissions from agricultural landscapes.

Irrigation Water Use – Improving irrigation water use efficiency and conservation on U.S. cropland.

Land Use – Improving productivity on U.S. cropland.

Soil Carbon – Increasing soil carbon sequestration on U.S. cropland.

Soil Conservation – Reducing soil erosion on U.S. cropland.

Water Quality – Improving regional water quality through reduction in sediment, nutrient and pesticide loss from U.S. cropland.

OBJECTIVES AND SCOPE OF THIS REPORT

The overall objective of this report is to assess trends in eight key environmental indicators from 1980 to 2020. For five of the indicators – Land Use, Irrigation Water Use, Energy Use, Greenhouse Gas Emissions, and Soil Erosion – we use government statistics and scientific literature to calculate crop specific trends for the full time period (Part 1).

The five environmental indicators discussed in Part 1 assess the efficiency of crop production at the national scale from 1980-2020. Indicator calculations are described briefly below and more fully in Appendix A. These five indicators are calculated for 11 major crops (Table 1).

Land Use: The Land Use indicator measures the production efficiency of agricultural lands and is closely tied to crop yields, which are key to economically sustainable farming operations. Optimal yields are critical to economic sustainability and other efficiency indicators.

Soil Erosion: Sustainable agriculture strives to improve soil conservation by reducing erosion to preserve healthy soils for future productivity and land resiliency. Soils are highly variable throughout the country, having been formed over millennia by natural geologic and climatic processes and impacted by land use history and management. Soil erosion occurs when the soil surface is exposed to water and wind. While soil continues to form, the rate is much slower than losses due to erosion in and near farm fields (Montgomery, 2007). The Soil Erosion indicator included in this report is a high-level assessment of the rate of soil loss from cultivated lands.

Irrigation Water Use: Water is an important limiting factor for crop production where precipitation is not sufficient or does not occur at the right time for optimum crop yields. Irrigation is increasingly limited by available surface and groundwater and is susceptible to shortages due to droughts. Agriculture is the single largest consumptive water user in the United States (Moore et al., 2015) and is thus the sector most vulnerable to changes in weather and climate (Marshall et al., 2015) and to depletion of groundwater resources (Konikow, 2014). As drought continues to expand and intensify across the western U.S., improvements in irrigation water use efficiency are critical to maintaining production without depleting aquifers and surface water storage reserves for other uses in water-stressed regions (North American Drought Monitor[1]). The Irrigation Water Use indicator assesses the efficiency of irrigation water applied in terms of the incremental improvement it produces in crop yield compared to yields on non-irrigated lands and is applicable only to irrigated lands.

Energy Use: From pumping irrigation water to manufacturing nitrogen fertilizer to powering farm equipment, agriculture uses energy in many forms. This indicator assesses trends in energy use efficiency of crop production in the U.S. by evaluating the amount of energy used relative to crop yield. Energy use is also an important indicator for evaluating the cost of production of a farm operation.

[1] North American Drought Monitor | Temperature, Precipitation, and Drought | National Centers for Environmental Information (NCEI) (noaa.gov)).

Greenhouse Gas Emissions: Greenhouse gas (carbon dioxide, nitrous oxide and methane) emissions from crop production come from three main sources. One is the emissions associated with energy use, which depend on both the amount of energy and the form (diesel, electricity, etc.) of that energy. Second is direct emissions from biological nutrient cycling in agricultural soils, which release nitrous oxide and, for flooded rice, methane. Third is emissions resulting from burning crop residues to clear fields after harvest. By examining the trends in these sources we can identify opportunities for emissions reductions that contribute to climate mitigation.

Overall, these five indicators, when calculated at a national scale, provide a broad view of the changes over time in the environmental impact of crop production. The calculations are designed to capture trends on a crop-specific basis.

TRENDS IN PEST MANAGEMENT

Over the past several years, Field to Market member organizations have explored opportunities for how to incorporate the environmental impacts of pest management decisions into the overall program. One outcome of this work was a 2020 report – *Trends in Pest Management in U.S. Agriculture: Identifying barriers to progress and solutions through collective action* (Field to Market, 2020a). The report examined crop-specific trends in Integrated Pest Management practice adoption as well as chemical use, with the following key findings:

- Adopting pest management practices that can reduce harmful impacts of chemical use on biodiversity, water quality and human health and address production challenges associated with increasing incidence of pesticide resistance presents an opportunity for the value chain to support farmers in changing practices.
- Building healthy soils can support healthy, resilient plants; therefore, a broad range of sustainable agriculture practices — including diverse crop rotations, cover crops and reduced tillage — can help to protect against crop damage from pests.
- Evaluating trade-offs is an important consideration. For example, weed management through chemical control can result in exposure and risk to non-target species; however, it can also facilitate adoption of conservation practices such as reduced tillage or cover crops.
- Drawing from extensive scientific literature on specific chemicals and management practices, as well as evaluations of how management has changed over time with the introduction of new pesticides, we can better understand how environmental impacts have changed over time.
- Working together, all sectors of the value chain can advance responsible pest management. Changes will be most effective at reducing impacts when done in coordination among farmers within a broader community and their support networks. Pest management must become a collaborative effort.

The Pest Management report presents data on chemical use and pest management practices from USDA surveys over the period 1990–2018. These data help to tell the story of specific pest management challenges facing different crops over the past several decades and identify opportunities for greater adoption of specific principles of Integrated Pest Management to protect biodiversity, water quality and human health.

In Part 2, we report directly on findings from government reports and scientific syntheses to understand trends in Field to Market's other three key environmental outcomes – Biodiversity, Soil Carbon and Water Quality. These outcomes represent complex biological systems for which simple calculations using statistical information, such as the indicators in Part 1, are insufficient to capture meaningful changes over time. These environmental impacts extend well beyond a farm field boundary to surface and groundwaters and the habitats that support many diverse species of plants and animals.

Biodiversity: Key to the SDGs of Life on Land and Life in Water is understanding how agricultural landscapes can be managed to support biodiversity and reduce harm to natural ecosystems. We present information from synthesis reports of the Intergovernmental Science-Policy Platform for Biodiversity and Ecosystem Services (IPBES) to better understand recent trends for key pollinator and bird species and how biodiversity has historically been impacted by U.S. agriculture.

Soil Carbon: Understanding soil carbon trends is key for promoting soil health and resilient agricultural systems while considering how agriculture can contribute to sequestering atmospheric carbon. Here we assess the latest findings from the USDA's Greenhouse Gas Inventory on soil carbon in major cropping systems from 1990-2015.

Water Quality: Agriculture can have a detrimental impact on water quality through erosion, runoff and leaching of excess fertilizers and crop chemicals. These impacts vary greatly and depend not just on farming practices but on the soil properties, climate and hydrology of a region. In this report, we look to regional assessments of progress on improvements in water quality in critical watersheds and coastal waters, including the Chesapeake Bay, Gulf of Mexico and Mississippi River Basin.

ECONOMIC SUSTAINABILITY: TRENDS IN FARM FINANCIAL WELL-BEING

Previous versions of the National Indicators Report have included a section on social and economic trends in addition to environmental impact trends. In 2020, Field to Market commissioned a separate report on economic sustainability in response to member interest in exploring how to better support adoption of sustainable practices during times of challenging fluctuations in commodity prices and global trade and value chain disruptions due to the COVID-19 pandemic (Swanson and Schnitkey, 2020). The report focused on three financial indicators – Farm Financial Health, Farm Profitability and Farm Financial Efficiency and explored trends over time based on data collected by the USDA Economic Research Service with these key findings:

- Overall, the financial well-being of farms has decreased from 2013, largely because commodity prices have declined. As a result, farm financial health has declined, profitability has declined and financial efficiency has declined.
- While overall financial health has not reached crisis levels like that of the 1980s, downward trends are a sign for caution, given the Federal government supports in recent years with programs that are not guaranteed to continue.
- In recent years, farmers have been able to maintain profitability and financial efficiency despite low values of production due to government support and cost reduction efforts as well as low interest rates and growth in assets.
- This financial situation will influence management decisions, prioritizing those that have immediate positive profit implications, such as reduced tillage. Practices that reduce immediate profitability will be more challenging to adopt, particularly if those practices negatively impact yields in the short term or come with investment expense, such as cover crops.
- Farmers are in a unique position to deliver broader environmental benefits to society based on their management decisions; however, they are not currently in a position where they can bear the full cost of this effort.
- The supply chain should consider creative mechanisms that support farmers in transitioning to practices that will deliver more sustainable outcomes.

Field to Market has responded to this report by establishing a Standing Committee to explore innovative finance mechanisms and to bring greater focus to how the value chain can support growers in managing the agronomic and financial risk inherent in transitioning to new practices that are necessary to build a more resilient and sustainable food and agriculture system.

PART 1: TRENDS IN ENVIRONMENTAL INDICATORS: 1980-2020

OVERVIEW

Many transformations in the U.S. agriculture sector were witnessed between 1980 and 2020. Continuous innovation in technology, shifting demands for food, feed, fiber and fuel both domestically and internationally, and conservation practice adoption are just a few of the overarching drivers that have shifted the U.S. agricultural landscape and resulting environmental impacts. Here we review the results for five environmental indicators for 11 crops and summarize major trends and factors driving those trends over the past 40 years. To provide context to the indicators' results, we provide background information on trends in crop production, location of production and planted acreage for each crop. Additional detailed supplementary information on trends in crop management that are referenced here can be downloaded from the report website.

Four of the indicators here are expressed in terms of the units of crop production:

- **Land Use Indicator**: A measure of the efficient use of land (acres per unit of production)
- **Irrigation Water Use Indicator**: A measure of the efficient use of irrigation water on land equipped for irrigation (acre-inches of water applied per additional unit of production gained from the use of irrigation).
- **Energy Use Indicator**: A measure of the efficient use of energy (British Thermal Units (BTU) per unit of production).
- **Greenhouse Gas Emissions Indicator**: A measure of emissions from production (pounds carbon dioxide Eq. per unit of production).

Table 1: Crops included and unit of production for analysis.

CROP	YIELD UNIT	DESCRIPTION
Barley	bushel	Bushel, 48 lb. of barley grain per bushel (14.5% moisture)
Corn (grain)	bushel	Bushel, 56 lb. of corn grain per bushel (15.5% moisture)
Corn (silage)	ton	2000 pounds (lb.) (65% moisture)
Cotton	lb. of lint	Pounds (lb.) of lint (5% moisture)
Peanuts	lb.	Pounds (lb.) (7% moisture)
Potatoes	cwt	Hundredweight, (100 lb.)
Rice	cwt	Hundredweight, (100 lb.) (12.5% moisture)
Sorghum	bushel	Bushel, 56 lb. of sorghum grain per bushel (14% moisture)
Soybeans	bushel	Bushel, 60 lb. of soybean seed per bushel (13% moisture)
Sugar beets	ton of sugar	2000 pounds (lb.)
Wheat	bushel	Bushel, 60 lb. of wheat grain per bushel (13.5% moisture)

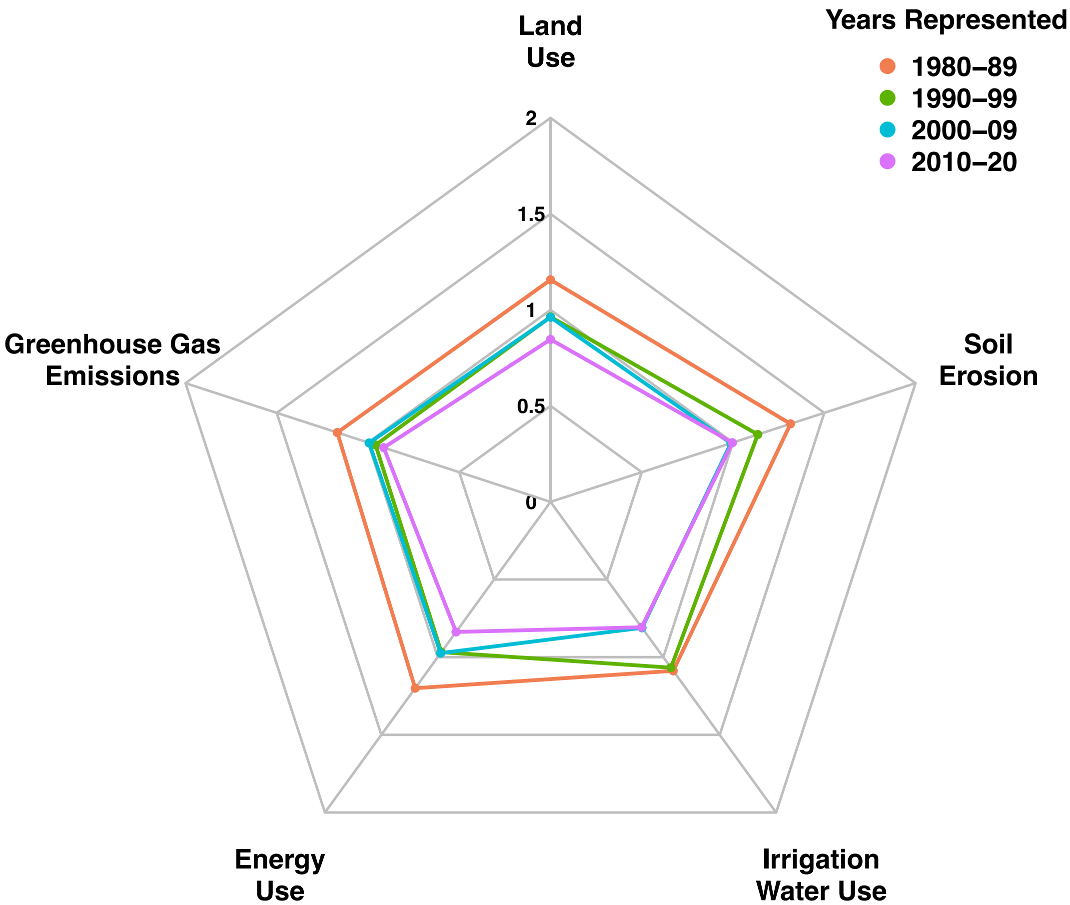
The fifth indicator is **Soil Erosion**, which is expressed as the amount of soil lost to wind and water erosion per acre. Reductions in loss of soil per acre are key to sustaining productivity, regardless of crop yield values. Detailed methodology for calculating the national indicators can be found in Appendix A.

1. BARLEY

Barley is a small grain crop predominantly grown in the north and west of the country, with the highest planted acreage in North Dakota, Montana and Idaho for the year 2020. Figure 1.1.1 illustrates the difference in the average indicator value for each decade and demonstrates clear improvement over time in land use, energy and greenhouse gas (GHG) emissions with a plateauing of soil erosion and irrigation water use in the past two decades. Table 1.1.1 presents a summary of all indicators for barley for reference years.

Figure 1.1.1. Summary chart of indicators for barley during 1980-2020

Data are presented in index form, where all indicators have been scaled by indicators averages for the period 1998-2002. A 0.1 point change is equal to a 10 percent difference. Index values allow for comparison of change across indicators with different units of measure. A smaller area represents improvement over time.



Indicators averages for barley for the period 1998-2002

Indicator	Value	Units
Land Use	0.0193	Planted Acres Per Bushel
Irrigation Water Use	0.421	Acre-inches Per Bushel
Soil Erosion	5.85	Tons Soil Loss Per Acre
Energy Use	67,300	BTU Per Bushel
Greenhouse Gas Emissions	16.9	Pounds of CO_2 Eq. Per Bushel

Table 1.1.1. Summary of indicators for barley

Year	Land Use	Irrigation Water Use	Energy Use	Greenhouse Gas Emissions	Soil Erosion
	Planted Acres Per Bushel	Acre Inches Per Bushel	BTU Per Bushel	Pounds of CO_2e Per Bushel	Tons of Soil Loss Per Acre
1980	0.0213	0.4663	79,797	19.4	7.8
1990	0.0208	0.4524	73,345	18.1	7.2
2000	0.0187	0.4041	65,276	16.4	6
2010	0.0173	0.3239	61,266	16.3	5.5
2020	0.0159	0.3562	52,189	14.6	6.6

LAND USE

After an increase in area and production during the 1980s, area and production have declined since 1990 (Figures 1.1.2 and 1.1.3, respectively). The rate of decline has slowed over the past decade (2010s) and the land use indicator has plateaued during this time, indicating steady, but not increasing, crop yield (Figure 1.1.4). This leveling out of crop yield will influence the other efficiency indicators.

Figure 1.1.2. Area planted (million acres) to barley during 1980-2020

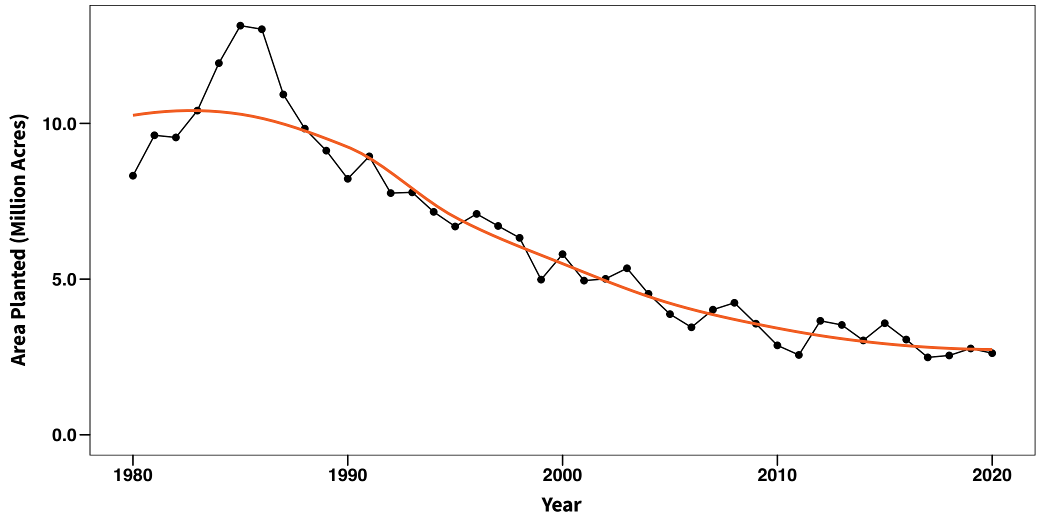


Figure 1.1.3. Total production (million bushels) of barley during 1980-2020

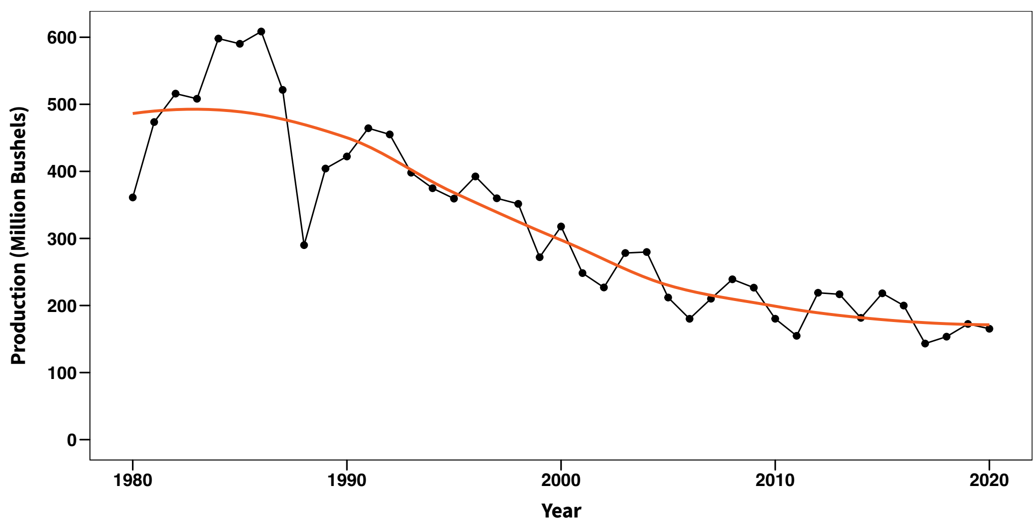
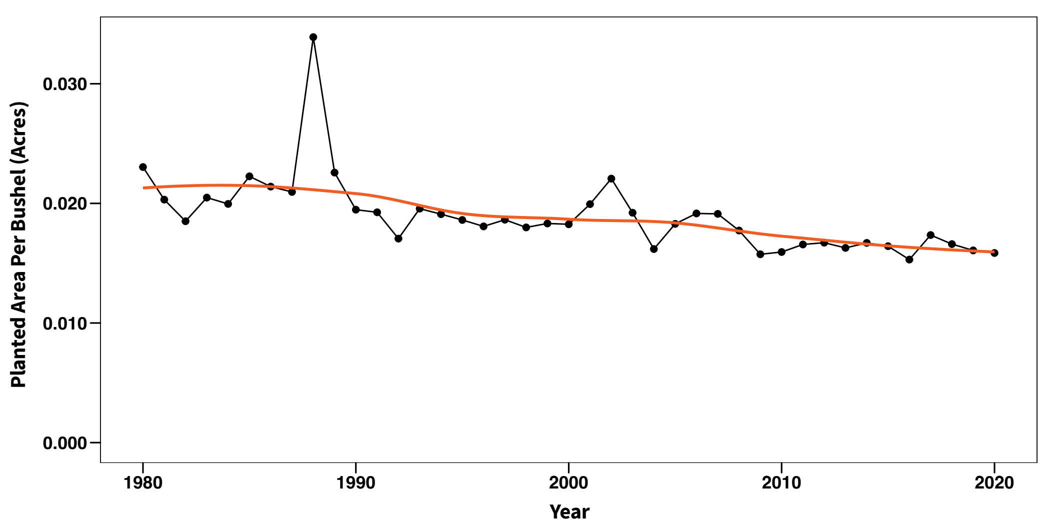


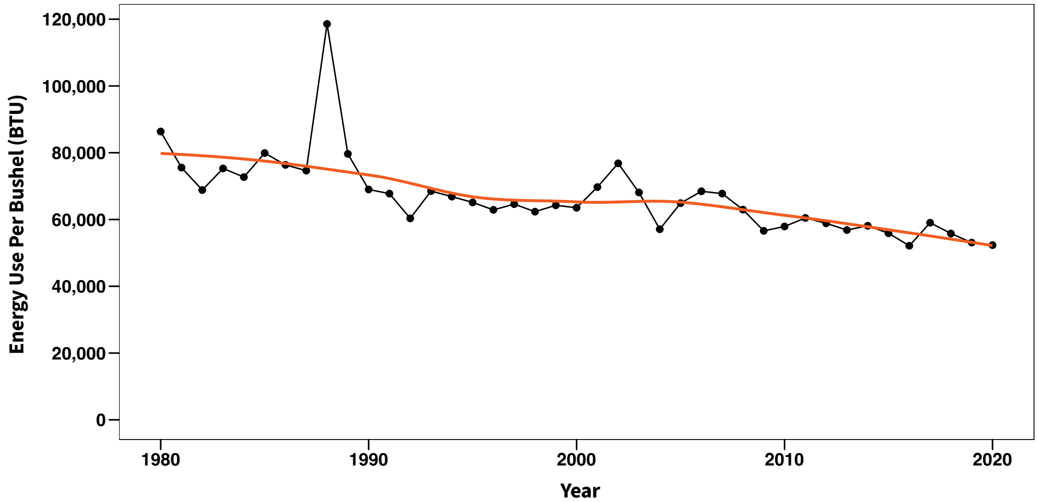
Figure 1.1.4. Land use efficiency (acres planted / bushel) for barley during 1980-2020



ENERGY USE

Energy use efficiency for barley has improved steadily since 1990 (Figure 1.1.5). Energy use per acre (Figure B.1) has also shown improvements in the most recent period (2010s), which can largely be attributed to declines in energy use for management and are embedded in fertilizer production (Figure B.2).

Figure 1.1.5. Energy use efficiency (BTU / bushel) for barley during 1980-2020



GREENHOUSE GAS EMISSIONS

Greenhouse gas (GHG) emissions per bushel of barley produced have declined over the 40-year period of analysis (Figure 1.1.6). However, on a per acre basis, emissions increased between 2000 and 2010, before beginning to decline again (Figure B.3). One major driver of this trend is nitrous oxide emissions from synthetic fertilizer and manure (Figure B.4). Applications of both have increased over time with a slight reduction in synthetic nitrogen application in the past five years. There has also been a small increase in emissions related to the production and application of a larger volume of crop protectants, principally fungicides, since 2000 that is contributing to the emissions trend. The top four contributors for energy use and GHG emissions for barley during 2010-2020 are listed in Table 1.1.2.

Figure 1.1.6. Greenhouse gas emissions (lb. CO_2 Eq. / bushel) for barley during 1980-2020

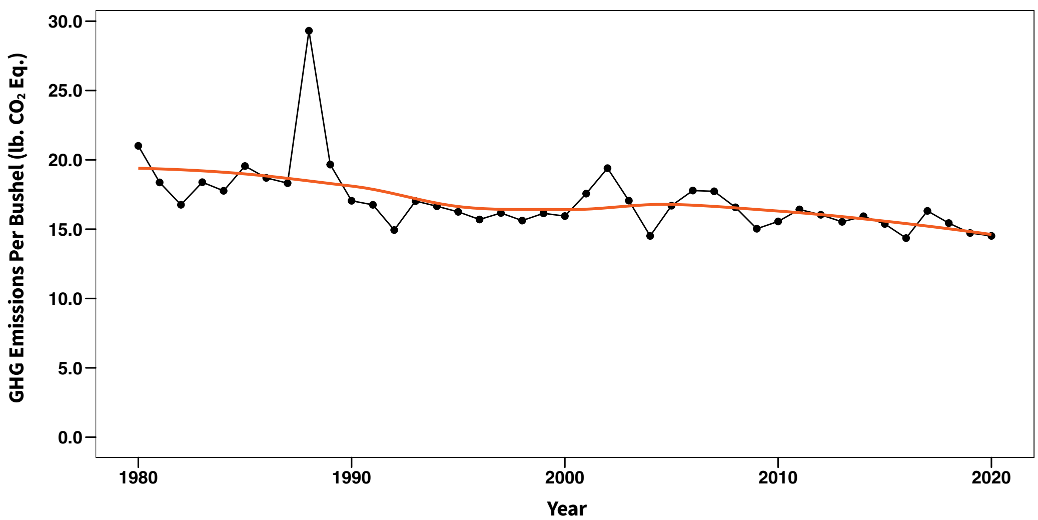


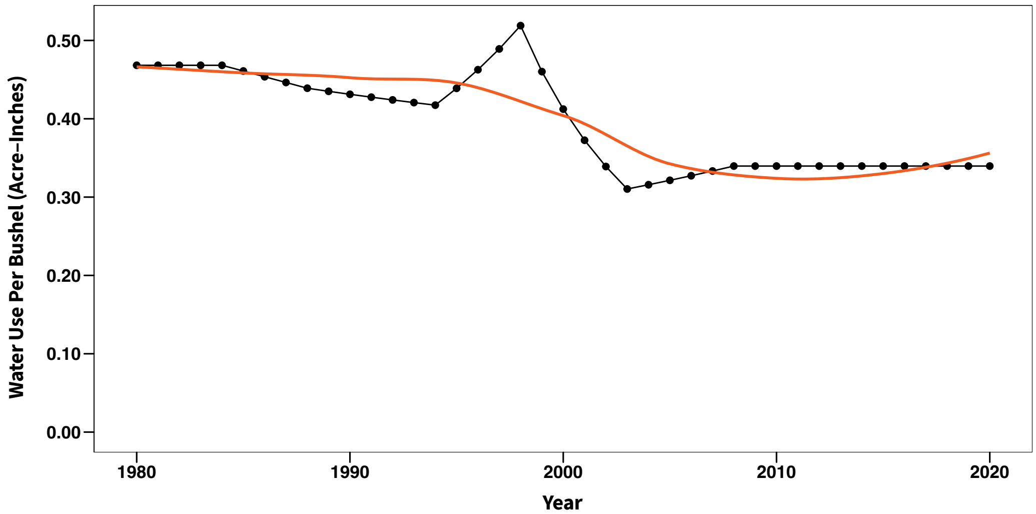
Table 1.1.2. Top four contributors for barley for the EU and GHG Emissions indicators during 2010-2020

ENERGY USE	GHG EMISSIONS
Fertilizer	Nitrous Oxide
Management	Fertilizer
Irrigation	Management
Seed	Irrigation

IRRIGATION WATER USE

Irrigation water use efficiency for barley has improved over the full period of analysis (Figure 1.1.7). Initial declines in the 1980s were followed by increases in the 1990s with further declines since 2000. In the most recent decade, improvement in water use efficiency has continued but the rate has slowed. This reflects incremental improvements in the efficiency of water use in this period, with greater gains made in the 2000-2010 period. This improvement in irrigation efficiency has also led to improvement in energy use efficiency for barley in the 2010s. The last available Irrigation and Water Management Survey for barley in 2008 indicated that approximately 20% of harvested acreage was irrigated when compared to the total harvested acres.

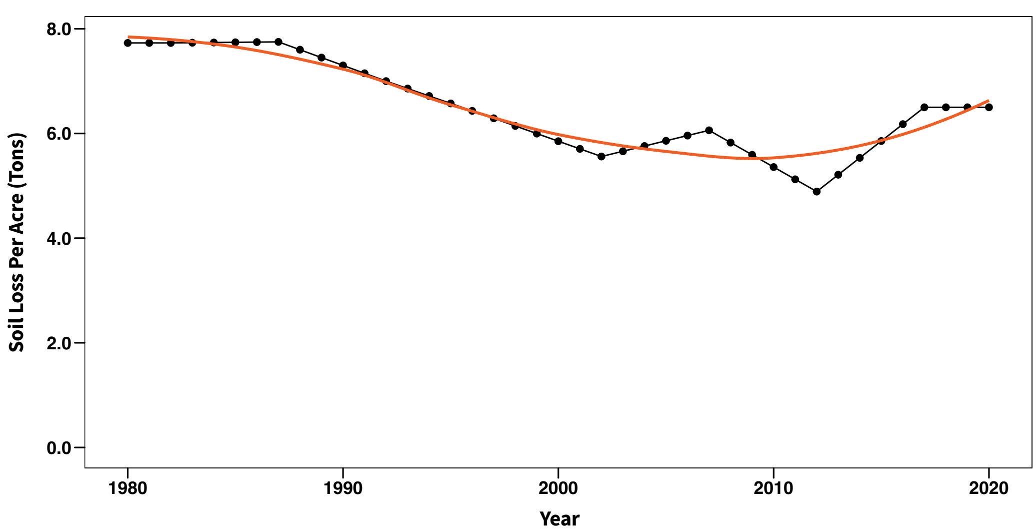
Figure 1.1.7. Irrigation water use efficiency (acre-inches / bushel) for barley during 1980-2020



SOIL EROSION

Soil erosion for barley declined from 1980 through to 2000, with an additional period of decline from 2005-2010 (Figure 1.1.8). However, in the most recent decade, soil erosion has been increasing despite an increase in no-till for barley since 2005.

Figure 1.1.8. Soil erosion (tons soil loss / acre / year) from fields producing barley during 1980-2020

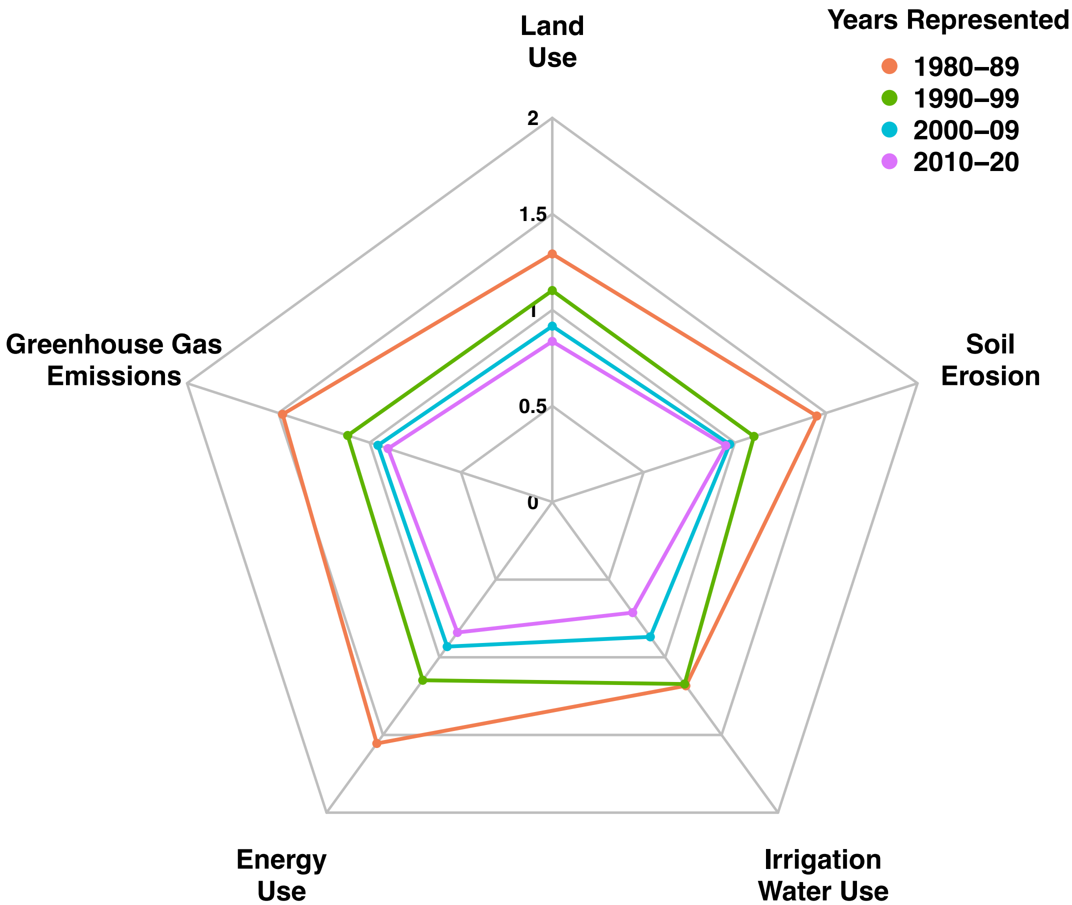


2. CORN (GRAIN)

Corn is one of the most extensively grown crops in the United States with some production in almost every state. Corn can be harvested either for grain or for silage, depending on markets, weather and other environmental conditions. The highest acreage of corn harvested for grain occurs in the Midwest states of Iowa, Illinois, Indiana, Minnesota and Nebraska, with production area in South Dakota and Kansas increasing over the past 15 years. The summary graphic for corn grain indicates improvements over time in most indicators, with that improvement slowing over time, and stalling for soil erosion in the 2010s (Figure 1.2.1). A summary of all corn for grain indicators is shown in Table 1.2.1.

Figure 1.2.1. Summary chart of indicators for corn grain during 1980-2020

Data are presented in index form, where all indicators have been scaled by indicator averages for the period 1998-2002. A 0.1 point change is equal to a 10 percent difference. Index values allow for comparison of change across indicators with different units of measure. A smaller area represents improvement over time.



Indicators averages for corn grain for the period 1998-2002

Indicator	Value	Units
Land Use	0.00757	Planted Acres Per Bushel
Irrigation Water Use	0.254	Acre-inches Per Bushel
Soil Erosion	4.88	Tons Soil Loss Per Acre
Energy Use	48,700	BTU Per Bushel
Greenhouse Gas Emissions	12.8	Pounds of CO_2 Eq. Per Bushel

Table 1.2.1. Summary of indicators for corn grain

Year	Land Use	Irrigation Water Use	Energy Use	Greenhouse Gas Emissions	Soil Erosion
	Planted Acres Per Bushel	Acre Inches Per Bushel	BTU Per Bushel	Pounds of CO_2e Per Bushel	Tons of Soil Loss Per Acre
1980	0.0104	0.3497	83,276	20.6	7.8
1990	0.009	0.2865	64,551	16.3	6.1
2000	0.0075	0.2638	48,094	12.6	4.8
2010	0.0066	0.1998	42,873	11.9	4.6
2020	0.0058	0.1533	37,791	10.7	4.7

LAND USE

Area planted to corn has increased since the late 1980s but plateaued during the 2010s (Figure 1.2.2), while total production has continued to increase (Figure 1.2.3). The land use indicator reflects this increasing yield trend, demonstrating that it takes less land to produce a bushel of corn in 2020 than in 1980. (Figure 1.2.4). The trend for the 2010-2020 period is largely influenced by the low yields of 2012 in response to extreme weather events. There is a flattening of the land use efficiency indicator from 2014-2020, indicating a plateau in the yield improvement trend.

Figure 1.2.2. Area planted (million acres) to corn grain during 1980-2020

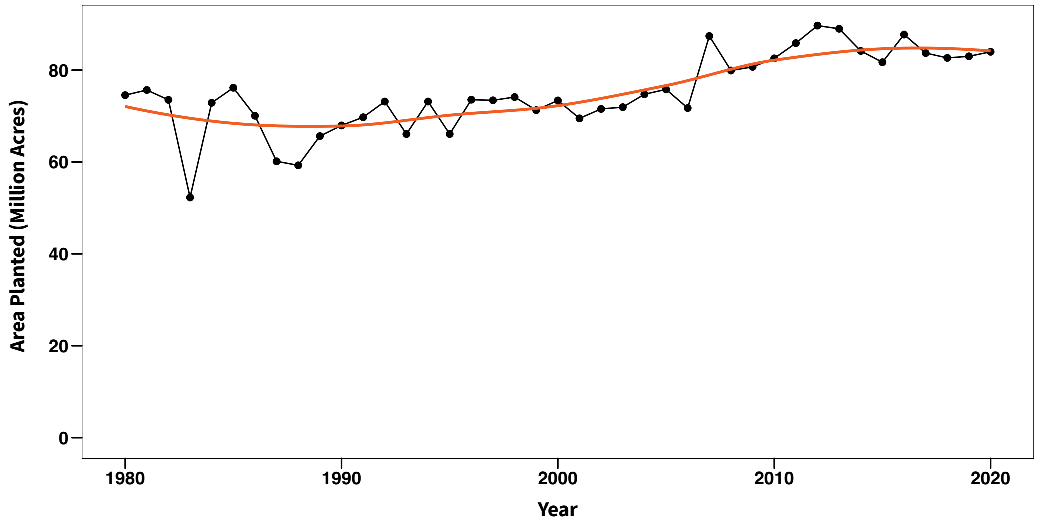


Figure 1.2.3. Total production (million bushels) of corn grain during 1980-2020

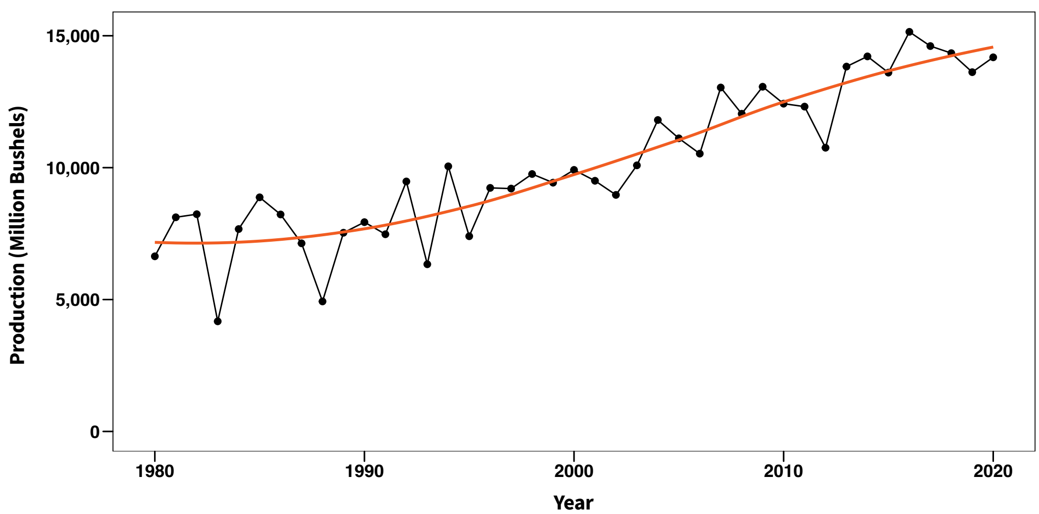
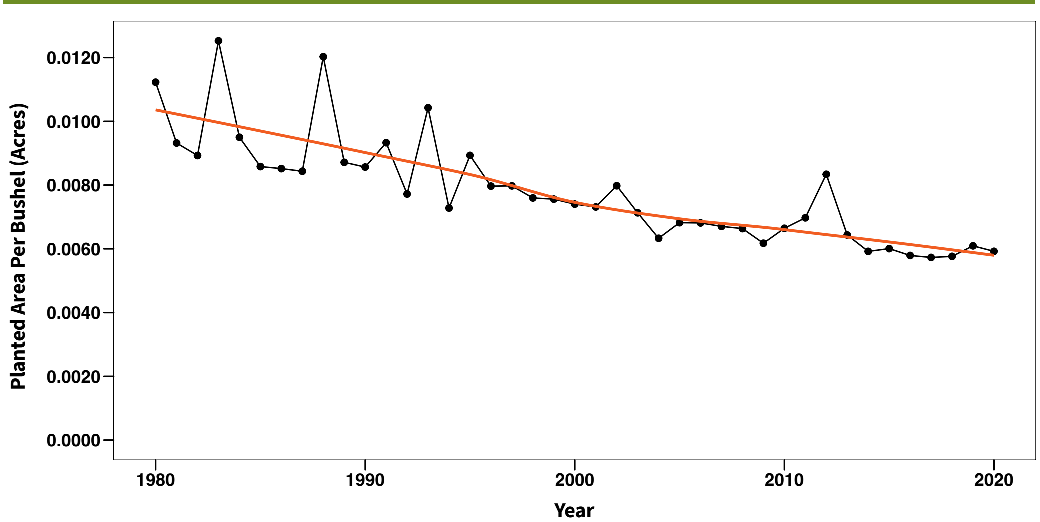


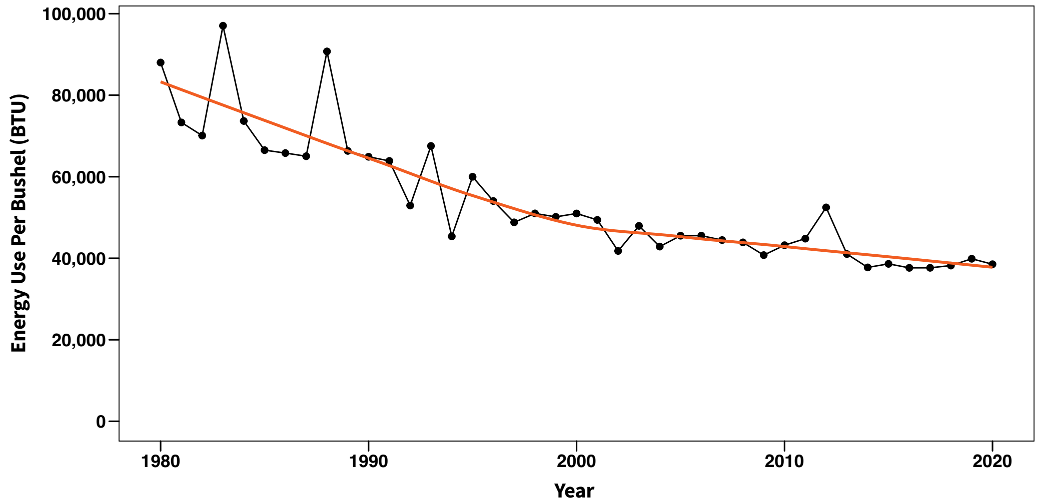
Figure 1.2.4. Land use efficiency (acres planted / bushel) for corn grain during 1980-2020



ENERGY USE

Energy use efficiency has improved throughout the period of analysis up until 2010 – however, since 2014, corn energy use efficiency has plateaued (Figure 1.2.5). The energy use per acre indicates a leveling off and slight increase in energy use for corn production (Figure B.5). This may reflect the increase in inputs, in particular fertilizers, fungicides and herbicides since the year 2000.

Figure 1.2.5. Energy use efficiency (BTU / bushel) for corn grain during 1980-2020



GREENHOUSE GAS EMISSIONS

GHG emissions per bushel of corn (Figure 1.2.6) largely follows the energy use trend for corn, with the major contributor being nitrous oxide emissions (Figure B.8). Small GHG emission increases per acre (Figure B.7) since 2000 can be attributed in part to the factors behind the plateauing of energy use, with the additional contribution of higher fertilizer nitrogen applications leading to greater nitrous oxide emissions. While manure is applied to corn grain, it contributes less than 5% of the total nitrogen applied in the most recent decade, therefore the nitrous oxide emissions increase is largely driven by synthetic nitrogen applications, which have been rising steadily since 2000. The top four contributors for energy use and GHG emissions for corn grain during 2010-2020 are listed in Table 1.2.2.

Figure 1.2.6. Greenhouse gas emissions (lb. CO_2 Eq. / bushel) for corn grain during 1980-2020

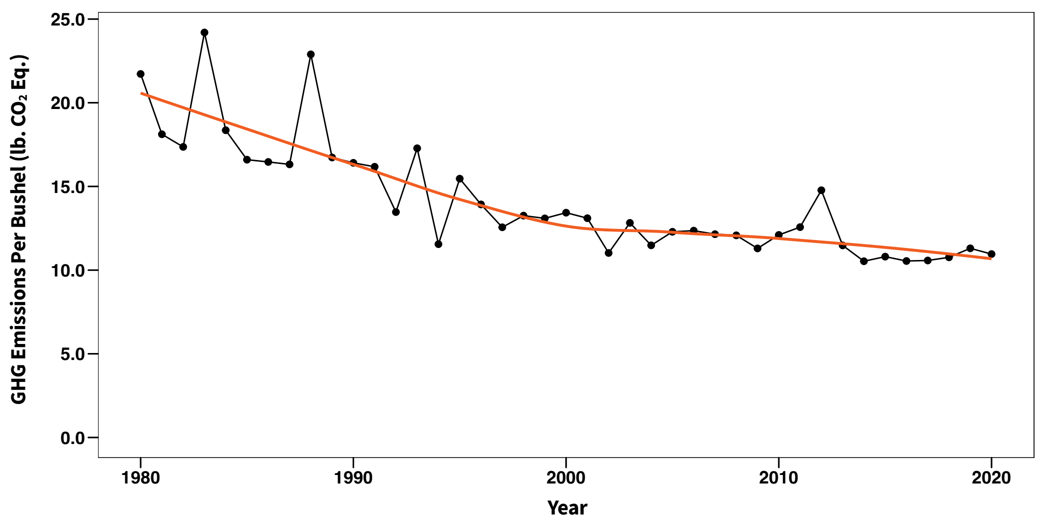


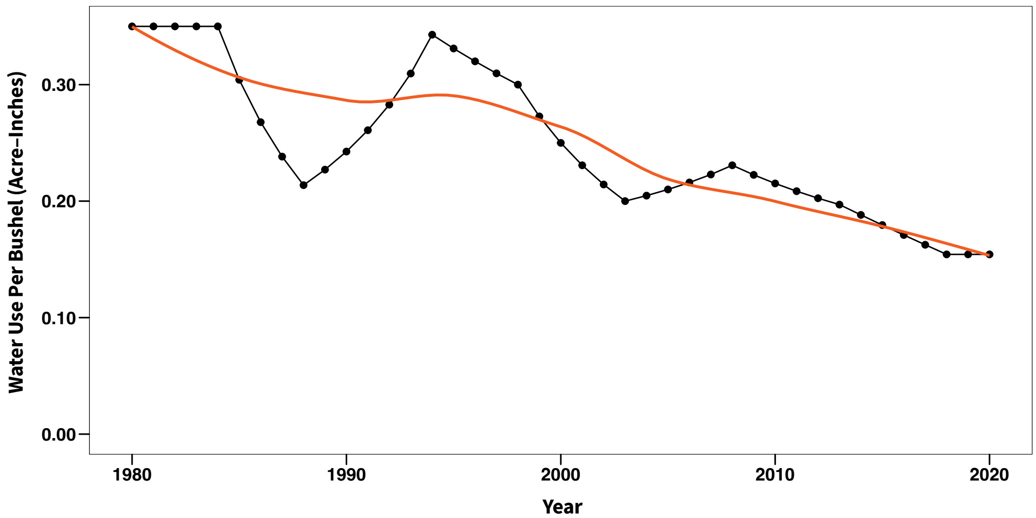
Table 1.2.2. Top four contributors for corn grain for the EU and GHG Emissions indicators during 2010-2020

ENERGY USE	GHG EMISSIONS
Fertilizer	Nitrous Oxide
Management	Fertilizer
Drying	Management
Crop Protection	Drying

IRRIGATION WATER USE

Irrigation water use efficiency fluctuated in the first half of the study period as the area planted to corn expanded and reached a high value in the mid-1990s (Figure 1.2.7). Since then, the irrigation water use efficiency has improved steadily for corn. The average irrigated harvested acreage across the 2008, 2013 and 2018 Irrigation and Water Management Survey for corn grain was approximately 15% of the total harvested acres.

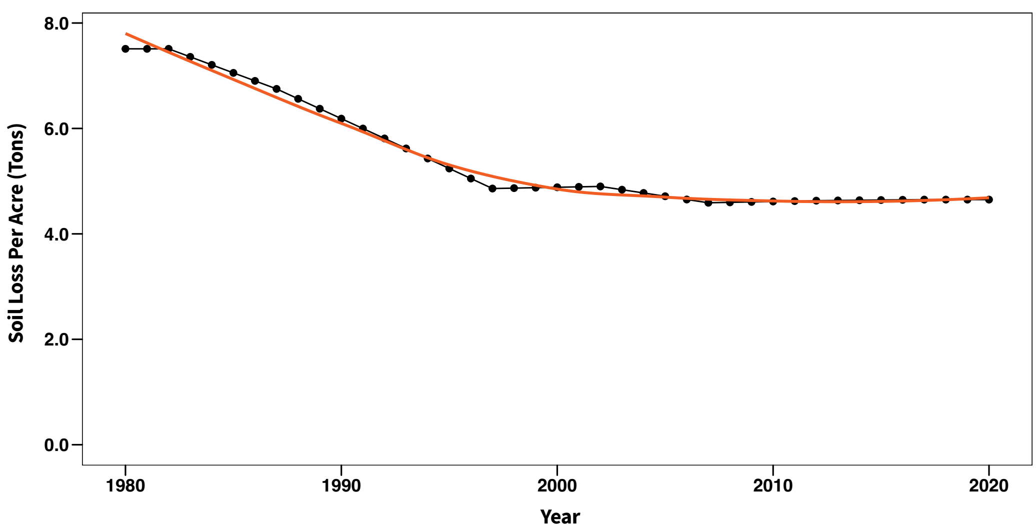
Figure 1.2.7. Irrigation water use efficiency (acre-inches / bushel) for corn grain during 1980-2020



SOIL EROSION

Soil erosion for corn grain has largely plateaued since 2000 (Figure 1.2.8). While substantial improvements were seen in the period from 1980-2000, those have not continued. One major driver is tillage, and available data indicate that the share of corn under conventional tillage practices remains over 30%, with another 40% in a reduced tillage system and less than 30% under no tillage. Shifts over time in the location of production to areas farther west – which may be more susceptible to wind erosion – may also be influencing this trend.

Figure 1.2.8. Soil erosion (tons soil loss / acre / year) from fields producing corn grain during 1980-2020



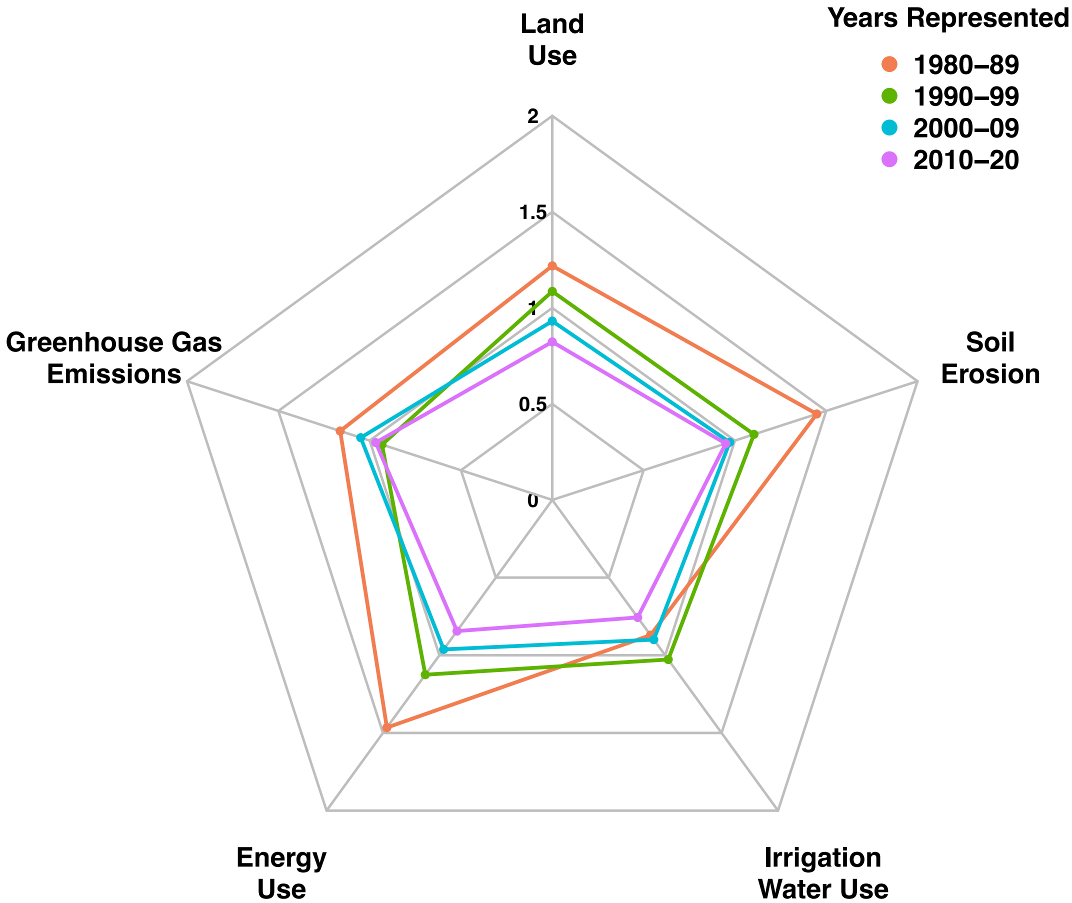
3. CORN (SILAGE)

Corn is also grown for silage for animal feed. Silage corn production practices are similar to those for corn grain in the first part of the growing season, but the entire stalk is harvested earlier in the season leaving far less crop residue after harvest. Therefore, we consider it here as a separate cropping system than corn for grain. A producer may decide partway through the season to harvest the corn crop as silage, rather than wait to harvest as grain, depending on market and weather conditions. Silage corn is grown in almost every U.S. state, with high production in the upper Midwest states and other large dairy states, including New York, Pennsylvania and California.

The summary chart for corn silage illustrates overall improvements in energy use and land use, but with a recent reversal in the energy use trend and a fluctuation over time in irrigation water use (Figure 1.3.1). A summary of all indicators for corn silage for reference years is shown in Table 1.3.1. Note that the soil erosion indicator for corn silage is the same data as presented for corn grain and is discussed in the previous section (for more information see Appendix A, section Corn for Grain and Silage).

Figure 1.3.1. Summary chart of indicators for corn silage during 1980-2020

Data are presented in index form, where all indicators have been scaled by indicator averages for the period 1998-2002. A 0.1 point change is equal to a 10 percent difference. Index values allow for comparison of change across indicators with different units of measure. A smaller area represents improvement over time.



Indicators averages for corn silage for the period 1998-2002

Indicator	Value	Units
Land Use	0.064	Planted Acres Per Ton
Irrigation Water Use	2.79	Acre-inches Per Ton
Soil Erosion	4.88	Tons Soil Loss Per Acre
Energy Use	398,000	BTU Per Ton
Greenhouse Gas Emissions	141	Pounds of CO_2 Eq. Per Ton

Table 1.3.1. Summary of indicators for corn silage

Year	Land Use	Irrigation Water Use	Energy Use	Greenhouse Gas Emissions	Soil Erosion
	Planted Acres Per Ton	Acre Inches Per Ton	BTU Per Ton	Pounds of CO_2e Per Ton	Tons of Soil Loss Per Acre
1980	0.0761	2.801	595,859	168.9	7.8
1990	0.0756	2.5028	520,679	147.2	6.1
2000	0.0629	2.8568	392,724	136.2	4.8
2010	0.0557	2.2506	358,846	147	4.6
2020	0.0493	2.109	312,716	122.2	4.7

LAND USE

Area planted to corn for silage declined from 1980 to 1990, was roughly level until around 2010 and has started to increase in recent years (Figure 1.3.2). Overall, total production of corn silage has increased since 1990. (Figure 1.3.3). There are several spikes in the acreage data (Figure 1.3.2) likely attributed to weather events where corn planted initially for grain was instead harvested for silage to avoid economic loss of the entire crop. One such spike was observed in 2012, a year with severe drought. The land use efficiency of corn silage production has steadily improved since 1990, indicating increasing yields per acre harvested (Figure 1.3.4).

Figure 1.3.2. Area planted (million acres) to corn silage during 1980-2020

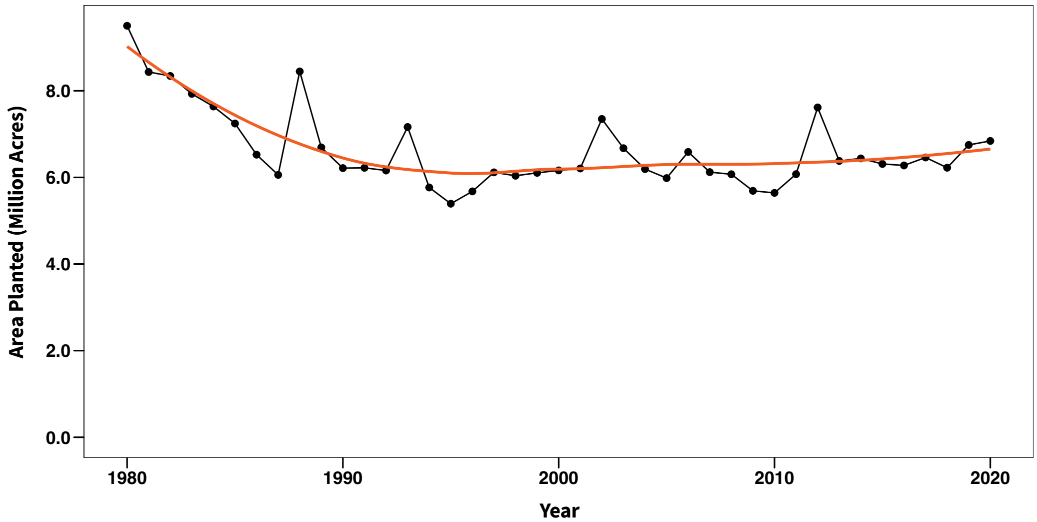


Figure 1.3.3. Total production (million tons) of corn silage during 1980-2020

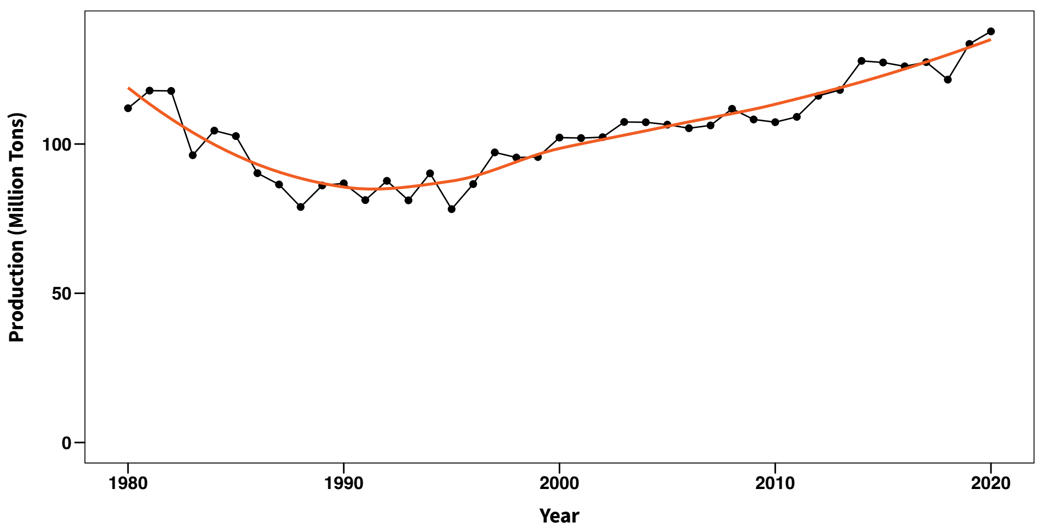
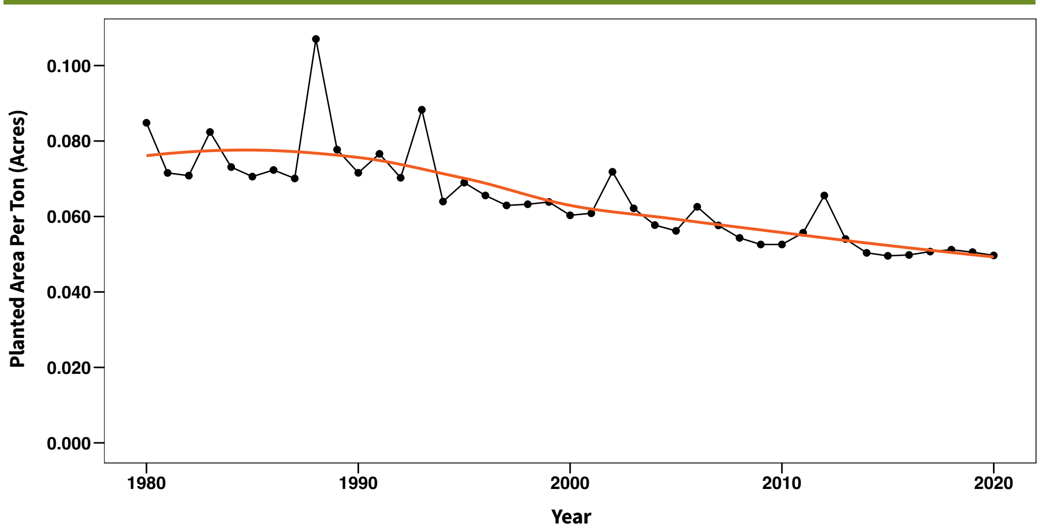


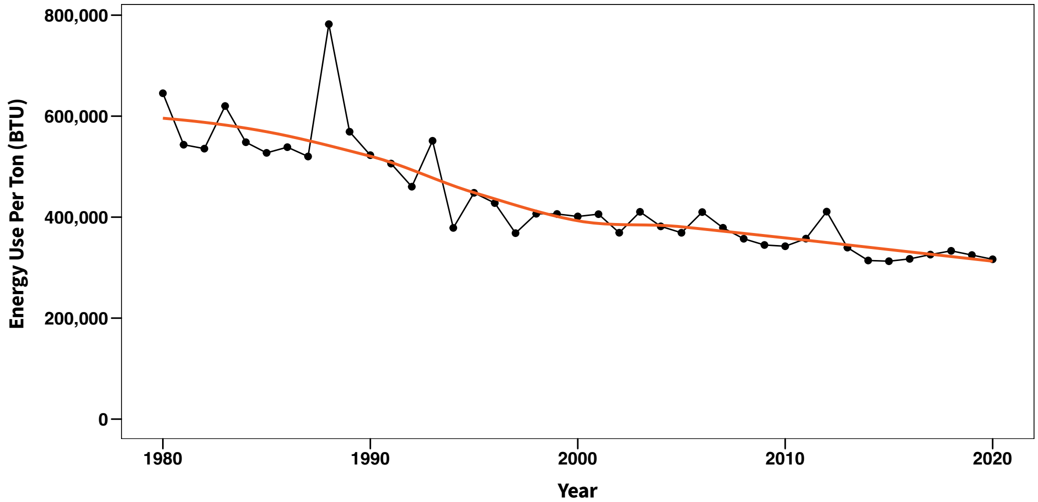
Figure 1.3.4. Land use efficiency (acres planted / ton) for corn silage during 1980-2020



ENERGY USE

Overall energy use efficiency has improved through 2010 for corn silage, with a leveling off in the past decade (Figure 1.3.5). Energy embedded in the production of fertilizers and field operations (management) are the major components for the energy use efficiency indicator (Figure B.10).

Figure 1.3.5. Energy use efficiency (BTU / ton) for corn silage during 1980-2020



GREENHOUSE GAS EMISSIONS

Emissions associated with corn silage production do not show a clear trend, with emissions per unit of yield lower in 2020 than in 1980, but with the lowest values achieved in the 1990s (Figure 1.3.6). Emissions per acre have increased since 2000 (Figure B.11), with the primary component of increase being nitrous oxide emissions. Nitrogen content from manure applied to fertilize corn for silage has a considerable impact. The top four contributors for corn silage for energy use and GHG emissions during 2010-2020 are listed in Table 1.3.2.

Figure 1.3.6. Greenhouse gas emissions (lb. CO_2 Eq. / ton) for corn silage during 1980-2020

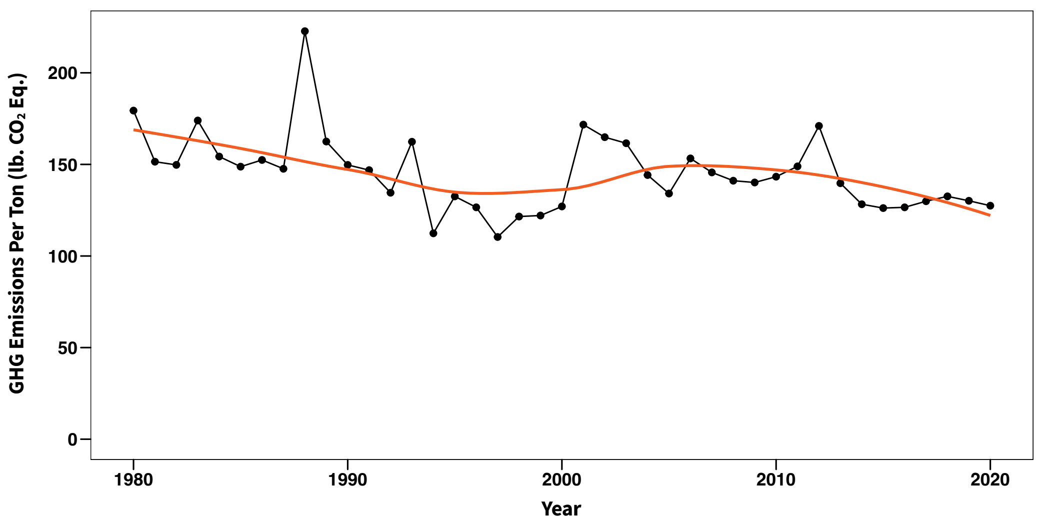


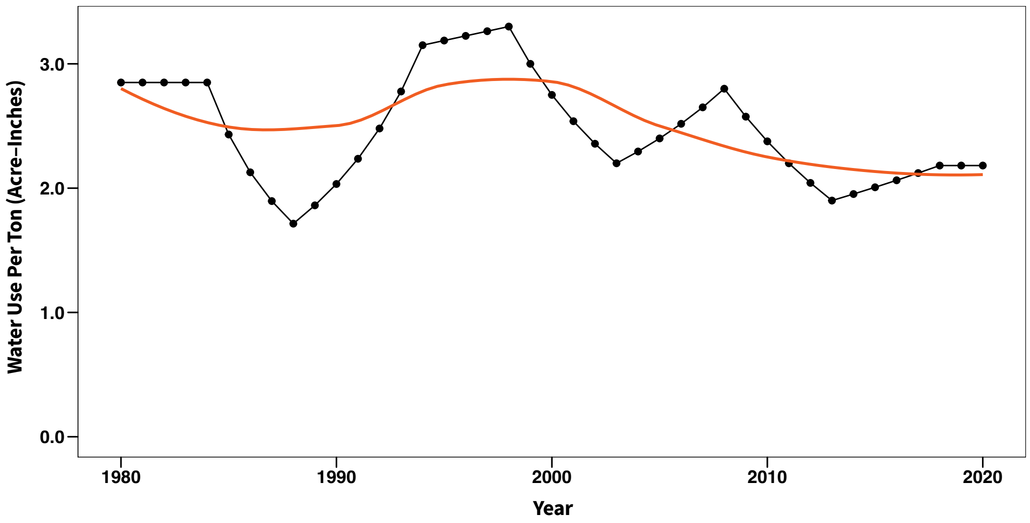
Table 1.3.2. Top four contributors for corn silage for the EU and GHG Emissions indicators during 2010-2020

ENERGY USE	GHG EMISSIONS
Fertilizer	Nitrous Oxide
Management	Fertilizer
Irrigation	Management
Crop Protection	Irrigation

IRRIGATION WATER USE

Irrigation water use efficiency for corn silage does not show a clear trend (Figure 1.3.7). The water use efficiency in 2020 is lower than that in the late 1980s, following variable patterns in the subsequent years. The trend is similar to that for corn grain. Over time, the share of irrigated acreage for corn silage has been increasing. The average irrigated harvested acres across the 2008, 2013 and 2018 Irrigation and Water Management Survey for corn silage was approximately 27% of the total harvested acres.

Figure 1.3.7. Irrigation water use efficiency (acre-inches / ton) for corn silage during 1980-2020

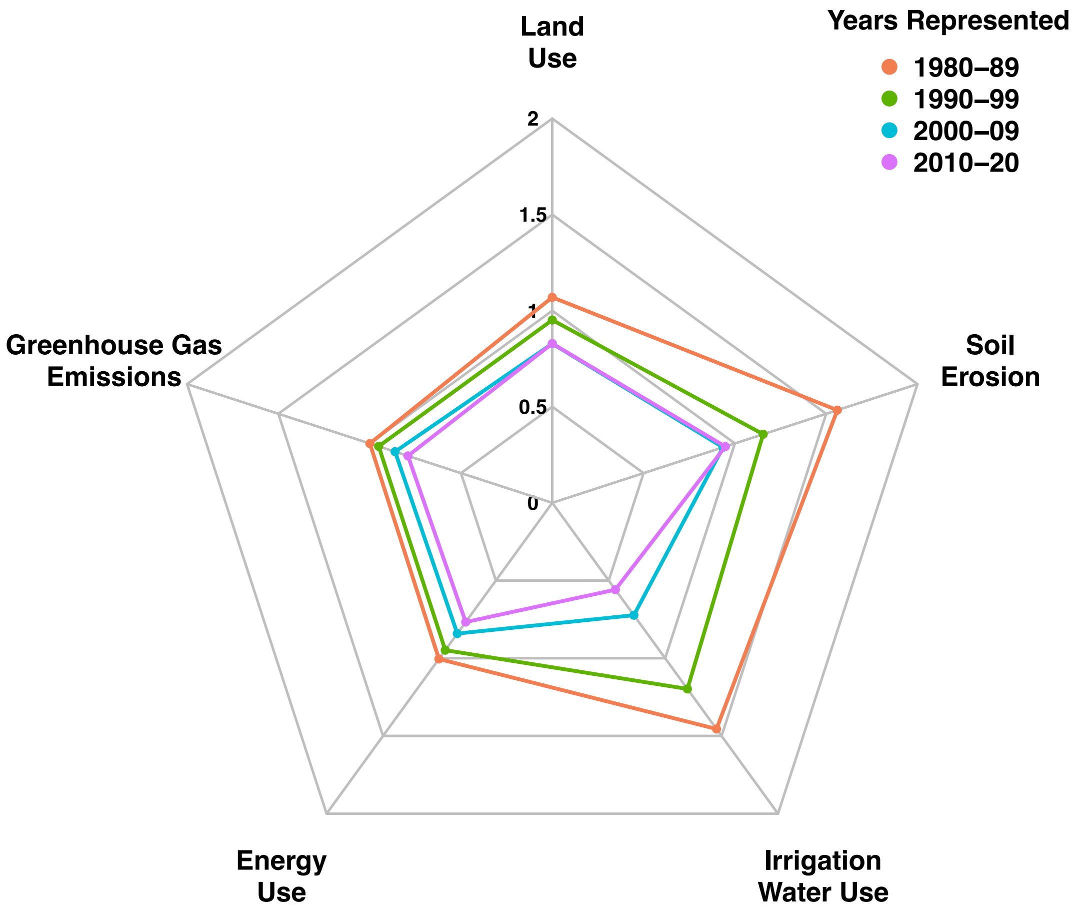


4. COTTON

Cotton is predominantly grown throughout the southern U.S., with the most acreage historically in Texas. The summary chart for cotton indicates steady improvement over time in energy use, GHG emissions and irrigation water use, with recent trends since 2010 stalling in soil erosion and land use (Figure 1.4.1). Table 1.4.1 presents a summary of all indicators for cotton for reference years.

Figure 1.4.1. Summary chart of indicators for cotton during 1980-2020

Data are presented in index form, where all indicators have been scaled by indicator averages for the period 1998-2002. A 0.1 point change is equal to a 10 percent difference. Index values allow for comparison of change across indicators with different units of measure. A smaller area represents improvement over time.



Indicators averages for cotton for the period 1998-2002

Indicator	Value	Units
Land Use	0.0018	Planted Acres Per lb. of Lint
Irrigation Water Use	0.0421	Acre-inches Per lb. of Lint
Soil Erosion	11.2	Tons Soil Loss Per Acre
Energy Use	7,780	BTU Per lb. of Lint
Greenhouse Gas Emissions	1.79	Pounds of CO_2 Eq. Per lb. of Lint

Table 1.4.1. Summary of indicators for cotton

Year	Land Use	Irrigation Water Use	Energy Use	Greenhouse Gas Emissions	Soil Erosion
	Planted Acres Per lb. of Lint	Acre Inches Per lb. of Lint	BTU Per lb. of Lint	Pounds of CO_2e Per lb. of Lint	Tons of Soil Loss Per Acre
1980	0.0023	0.0629	9,022	2	19.5
1990	0.0017	0.0566	7,185	1.7	14.7
2000	0.0016	0.0406	7,271	1.7	11.2
2010	0.0014	0.0233	5,983	1.4	10.3
2020	0.0016	0.0262	6,259	1.5	10.7

LAND USE

The acreage planted to cotton has varied from eight to more than 16 million acres over the study period (Figure 1.4.2), and total production has seen variability in the 2000-2020 period (Figure 1.4.3). The land use indicator for cotton shows increased efficiency (yield) in the 1980s and 2000s with reduced yield through the 1990s and a leveling of yield in the 2010s, with significant interannual variability throughout the study period (Figure 1.4.4).

Figure 1.4.2. Area planted (million acres) to cotton during 1980-2020

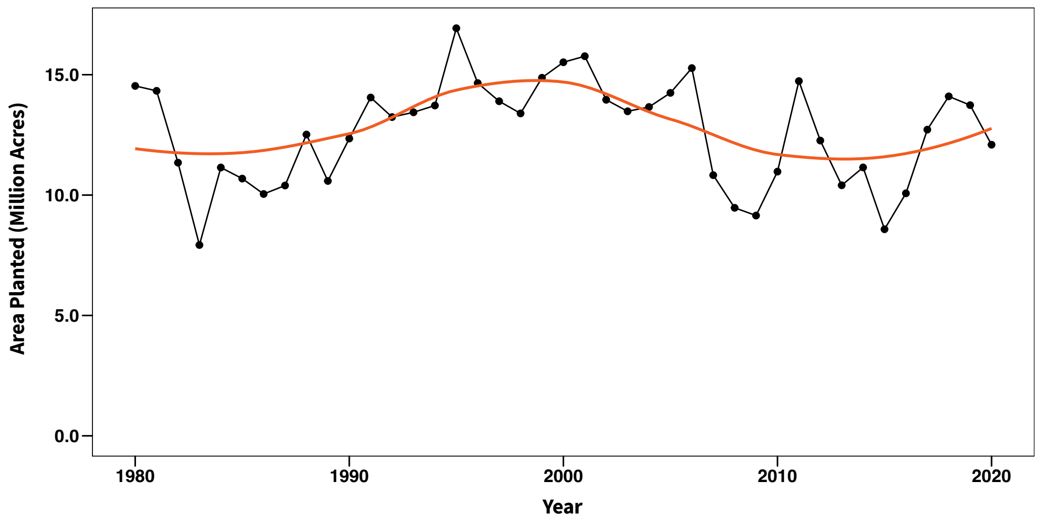


Figure 1.4.3. Total production (million lb. of lint) of cotton during 1980-2020

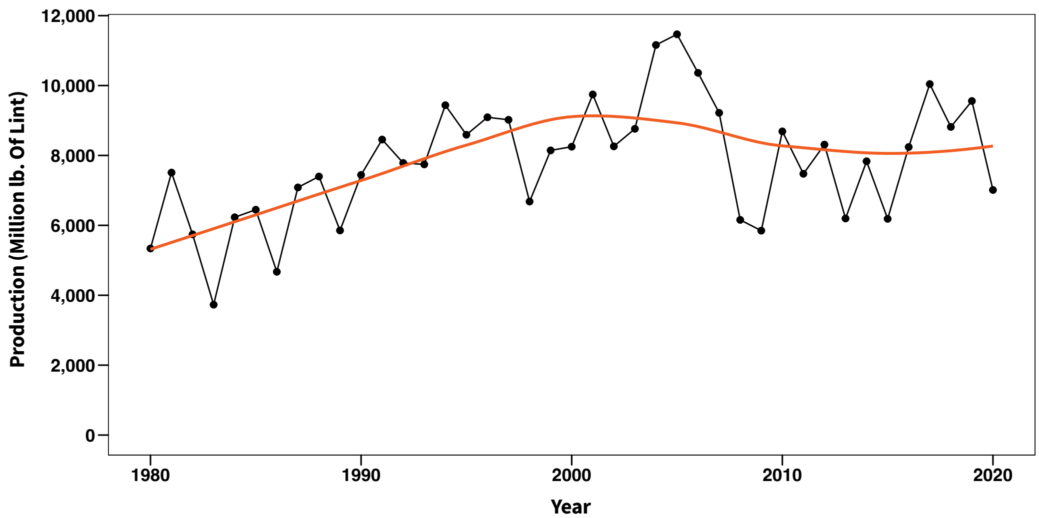
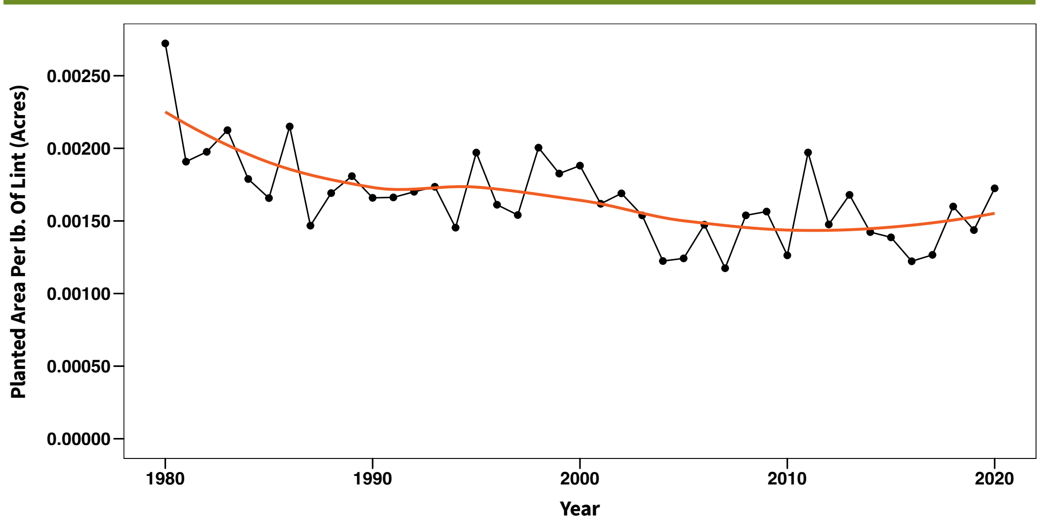


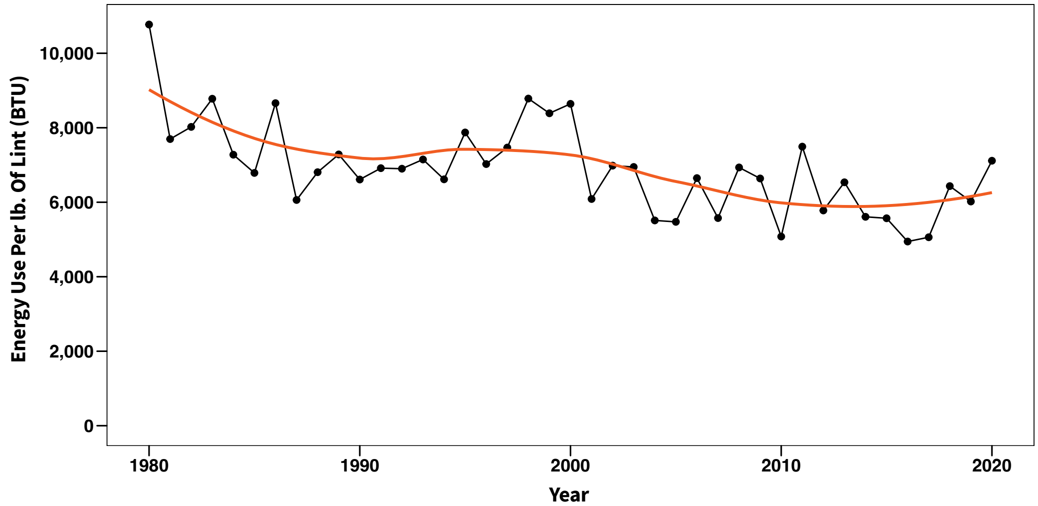
Figure 1.4.4. Land use efficiency (acres planted / lb. of lint) for cotton during 1980-2020



ENERGY USE

Energy use efficiency for cotton production has improved through the study period (Figure 1.4.5). Energy use per acre shows variability and higher values in the 1990s and 2000s compared to the 2010s, however, the 2010s show a moderate rate of increase in energy use per acre (Figure B.13). Energy used for management energy and fertilizer and crop protectant manufacturing are the greatest contributors to energy use per pound of harvested lint and show an upward trend for the last four years of this study (Figure B.14).

Figure 1.4.5. Energy use efficiency (BTU / lb. of lint) for cotton during 1980-2020



GREENHOUSE GAS EMISSIONS

Trends for GHG emissions from cotton production are similar to energy use efficiency, with some reductions followed by a leveling off in the past decade (Figure 1.4.6). The top four contributors for energy use and GHG emissions for cotton during 2010-2020 are listed in Table 1.4.2.

Figure 1.4.6. Greenhouse gas emissions (lb. CO_2 Eq. / lb. of lint) for cotton during 1980-2020

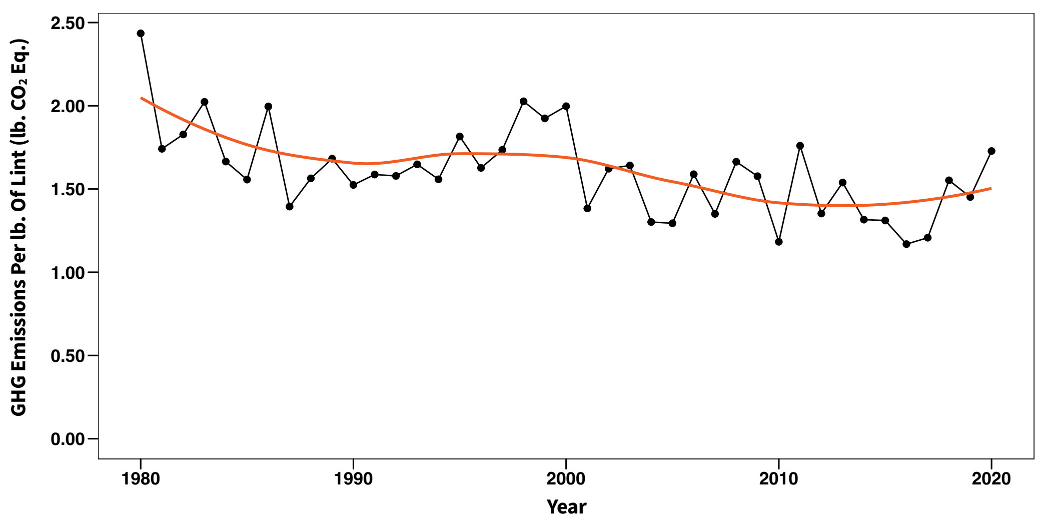


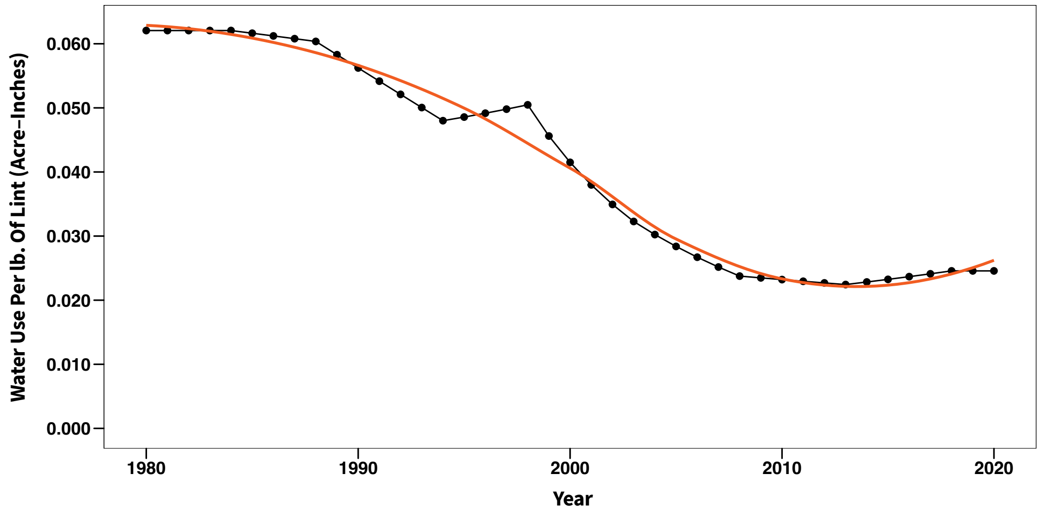
Table 1.4.2. Top four contributors for cotton for the EU and GHG Emissions indicators during 2010-2020

ENERGY USE	GHG EMISSIONS
Fertilizer	Nitrous Oxide
Management	Fertilizer
Crop Protection	Management
Drying	Crop Protection

IRRIGATION WATER USE

Irrigation water use efficiency for cotton showed consistent improvement from 1980 through 2010, but has been largely unchanged since around 2008 (Figure 1.4.7). Water use per acre by cotton has decreased likely in part due to the shift of production away from California, Arizona and New Mexico. In 1980, approximately 16% of planted acreage for cotton was in those three arid states, dropping to less than 2.7% in 2020. Water application rates for cotton have decreased approximately 38% during the period of this study, from 25.2 to 15.6 acre-inches/acre. The average irrigated harvested acreage across the 2008, 2013 and 2018 Irrigation and Water Management Survey for cotton was approximately 39% of the total harvested acres.

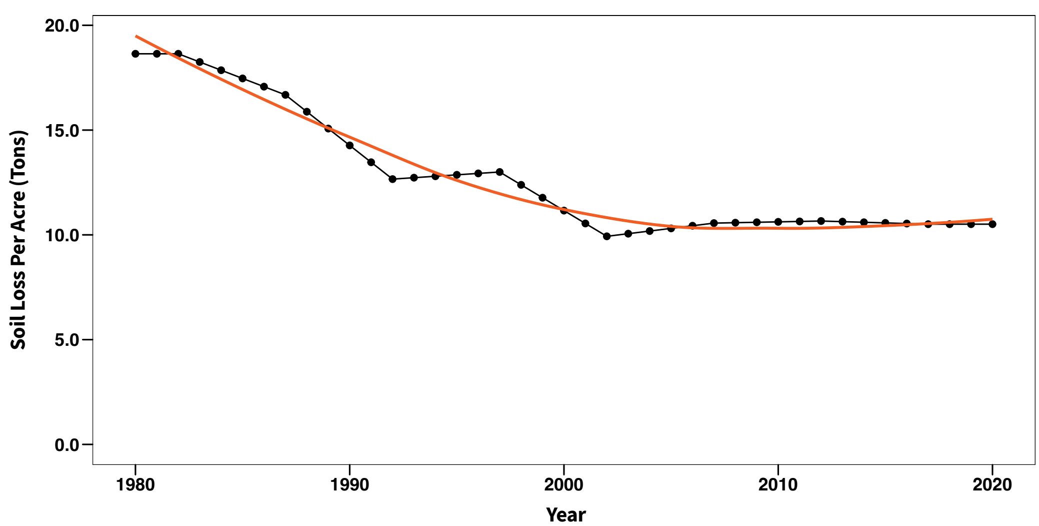
Figure 1.4.7. Irrigation water use efficiency (acre-inches / lb. of lint) for cotton during 1980-2020



SOIL EROSION

Soil erosion trends for cotton is very similar to that for corn, showing clear improvement for the period 1980-2000 but since then, holding steady with a consistent erosion rate of nearly 11 tons of soil loss per acre (Figure 1.4.8). While there was rapid adoption of no-till technologies in the period from 1990-2010, the share of no-till cotton has remained steady near 18% over the past decade, with a further 20% grown using reduced tillage and the remaining 60% still using conventional tillage.

Figure 1.4.8. Soil erosion (tons soil loss / acre / year) from fields producing cotton during 1980-2020

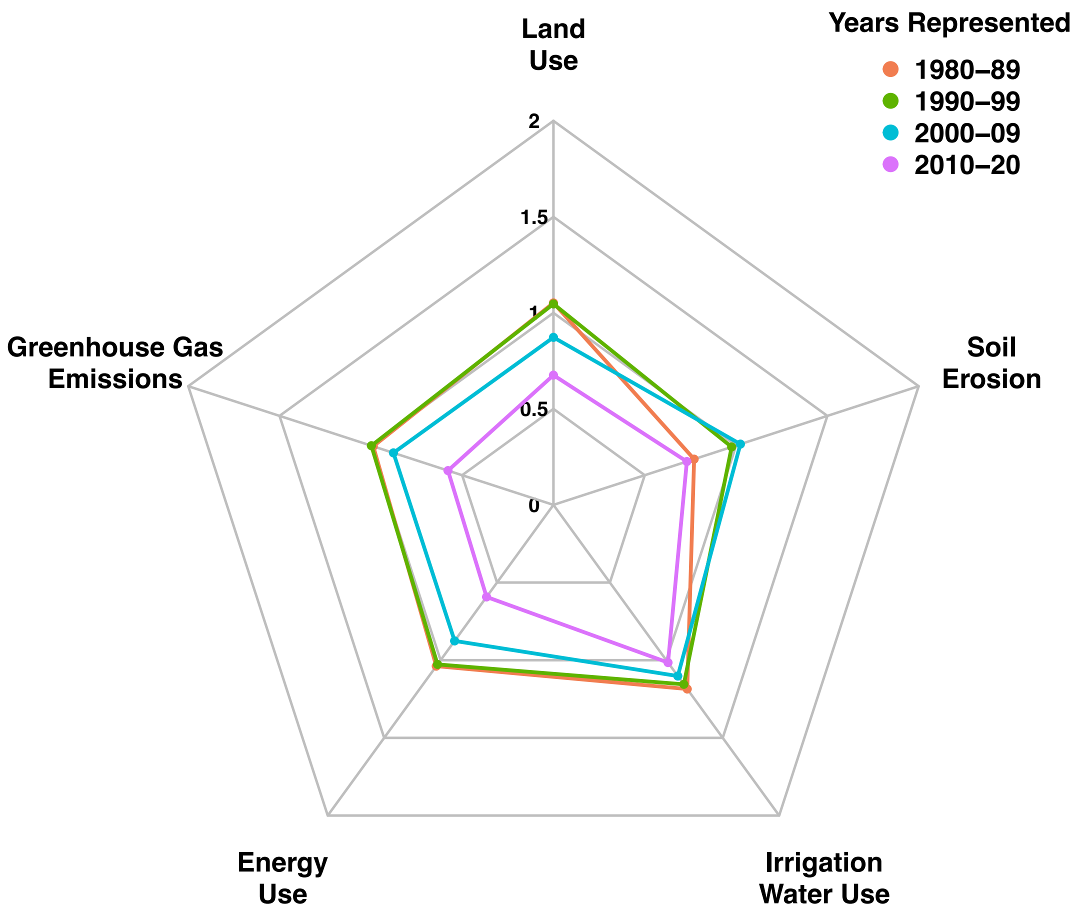


5. PEANUTS

Peanut production in the United States is concentrated in the south, with large acreage in the states of Georgia, Texas and Alabama, with Florida and the Carolinas also contributing significant acreage at different times over the past 40 years. The summary chart for peanuts indicates mixed results, representing a lack of clear trends over the study period (Figure 1.5.1). Values for energy use, GHG emissions and land use for the most recent period (2010-2020) are considerably lower than previous periods, while soil erosion and irrigation water use have seen more moderate improvements. A summary of all indicators for peanuts for reference years is shown in Table 1.5.1.

Figure 1.5.1. Summary chart of indicators for peanuts during 1980-2020

Data are presented in index form, where all indicators have been scaled by indicator averages for the period 1998-2002. A 0.1 point change is equal to a 10 percent difference. Index values allow for comparison of change across indicators with different units of measure. A smaller area represents improvement over time.



Indicators averages for peanuts for the period 1998-2002

Indicator	Value	Units
Land Use	0.000405	Planted Acres Per lb.
Irrigation Water Use	0.0115	Acre-inches Per lb.
Soil Erosion	8.97	Tons Soil Loss Per Acre
Energy Use	1,740	BTU Per lb.
Greenhouse Gas Emissions	0.344	Pounds of CO_2 Eq. Per lb.

Table 1.5.1. Summary of indicators for peanuts

Year	Land Use	Irrigation Water Use	Energy Use	Greenhouse Gas Emissions	Soil Erosion
	Planted Acres Per lb	Acre Inches Per lb	BTU Per lb	Pounds of CO_2e Per lb	Tons of Soil Loss Per Acre
1980	0.0005	0.0133	1,960	0.4	6.4
1990	0.0004	0.0138	1,789	0.3	7.9
2000	0.0004	0.0119	1,689	0.3	9.4
2010	0.0003	0.0137	1,243	0.2	7.8
2020	0.0003	0.0075	880	0.2	6.4

LAND USE

Land planted to peanuts has fluctuated over the years (Figure 1.5.2) in response to several factors including quota systems in the early years of the study period that set limits on peanut acreage by state. The quota system for peanuts was ended in 2002 (Dohlman et al., 2004). Production has steadily increased, with the highest production occurring in the past decade (Figure 1.5.3). Land use efficiency has increased over the study period up to 2010 when it plateaued, indicating the recent production increases are largely due to greater planted area (Figure 1.5.4).

Figure 1.5.2. Area planted (million acres) to peanuts during 1980-2020

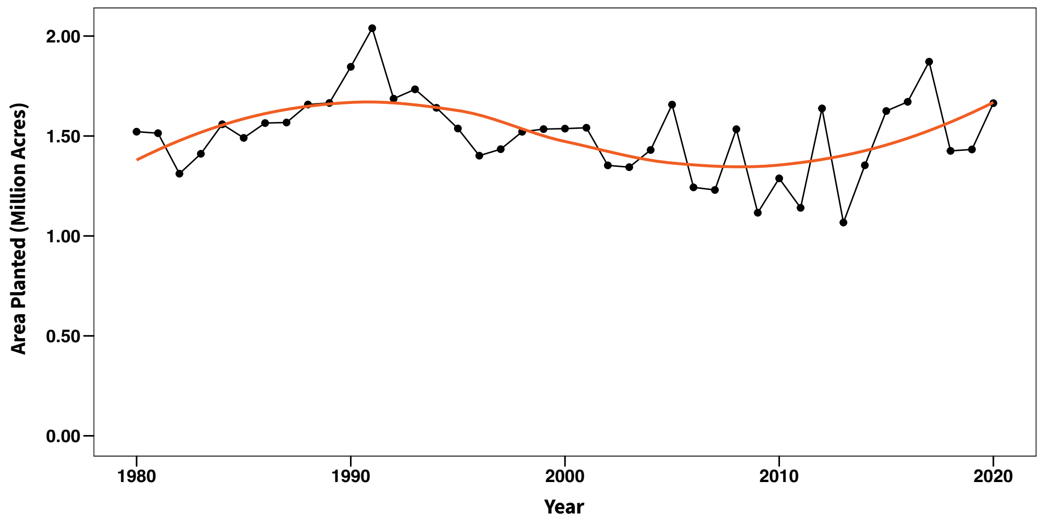


Figure 1.5.3. Total production (million lb) of peanuts during 1980-2020

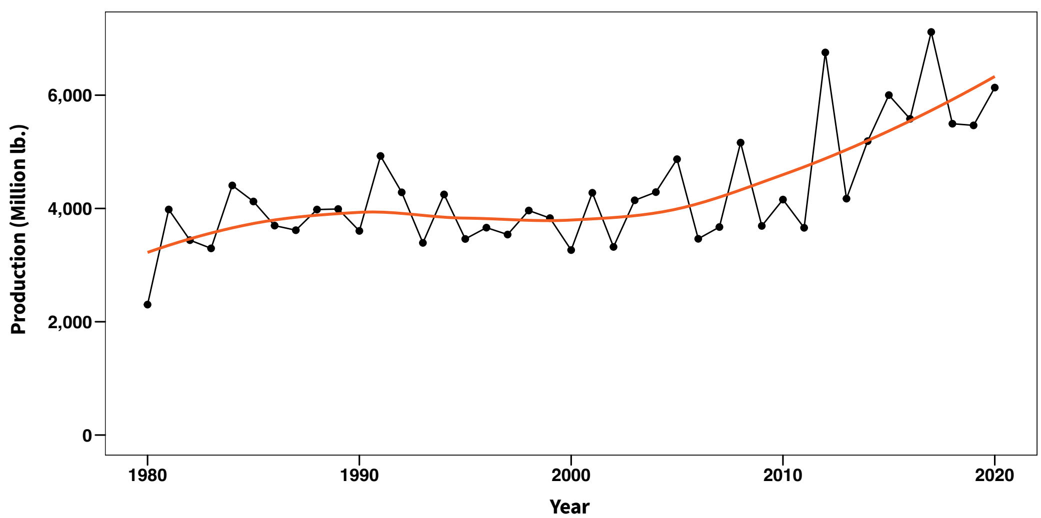
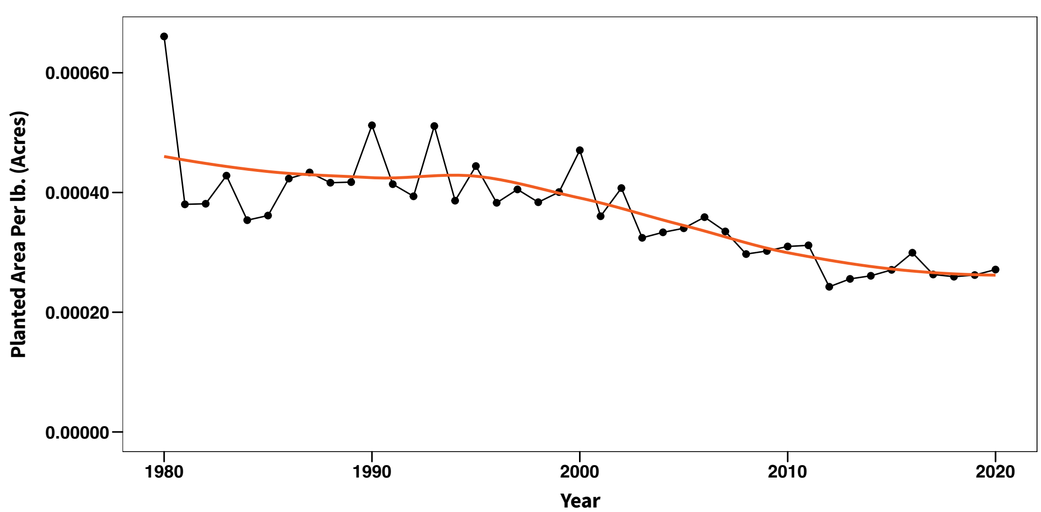


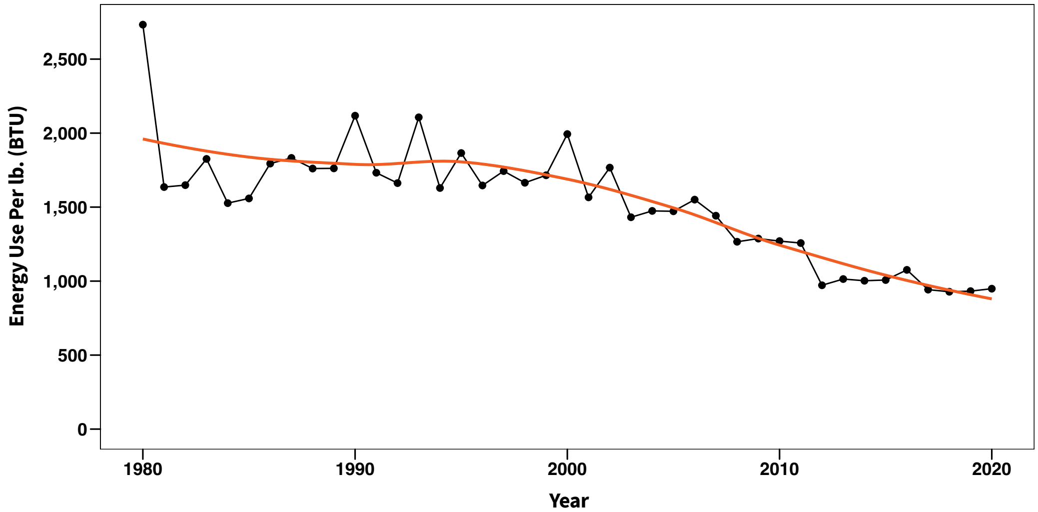
Figure 1.5.4. Land use efficiency (acres planted / lb) for peanuts during 1980-2020



ENERGY USE

Energy use per pound of peanut production has declined over the study period (Figure 1.5.5), and since the mid-2000s energy use per acre has also followed a declining trend (Figure B.17). A major component of energy use for peanuts is management energy – use of agricultural equipment – which has declined slightly since 2000 (Figure B.18) with an increase in adoption of reduced and no tillage practices for approximately 23% of acreage. Crop protectant energy use per pound of peanuts has also declined as application rates have declined for insecticides, fumigants and growth regulators from 2000-2020 (although herbicide has increased). Energy required to produce fertilizer for peanuts has declined due to lower fertilizer application rates.

Figure 1.5.5. Energy use efficiency (BTU / lb) for peanuts during 1980-2020



GREENHOUSE GAS EMISSIONS

Trends in GHG emissions largely follow those for energy use remaining steady or increasing in the first half of the study period and declining since 2000 (Figure 1.5.6). Most components of emissions have been declining, with the exception of those associated with crop drying (Figure B.20). As a nitrogen-fixing leguminous crop, peanuts require less applied nitrogen, and rates of synthetic nitrogen fertilizer have declined since 2000, contributing to the overall reduction in GHG emissions. The top four contributors for energy use and GHG emissions for peanuts during 2010-2020 are listed in Table 1.5.2.

Figure 1.5.6. Greenhouse gas emissions (lb. CO_2 Eq. / lb) for peanuts during 1980-2020

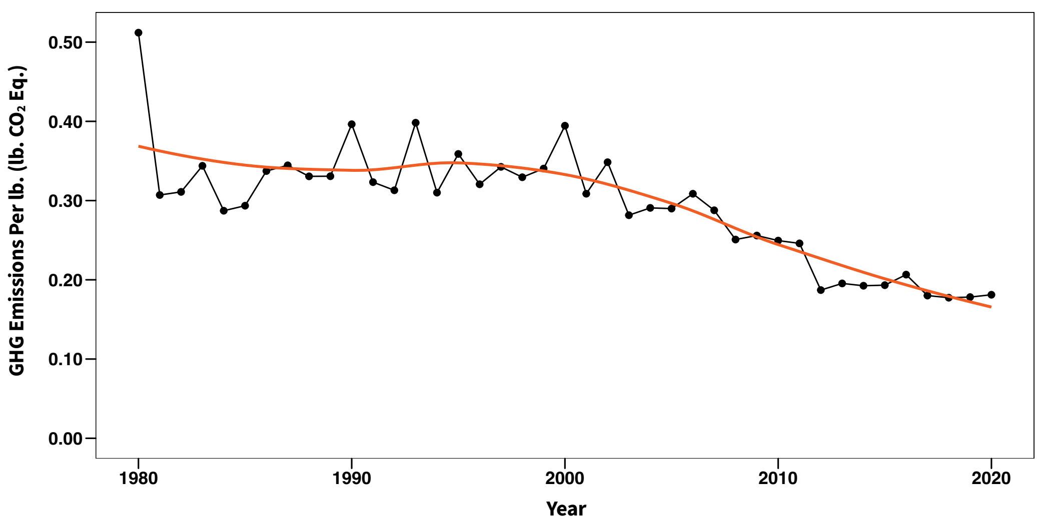


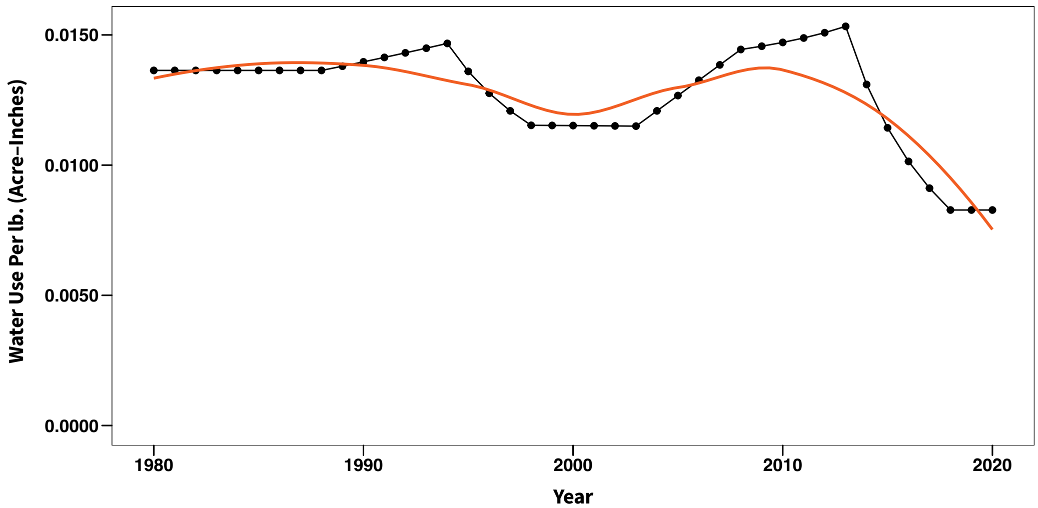
Table 1.5.2. Top four contributors for peanuts for the EU and GHG Emissions indicators during 2010-2020

ENERGY USE	GHG EMISSIONS
Management	Management
Crop Protection	Crop Protection
Fertilizer	Nitrous Oxide
Drying	Fertilizer

IRRIGATION WATER USE

Irrigation water use efficiency for peanuts does not follow a consistent trend, showing both increases and decreases at different points in time (Figure 1.5.7). This may be impacted by the shifting regions of peanut production across the south, with irrigation requirements higher in the western part of the growing region. In the most recent period of 2010-2020, irrigation efficiency has markedly improved. Across the 2008, 2013 and 2018 Irrigation and Water Management Survey for peanuts, the average irrigated harvested acreage was 35% of the total harvested acres.

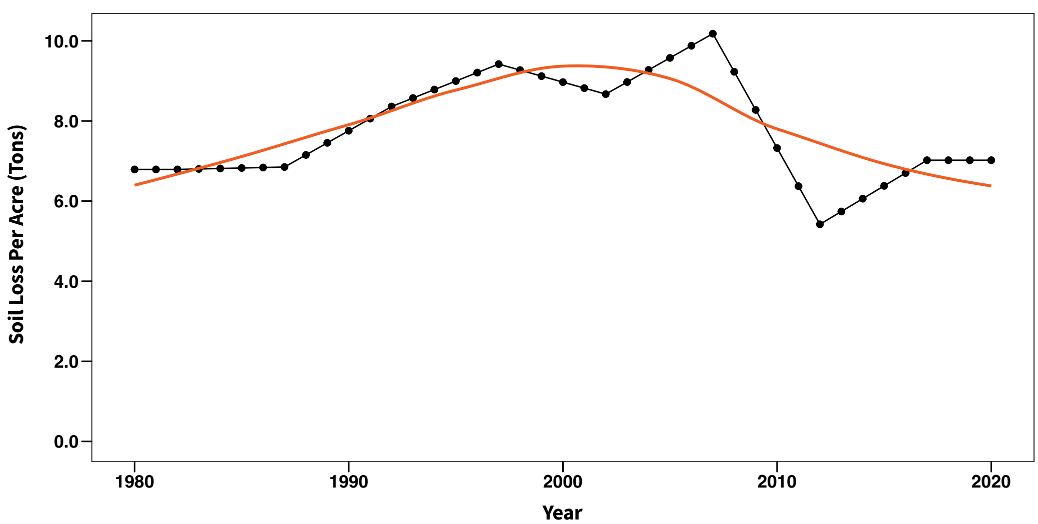
Figure 1.5.7. Irrigation water use efficiency (acre-inches / lb) for peanuts during 1980-2020



SOIL EROSION

Soil erosion for peanuts is also influenced by shifting production regions. Because they are more arid, Western peanut growing regions are more susceptible to wind erosion. Soil erosion has varied over time, but the values in 2020 are very similar to those from 1980, with higher erosion rates during the 1990s and 2000s (Figure 1.5.8).

Figure 1.5.8. Soil erosion (tons soil loss / acre / year) from fields producing peanuts during 1980-2020

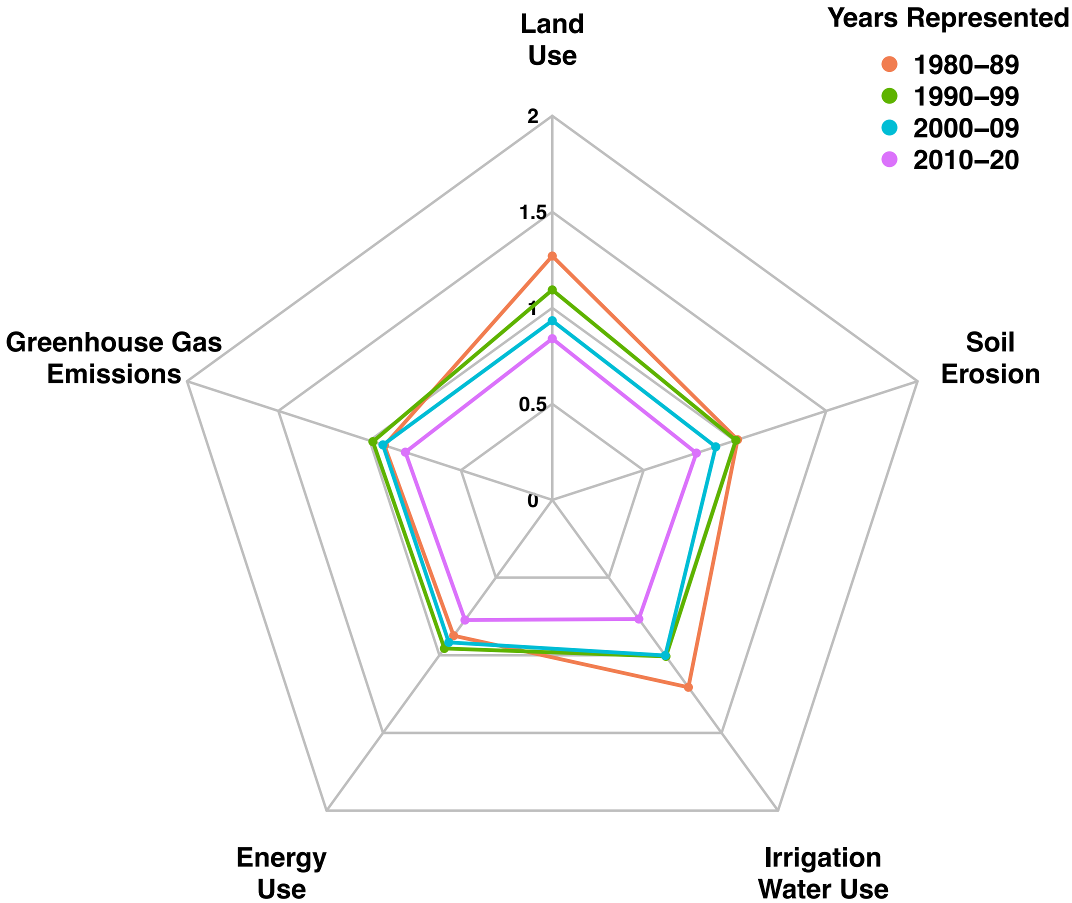


6. POTATOES

Potatoes are grown in many different regions of the country, with the largest acreage in northern and western states, including Idaho, Washington, North Dakota, Colorado and Wisconsin. Overall, potato production has become concentrated into fewer states over the study period. The summary chart for potatoes illustrates that the most recent decade has seen improvements across all indicators, with some mixed trends over the previous decades (Figure 1.6.1). Table 1.6.1 presents a summary of all indicators for potatoes for reference years.

Figure 1.6.1. Summary chart of indicators for potatoes during 1980-2020

Data are presented in index form, where all indicators have been scaled by indicator averages for the period 1998-2002. A 0.1 point change is equal to a 10 percent difference. Index values allow for comparison of change across indicators with different units of measure. A smaller area represents improvement over time.



Indicators averages for potatoes for the period 1998-2002

Indicator	Value	Units
Land Use	0.00285	Planted Acres Per cwt
Irrigation Water Use	0.166	Acre-inches Per cwt
Soil Erosion	10.3	Tons Soil Loss Per Acre
Energy Use	69,900	BTU Per cwt
Greenhouse Gas Emissions	14.7	Pounds of CO_2 Eq. Per cwt

Table 1.6.1. Summary of indicators for potatoes

Year	Land Use	Irrigation Water Use	Energy Use	Greenhouse Gas Emissions	Soil Erosion
	Planted Acres Per cwt	Acre Inches Per cwt	BTU Per cwt	Pounds of CO_2e Per cwt	Tons of Soil Loss Per Acre
1980	0.0038	0.2057	62,999	13.8	10.8
1990	0.0033	0.1824	62,608	13.8	10.4
2000	0.0028	0.1664	68,544	14.5	10
2010	0.0025	0.146	60,323	12.9	8.5
2020	0.0023	0.1169	46,210	10.4	7.5

LAND USE

Area planted to potatoes has declined since around the late 1990s (Figure 1.6.2), with overall production remaining steady since 2000 (Figure 1.6.3), indicating an increase in crop yield per acre. The land use efficiency indicator shows steady improvement throughout the study period. (Figure 1.6.4).

Figure 1.6.2. Area planted (million acres) to potatoes during 1980-2020

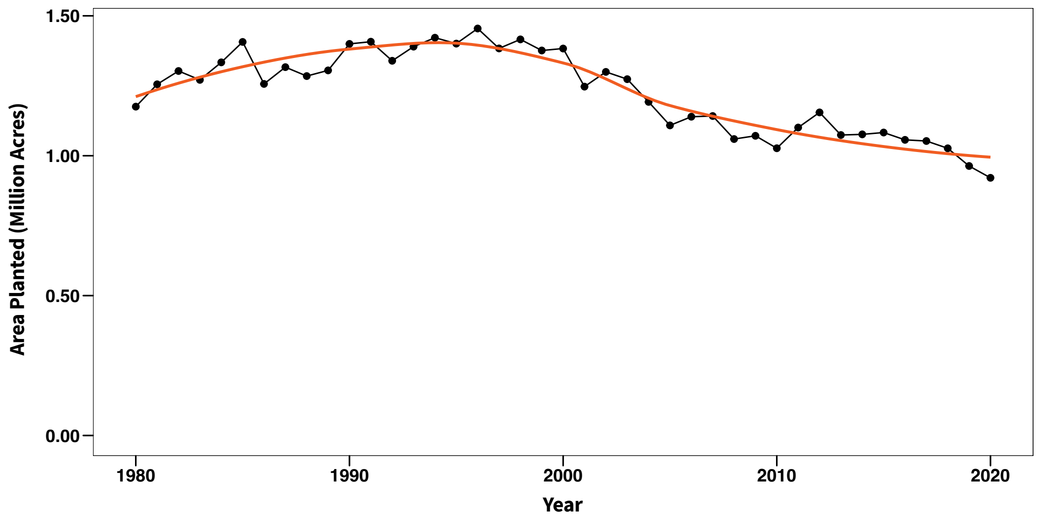


Figure 1.6.3. Total production (million cwt) of potatoes during 1980-2020

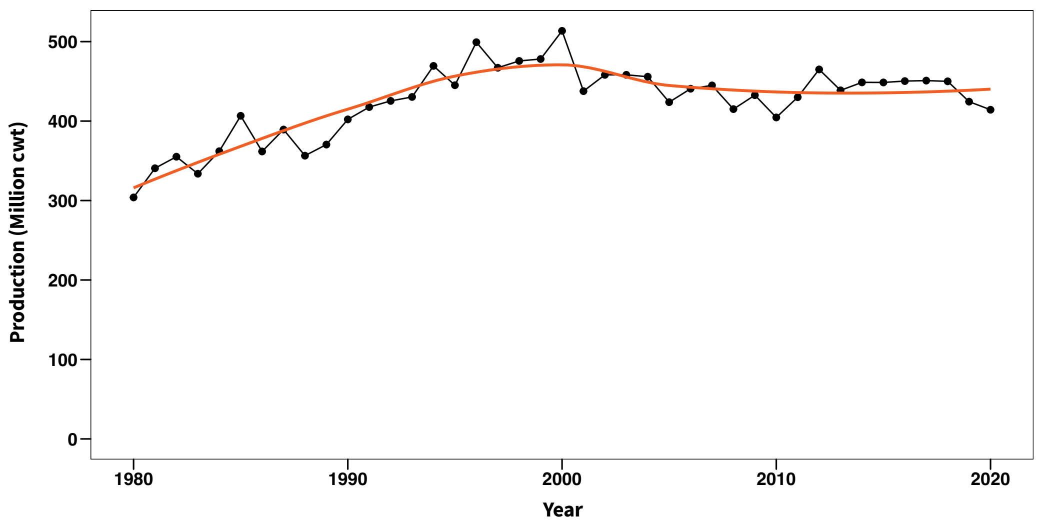
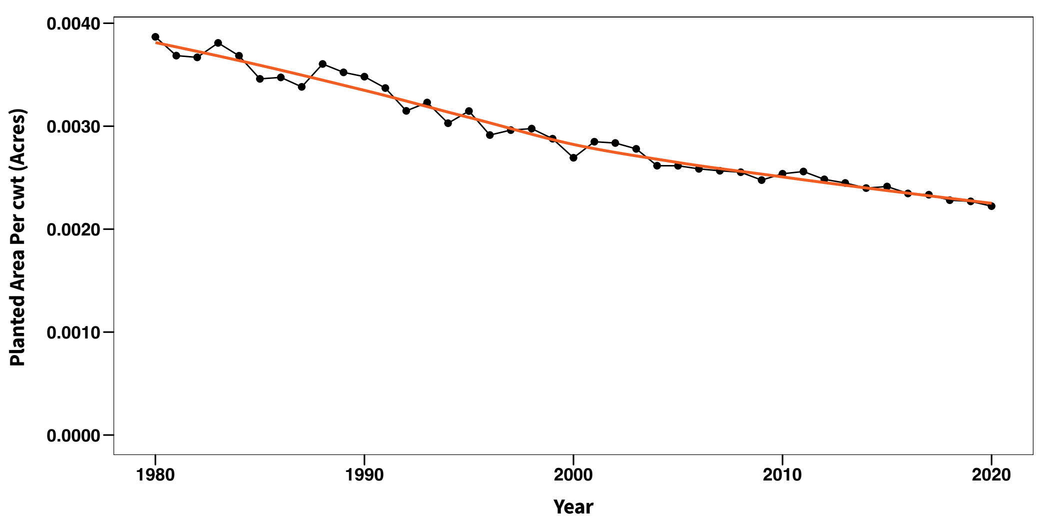


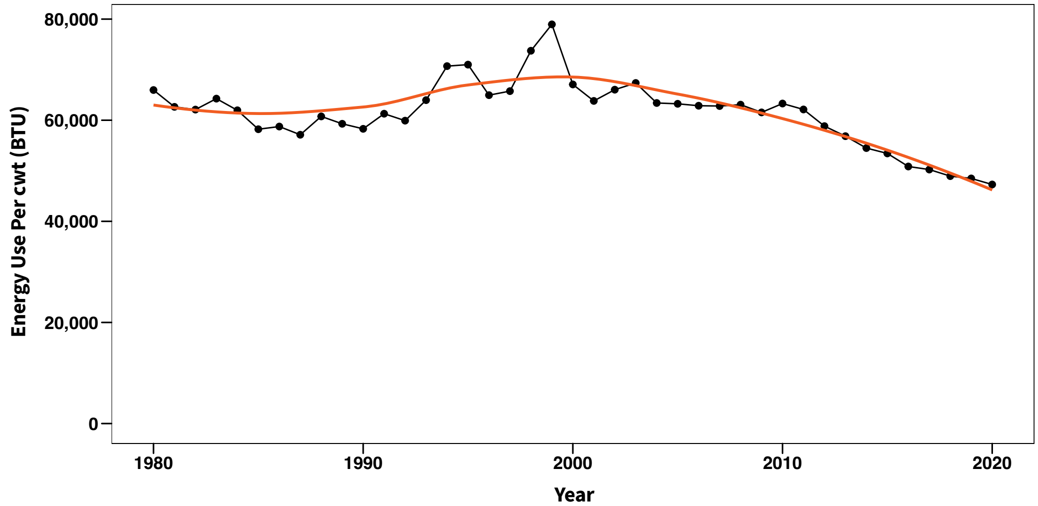
Figure 1.6.4. Land use efficiency (acres planted / cwt) for potatoes during 1980-2020



ENERGY USE

Energy use efficiency in potato production increased from 1980 through 2000 and has since declined on per unit of crop yield basis (Figure 1.6.5). Energy use per acre has seen a moderate rate of improvement in the 2010-2020 decade (Figure B.21). Crop protection products are a major energy use component in potatoes and influence the overall trend (Figure B.22). Most recently, while herbicide use has decreased, use of fungicides and fumigants have substantially increased throughout the study period.

Figure 1.6.5. Energy use efficiency (BTU / cwt) for potatoes during 1980-2020



GREENHOUSE GAS EMISSION

GHG emissions largely follow the same trend as energy use for potato production with reductions on a per unit of production basis (Figure 1.6.6) and moderate decreases on a per acre basis since 2010 (Figure B.23). The 1990s had several years of high energy use and GHG emissions. As with energy use, this seems mostly driven by increased crop protectant use and a recent increase in fertilizer nitrogen use. The top four contributors for energy use and GHG emissions for potatoes during 2010-2020 are listed in Table 1.6.2.

Figure 1.6.6. Greenhouse gas emissions (lb. CO_2 Eq. / cwt) for potatoes during 1980-2020

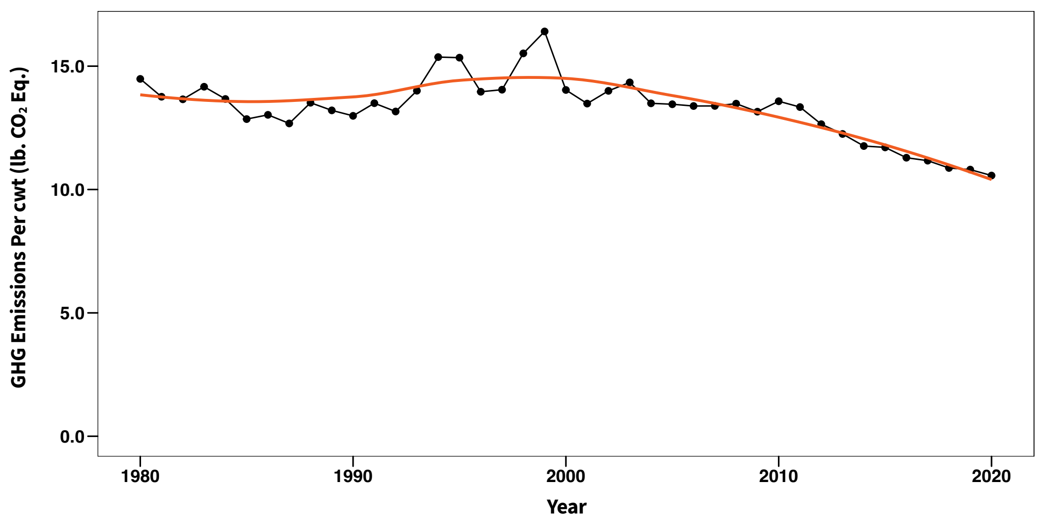


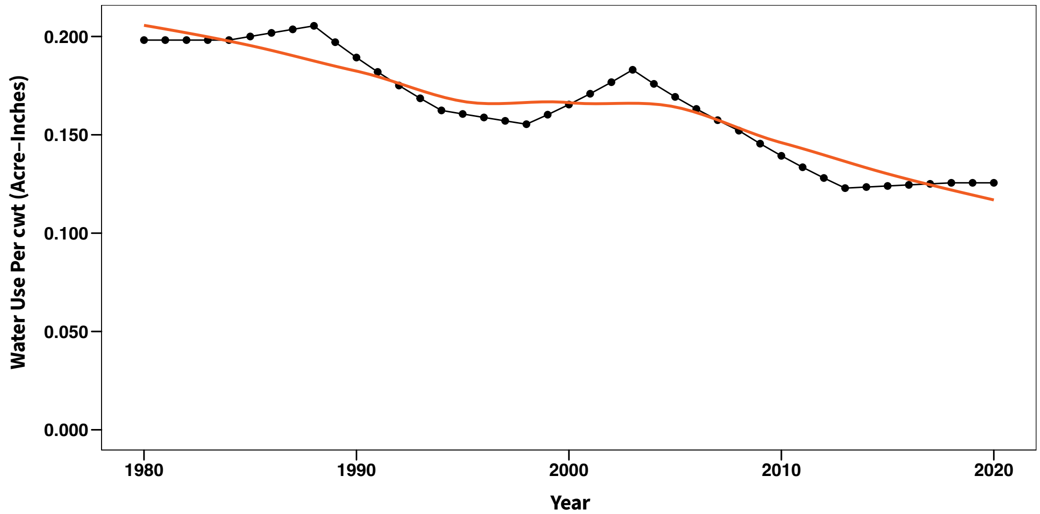
Table 1.6.2. Top four contributors for potatoes for the EU and GHG Emissions indicators during 2010-2020

ENERGY USE	GHG EMISSIONS
Crop Protection	Crop Protection
Fertilizer	Nitrous Oxide
Seed	Fertilizer
Management	Seed

IRRIGATION WATER USE

Irrigation water use efficiency for potatoes has improved over time, especially from 1990 to 2010, but has not seen further improvements in the most recent decade (Figure 1.6.7). Although national irrigation application rates for potatoes have held at approximately 20-23 acre-inches of water per acre for all decades of this study, yield has increased, resulting in considerable improvements in irrigation water use efficiency. The average irrigated harvested acreage was approximately 85% of total harvested acres across the 2013 and 2018 Irrigation and Water Management Survey for potatoes.

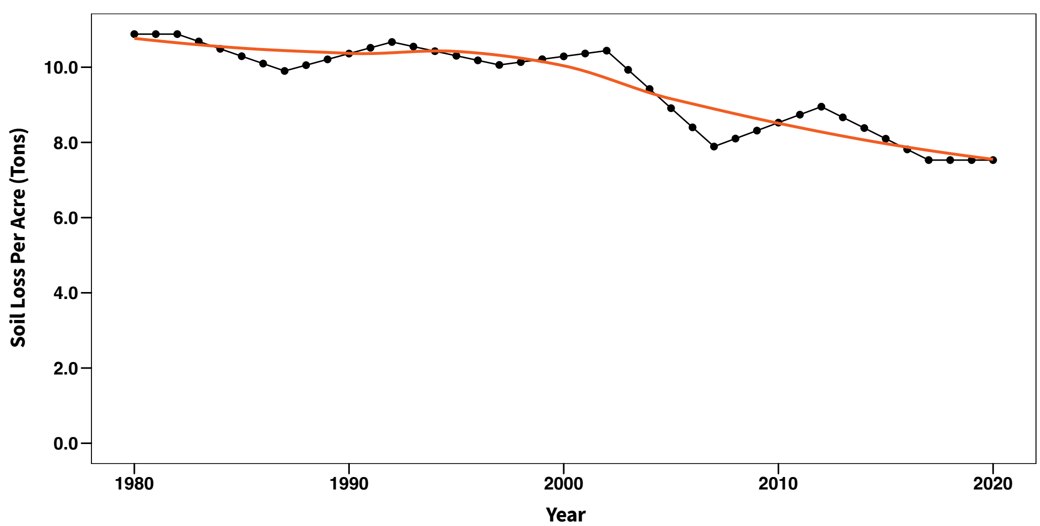
Figure 1.6.7. Irrigation water use efficiency (acre-inches / cwt) for potatoes during 1980-2020



SOIL EROSION

Soil erosion for potatoes has decreased throughout the study period with the largest improvements occurring in the early 2000s (Figure 1.6.8). The latest estimate shows that soil erosion from potato producing fields stands at 7.5 tons of soil loss per acre per year at the national level.

Figure 1.6.8. Soil erosion (tons soil loss / acre / year) from fields producing potatoes during 1980-2020

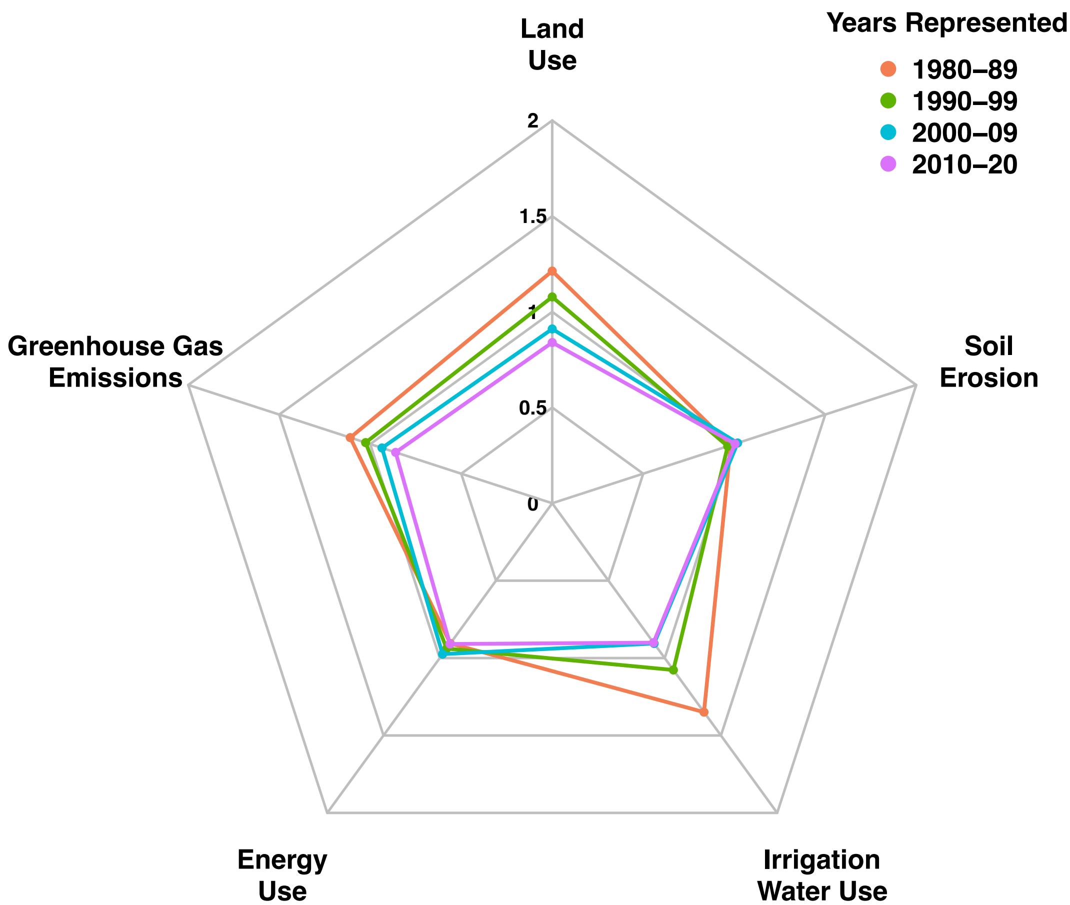


7. RICE

Rice is primarily grown in two regions of the United States – the Sacramento-San Joaquin Delta region of California and the Mississippi River valley states of Arkansas, Louisiana, Mississippi, Texas and Missouri. The largest share of planted acres is in Arkansas, with 48% of rice acres in 2020. The summary chart shows overall consistent improvement in land use and GHG emissions, with improvement in irrigation water use recently plateauing, and mixed results for energy use (Figure 1.7.1). A summary of all indicators for rice for reference years are presented in Table 1.7.1.

Figure 1.7.1. Summary chart of indicators for rice during 1980-2020

Data are presented in index form, where all indicators have been scaled by indicator averages for the period 1998-2002. A 0.1 point change is equal to a 10 percent difference. Index values allow for comparison of change across indicators with different units of measure. A smaller area represents improvement over time.



Indicators averages for rice for the period 1998-2002

Indicator	Value	Units
Land Use	0.0164	Planted Acres Per cwt
Irrigation Water Use	0.451	Acre-inches Per cwt
Soil Erosion	1.98	Tons Soil Loss Per Acre
Energy Use	146,000	BTU Per cwt
Greenhouse Gas Emissions	178	Pounds of CO_2 Eq. Per cwt

Table 1.7.1. Summary of indicators for rice

Year	Land Use	Irrigation Water Use	Energy Use	Greenhouse Gas Emissions	Soil Erosion
	Planted Acres Per cwt	Acre Inches Per cwt	BTU Per cwt	Pounds of CO_2e Per cwt	Tons of Soil Loss Per Acre
1980	0.0221	0.66	142,526	218.9	2
1990	0.0182	0.5351	129,139	183.8	1.9
2000	0.0162	0.4379	144,325	176.2	2
2010	0.0141	0.4041	139,938	159.2	2
2020	0.0135	0.3915	121,193	146.8	1.9

LAND USE

Land use in rice production in the U.S. has stayed relatively steady over the study period (Figure 1.7.2). Production increased from 1990 to 2005, and the trend has since leveled off (Figure 1.7.3). The land use efficiency indicator demonstrates increases in yield, showing improvement throughout the study period until decreasing in recent years (Figure 1.7.4).

Figure 1.7.2. Area planted (million acres) to rice during 1980-2020

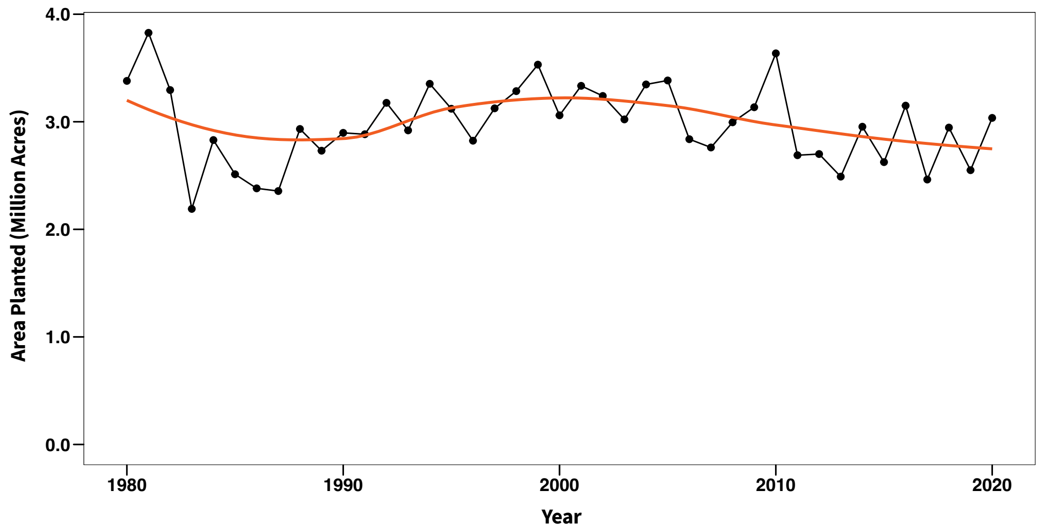


Figure 1.7.3. Total production (million cwt) of rice during 1980-2020

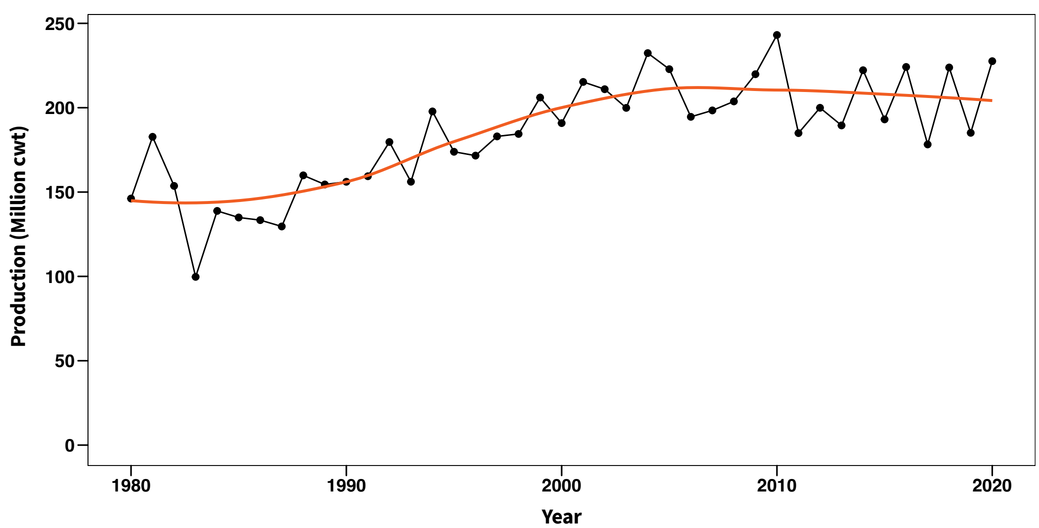
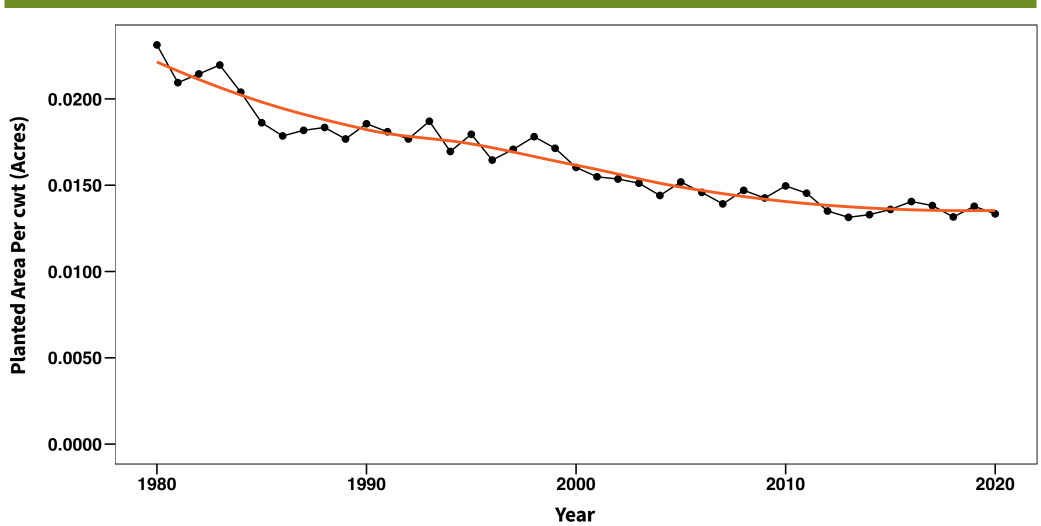


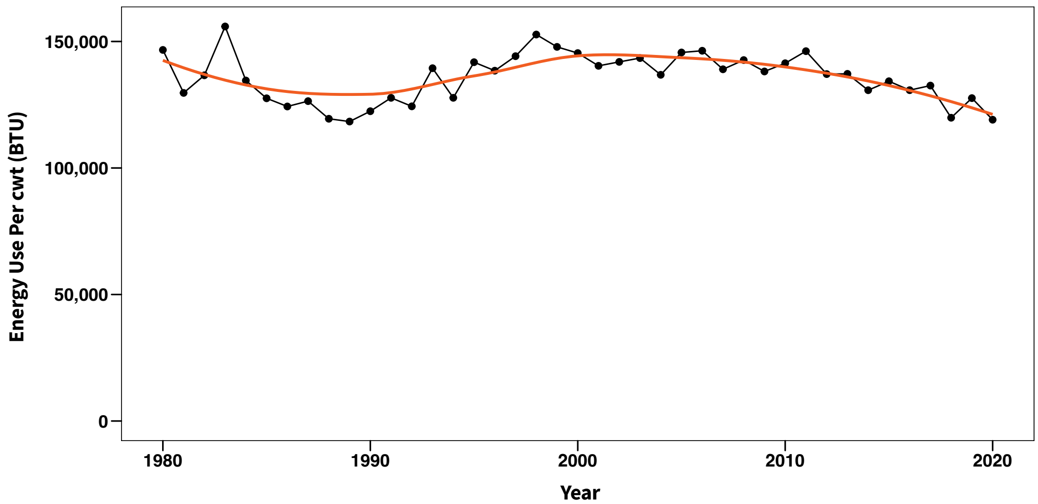
Figure 1.7.4. Land use efficiency (acres planted / cwt) for rice during 1980-2020



ENERGY USE

Energy use efficiency for rice production improved in the 1980s and the 2010s but decreased in the 1990s (Figure 1.7.5). On a per acre basis, energy used for rice production increased from 1980 until around 2010, when it began to decline (Figure B.25). The largest energy component for rice is fertilizer use, followed by irrigation (Figure B.26). Increases in the amount of fertilizer applied therefore are largely driving the increase in energy use.

Figure 1.7.5. Energy use efficiency (BTU / cwt) for rice during 1980-2020



GREENHOUSE GAS EMISSIONS

GHG emissions per unit of rice production declined through the 1980s, plateauing through the 1990s, then continued declining after 2000 (Figure 1.7.6). Emissions per acre had a moderate rate of increase from 1990 up to 2010, when it shifted to a slightly downward trend (Figure B.27). The primary component of emissions for rice is methane, consistently contributing over 80% of GHG emissions for this study, which results from anaerobic soil conditions in flooded fields. These emissions have increased slightly from 1990-present, although emissions on a per unit of production basis have declined due to increasing crop yields (Figure B.28). The top four contributors for rice for energy use and GHG emissions during 2010-2020 are listed in Table 1.7.2.

Figure 1.7.6. Greenhouse gas emissions (lb. CO_2 Eq. / cwt) for rice during 1980-2020

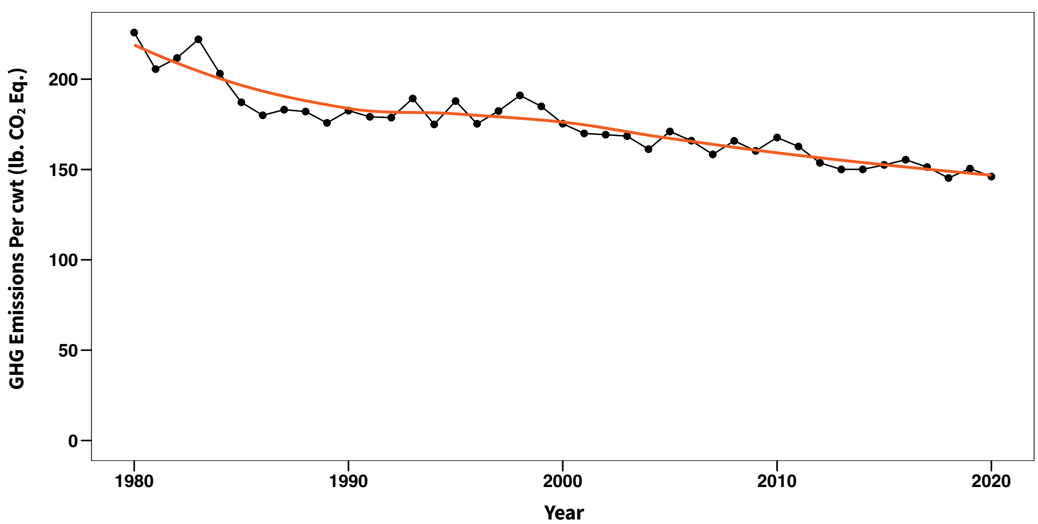


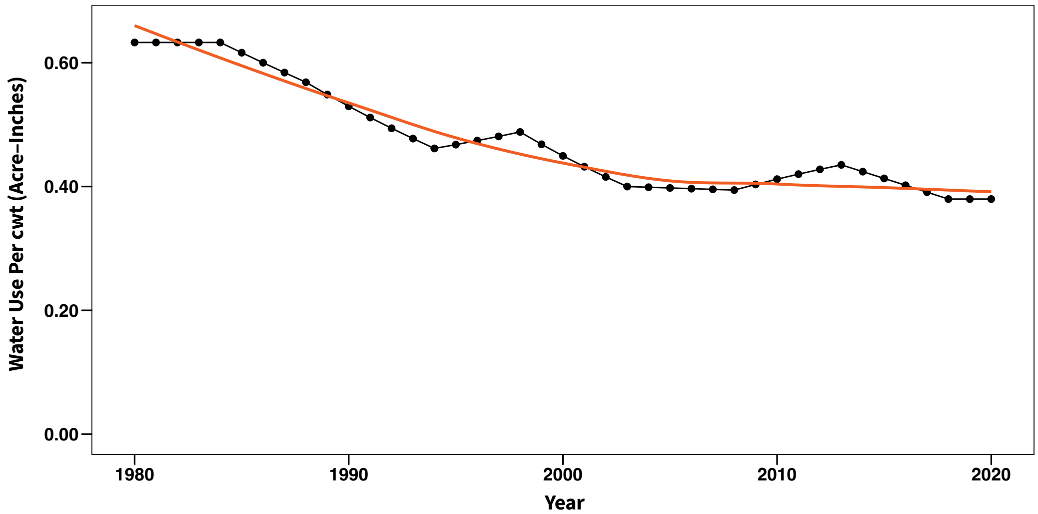
Table 1.7.2. Top four contributors for rice for the EU and GHG Emissions indicators during 2010-2020

ENERGY USE	GHG EMISSIONS
Fertilizer	Methane
Irrigation	Fertilizer
Management	Nitrous Oxide
Drying	Irrigation

IRRIGATION WATER USE

Irrigation water use efficiency for rice has also improved across the study period, with the greatest improvement occurring from 1980-2010 (Figure 1.7.7). In the early 2010s there was a period of lower irrigation water use efficiency, although in recent years it has again improved to the level of 2010. Research in Arkansas indicates increasing adoption of water conservation practices including intermittent flooding and row rice production (Hardke et al., 2021), however, data are not collected on such practices at the national scale. Reduced flooding time for rice fields also has a significant impact on methane emissions and it will be important to capture the extent of such practices in future editions of this report (Linquist et al., 2018).

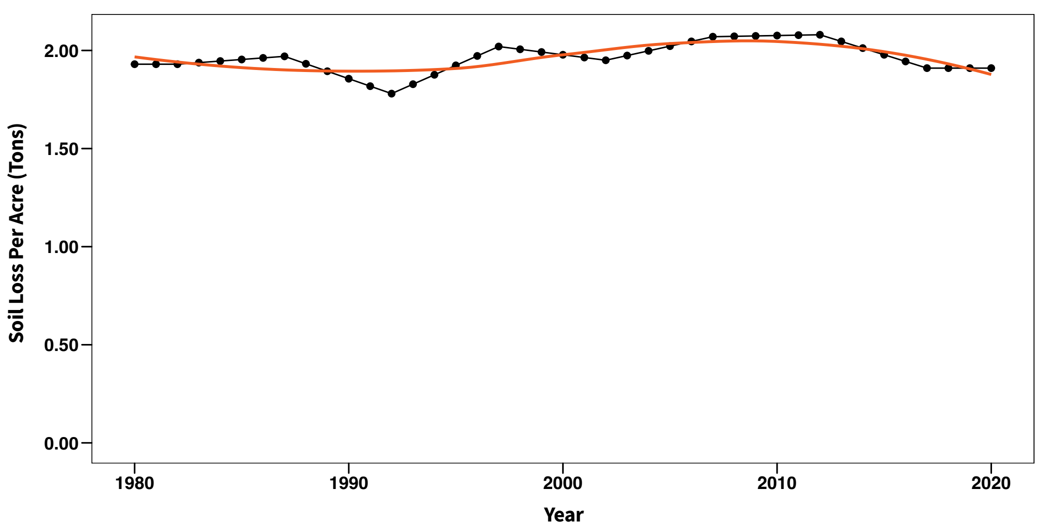
Figure 1.7.7. Irrigation water use efficiency (acre-inches / cwt) for rice during 1980-2020



SOIL EROSION

Rice is produced on flooded fields which are managed to have little to no slope in order to retain water. As a result, rice fields are generally less susceptible to soil erosion. The soil erosion indicator shows generally static, low levels of erosion throughout the study period (Figure 1.7.8), with erosion values ranging from 1.8 to 2.1 tons of soil loss per acre per year from rice-producing fields.

Figure 1.7.8. Soil erosion (tons soil loss / acre / year) from fields producing rice during 1980-2020

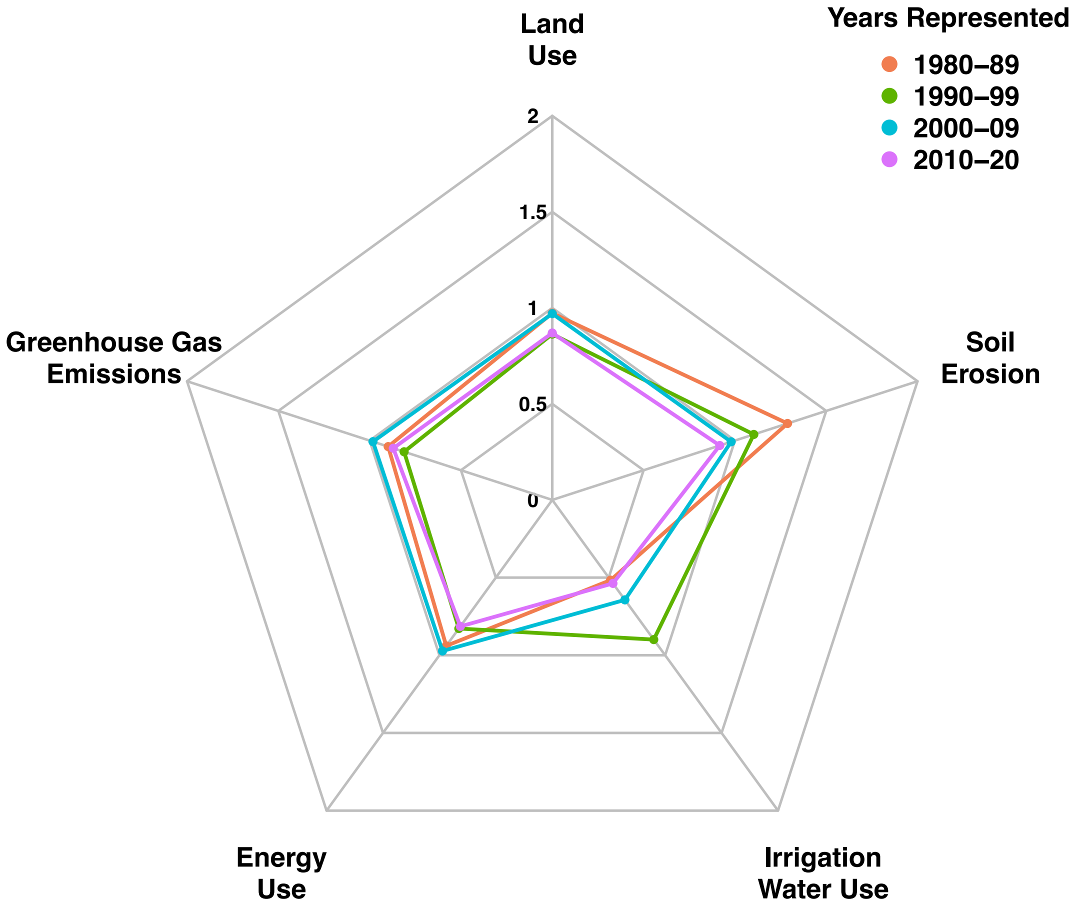


8. SORGHUM

Sorghum is a drought tolerant crop grown primarily in the Central Plains states, where nearly 70% of sorghum was planted in 2020; the remaining planted acreage was in Texas. Over the study period, the region of production has become more tightly centered on these states with only six states producing sorghum in 2020 compared to 24 states in 1980. The summary chart for sorghum shows mixed results across indicators, with the highest values for land use, emissions and energy use in the 2000s, for soil erosion in the 1980s, and for irrigation in the 1990s (Figure 1.8.1). Table 1.8.1 presents a summary of all indicators for sorghum for reference years.

Figure 1.8.1. Summary chart of indicators for sorghum during 1980-2020

Data are presented in index form, where all indicators have been scaled by indicator averages for the period 1998-2002. A 0.1 point change is equal to a 10 percent difference. Index values allow for comparison of change across indicators with different units of measure. A smaller area represents improvement over time.



Indicators averages for sorghum for the period 1998-2002

Indicator	Value	Units
Land Use	0.0192	Planted Acres Per Bushel
Irrigation Water Use	0.701	Acre-inches Per Bushel
Soil Erosion	6.95	Tons Soil Loss Per Acre
Energy Use	73,500	BTU Per Bushel
Greenhouse Gas Emissions	17.8	Pounds of CO_2 Eq. Per Bushel

Table 1.8.1. Summary of indicators for sorghum

Year	Land Use	Irrigation Water Use	Energy Use	Greenhouse Gas Emissions	Soil Erosion
	Planted Acres Per Bushel	Acre Inches Per Bushel	BTU Per Bushel	Pounds of CO_2e Per Bushel	Tons of Soil Loss Per Acre
1980	0.0217	0.3108	81,596	18.9	9.3
1990	0.0166	0.4903	60,349	14.2	8.3
2000	0.0181	0.6394	69,638	16.9	7
2010	0.0183	0.3474	66,703	16.7	6.5
2020	0.0136	0.4897	51,447	14	6.3

LAND USE

The overall acreage of cropland planted to sorghum has declined across the study period, leveling off in the 2010s with around 6 million acres planted (Figure 1.8.2). Production overall has also declined throughout the study period with a trend icrease in recent years (Figure 1.8.3). As a result, the land use efficiency indicator is relatively static across the time period in this study, indicating no significant trend in sorghum yields (Figure 1.8.4). Yields are also quite variable among years, likely reflecting water availability.

Figure 1.8.2. Area planted (million acres) to sorghum during 1980-2020

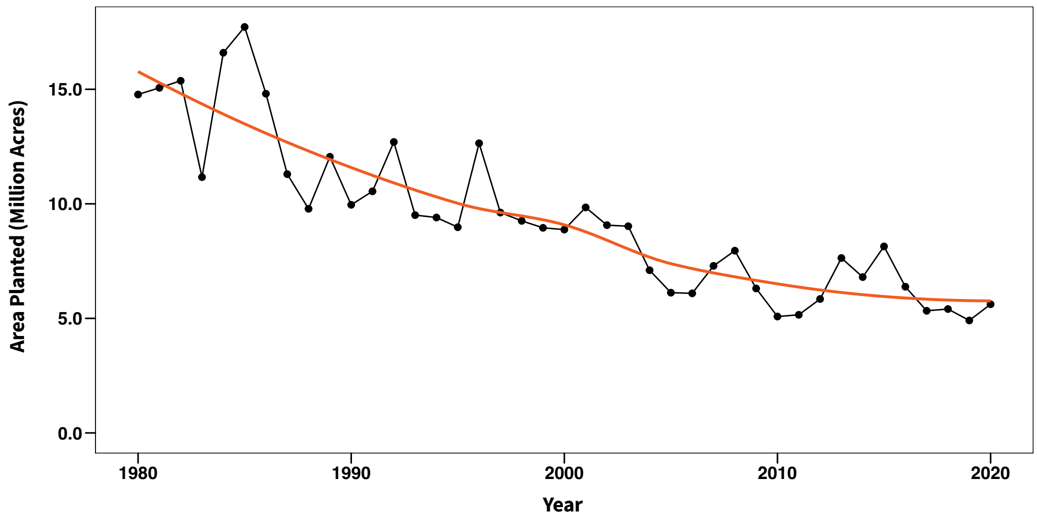


Figure 1.8.3. Total production (million bushels) of sorghum during 1980-2020

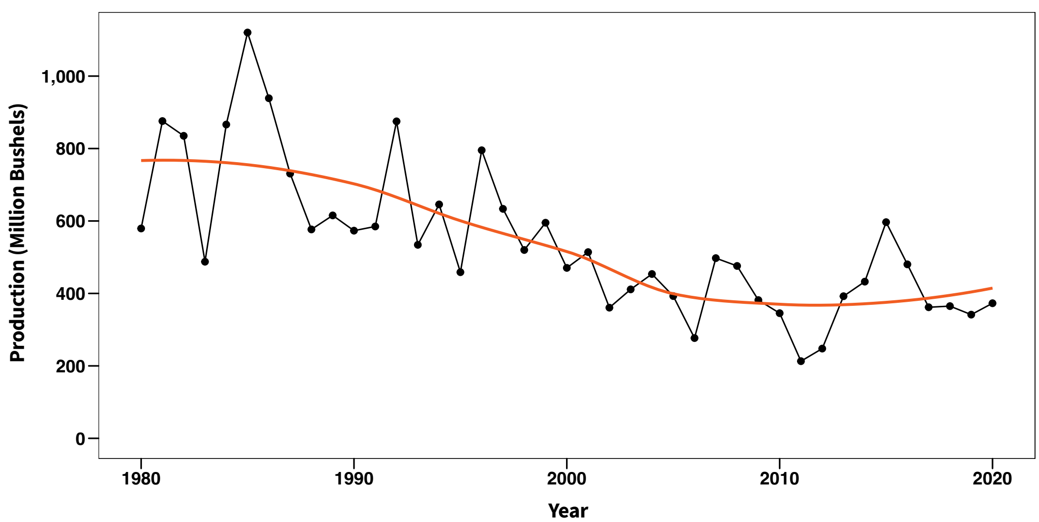
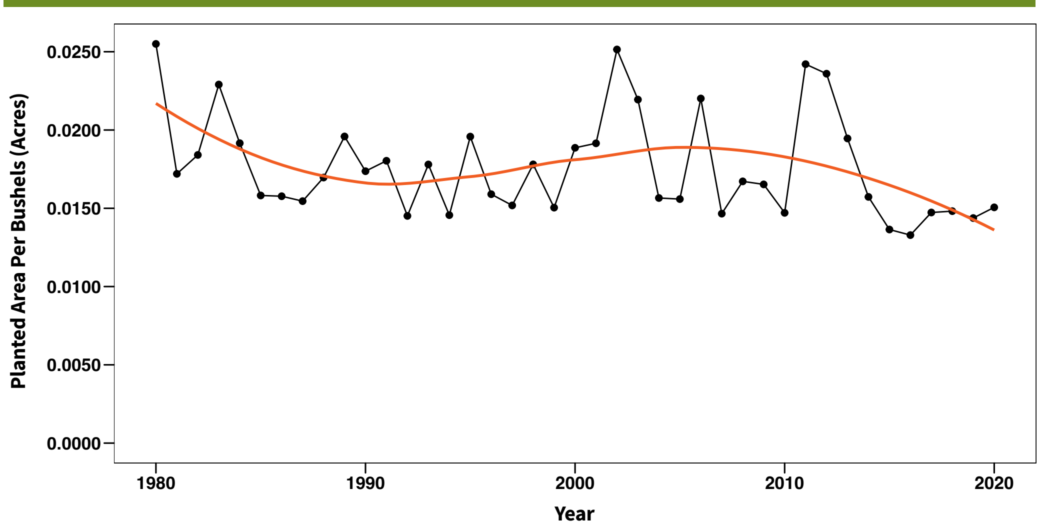


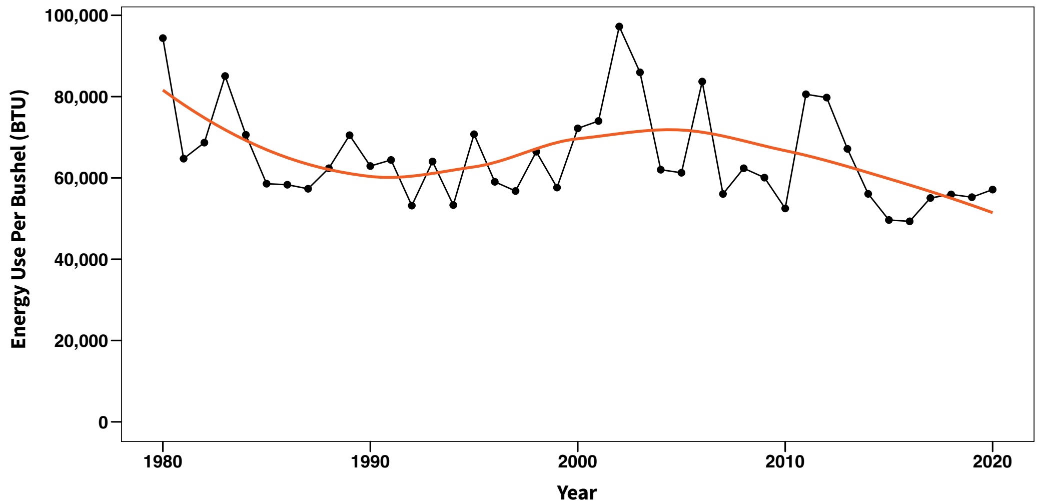
Figure 1.8.4. Land use efficiency (acres planted / bushel) for sorghum during 1980-2020



ENERGY USE

Energy use efficiency for sorghum on a per bushel basis has improved slightly over the study period, with wide interannual variation (Figure 1.8.5). One major factor in the energy use is increased applications of nitrogen and phosphorus fertilizers on sorghum over the study period. Energy used in crop protectants has also increased over time (Figure B.30), driven by greater herbicide use.

Figure 1.8.5. Energy use efficiency (BTU / bushel) for sorghum during 1980-2020



GREENHOUSE GAS EMISSIONS

GHG emissions for sorghum follow a pattern similar to energy use, with relatively high interannual variability but no strong trend in emissions per bushel produced (Figure 1.8.6). Emissions on a per acre basis have increased over the past decade (Figure B.31), driven by greater nitrous oxide emissions. Increases in both synthetic nitrogen fertilizer and manure use has led to increased nitrous oxide emissions since 2010 (Figure B.32). The top four contributors for energy use and GHG emissions for sorghum during 2010-2020 are listed in Table 1.8.2.

Figure 1.8.6. Greenhouse gas emissions (lb. CO_2 Eq. / bushel) for sorghum during 1980-2020

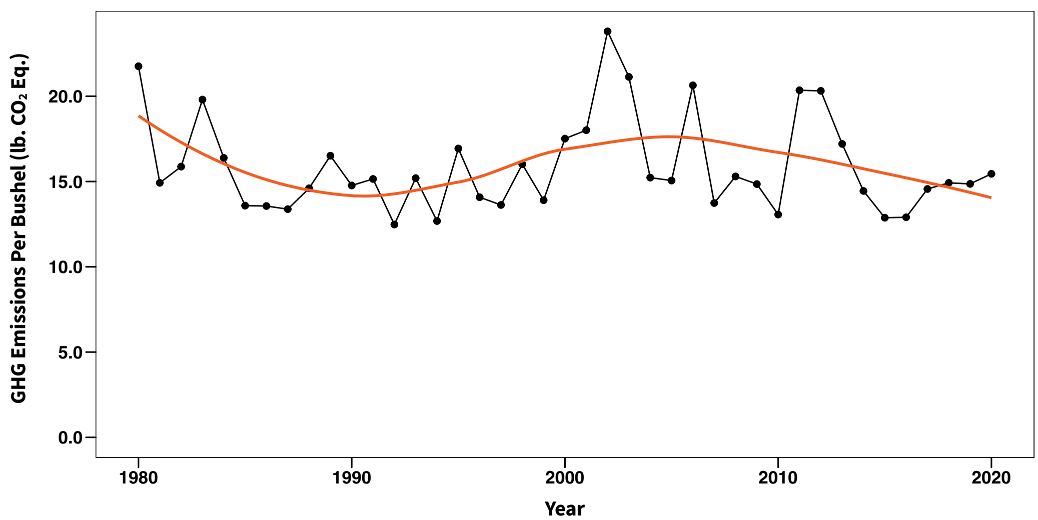


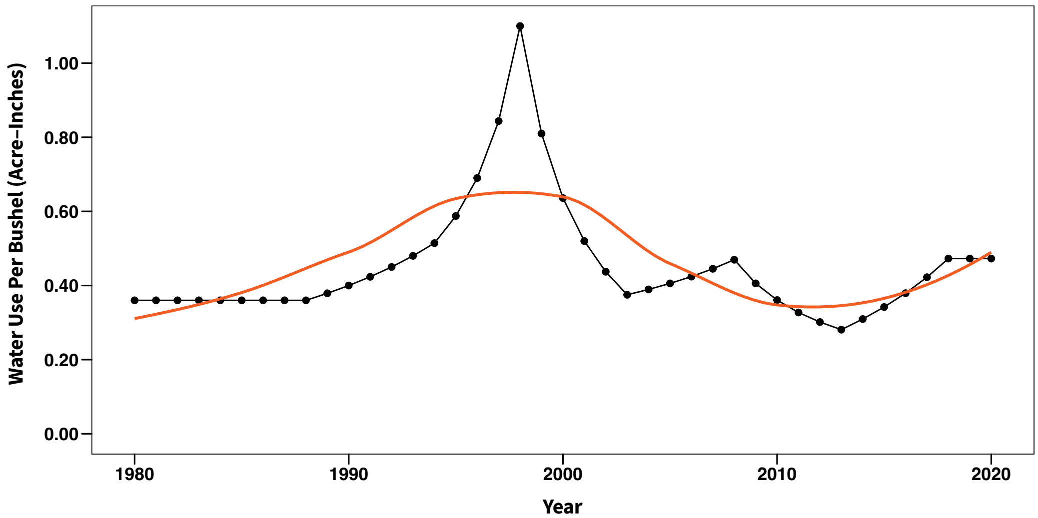
Table 1.8.2. Top four contributors for sorghum for the EU and GHG Emissions indicators during 2010-2020

ENERGY USE	GHG EMISSIONS
Fertilizer	Nitrous Oxide
Management	Fertilizer
Crop Protection	Management
Drying	Crop Protection

IRRIGATION WATER USE

Sorghum is a drought tolerant crop frequently grown in water-limited regions and requiring little supplemental irrigation except in very dry years. The most efficient production typically occurs under water-stressed conditions, rather than fully irrigated production (Assefa et al., 2010). From the 1980s through 2000, sorghum irrigation water use efficiency showed a downward trend, followed by some efficiency gains through about 2012 (Figure 1.8.7). The lack of a clear trend may be attributed to change over time in land equipped for irrigation as well as the relationship between irrigated and non-irrigated yield, which may be lower for sorghum than for other crops considered here. The average irrigated harvested acreage across the 2008, 2013 and 2018 Irrigation and Water Management Survey for sorghum was approximately 11% of total harvested acres. The share of irrigated acres has been in decline for the last three surveys.

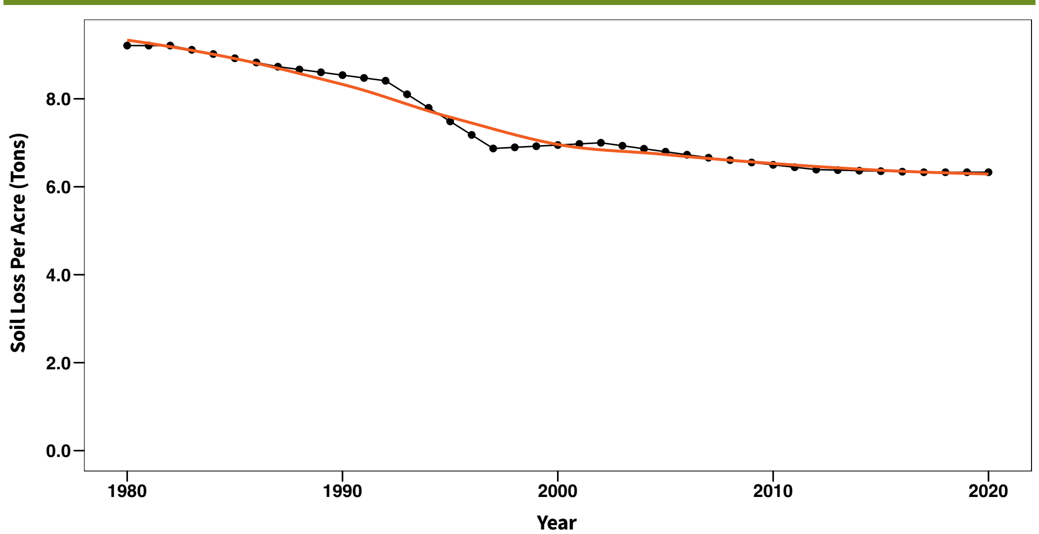
Figure 1.8.7. Irrigation water use efficiency (acre-inches / bushel) for sorghum during 1980-2020



SOIL EROSION

Soil erosion for sorghum has consistently declined since 1980, with the greatest improvement occurring in the 1990s (Figure 1.8.8). Sorghum has the greatest adoption rate of no tillage among crops considered in this study. No till has increased steadily over time; currently slightly less than 60% of sorghum acres use no till, 20% used reduced tillage with the remaining 20% in conventional tillage in 2020.

Figure 1.8.8. Soil erosion (tons soil loss / acre / year) from fields producing sorghum during 1980-2020

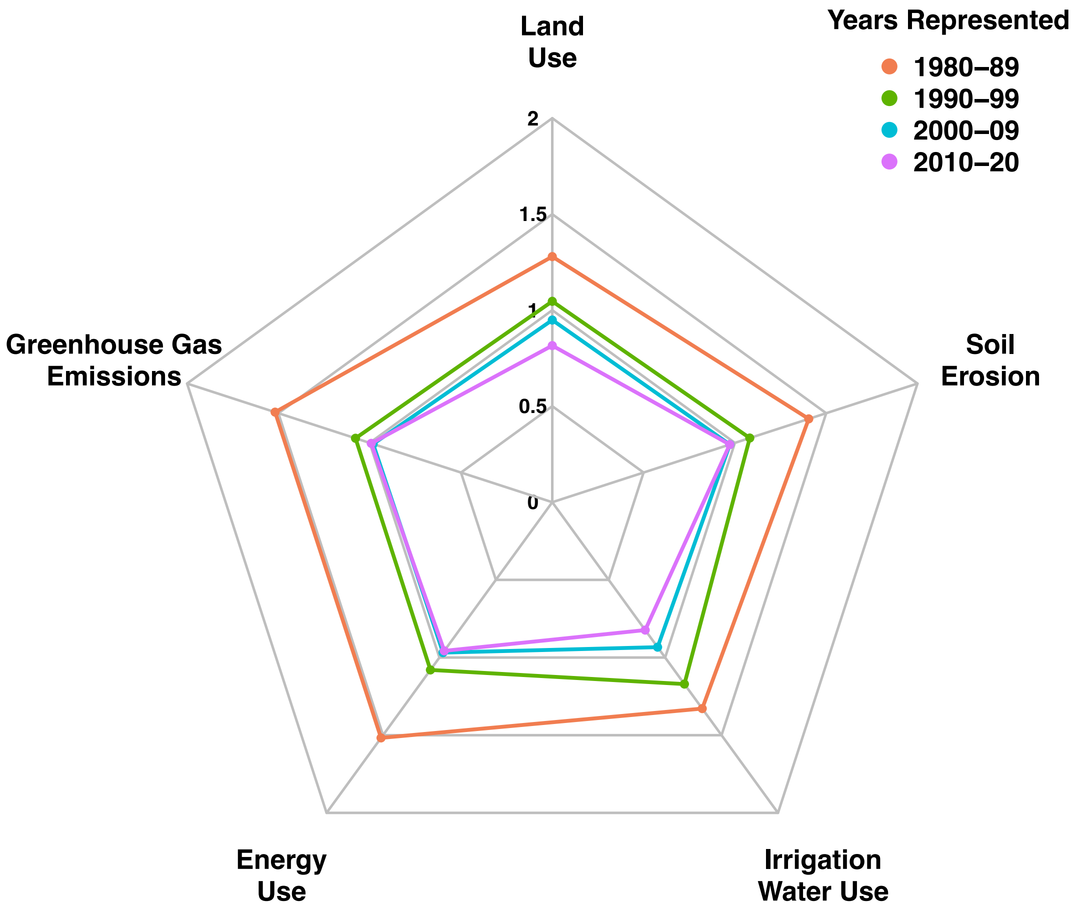


9. SOYBEANS

Soybeans are widely grown throughout the eastern half of the country, with the greatest production in Iowa, Illinois, Indiana, Missouri and Minnesota. Over time, a larger share of acreage has shifted farther west into the Dakotas and Nebraska. The summary chart for soybeans shows clear improvement from 1980-2000 across the indicators, with progress slowing in the past two decades (Figure 1.9.1). Land use and irrigation water use efficiency saw the greatest improvements over the last two decades, while little or no improvements were observed for soil erosion, energy use and GHG emissions. A summary of all indicators for soybeans for reference years is shown in Table 1.9.1.

Figure 1.9.1. Summary chart of indicators for soybeans during 1980-2020

Data are presented in index form, where all indicators have been scaled by indicator averages for the period 1998-2002. A 0.1 point change is equal to a 10 percent difference. Index values allow for comparison of change across indicators with different units of measure. A smaller area represents improvement over time.



Indicators averages for soybeans for the period 1998-2002

Indicator	Value	Units
Land Use	0.0267	Planted Acres Per Bushel
Irrigation Water Use	0.73	Acre-inches Per Bushel
Soil Erosion	4.78	Tons Soil Loss Per Acre
Energy Use	43,100	BTU Per Bushel
Greenhouse Gas Emissions	8.06	Pounds of CO_2 Eq. Per Bushel

Table 1.9.1. Summary of indicators for soybeans

Year	Land Use	Irrigation Water Use	Energy Use	Greenhouse Gas Emissions	Soil Erosion
	Planted Acres Per Bushel	Acre Inches Per Bushel	BTU Per Bushel	Pounds of CO_2e Per Bushel	Tons of Soil Loss Per Acre
1980	0.0371	1.0839	72,726	13.6	7.4
1990	0.0303	0.8921	54,184	10.1	5.8
2000	0.0264	0.7436	42,333	8	4.7
2010	0.0236	0.6822	41,464	7.9	4.6
2020	0.0197	0.4194	40,035	7.9	4.8

LAND USE

The area planted to soybeans in the U.S. declined in the 1980s before increasing steadily to the present day (Figure 1.9.2). Overall production has increased much more than can be explained by the area increase (Figure 1.9.3). Land use efficiency has consistently improved throughout the study period, indicating improvement in crop yield (Figure 1.9.4).

Figure 1.9.2. Area planted (million acres) to soybeans during 1980-2020

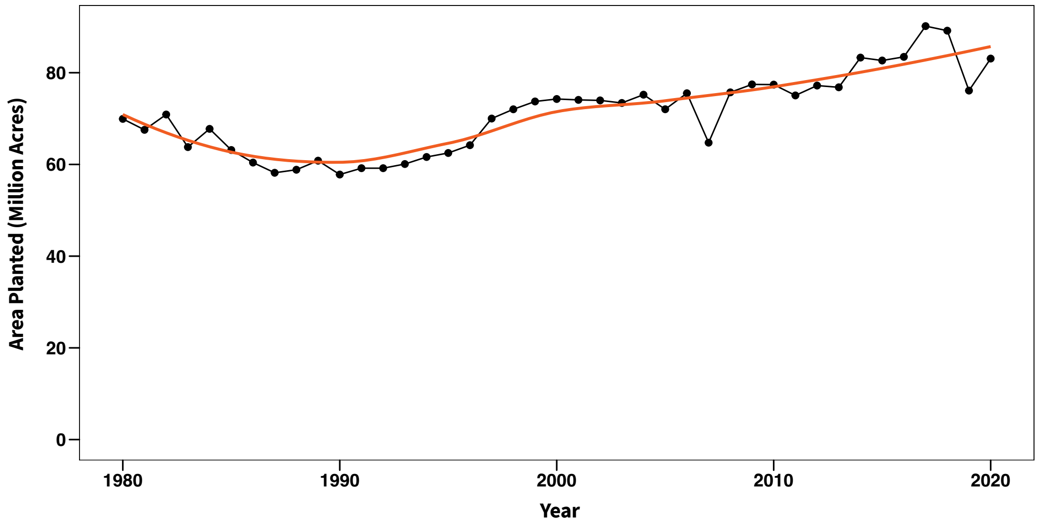


Figure 1.9.3. Total production (million bushels) of soybeans during 1980-2020

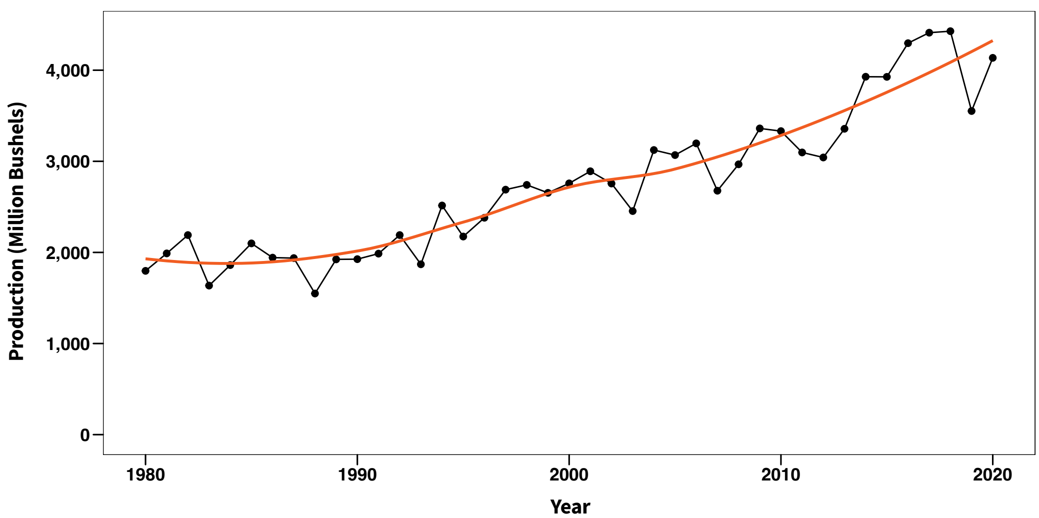
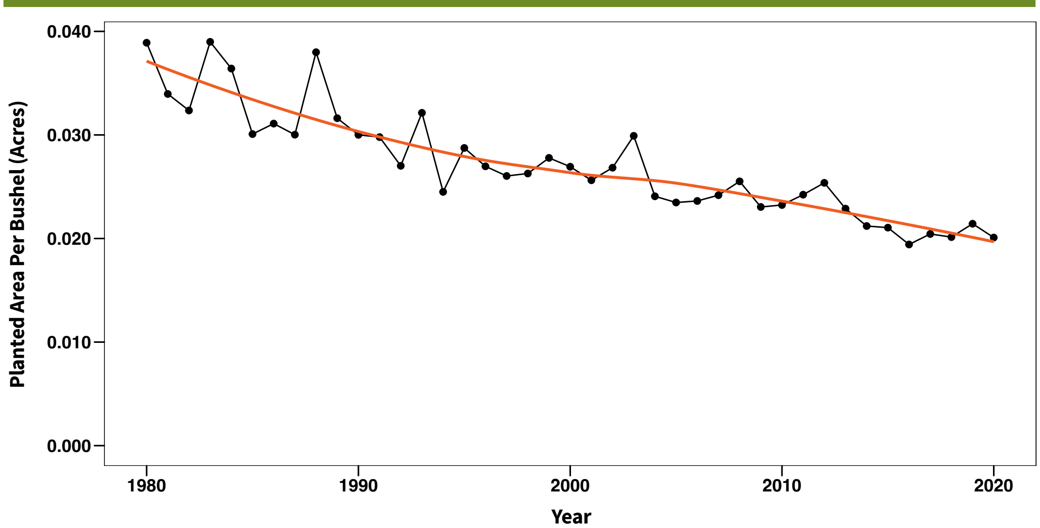


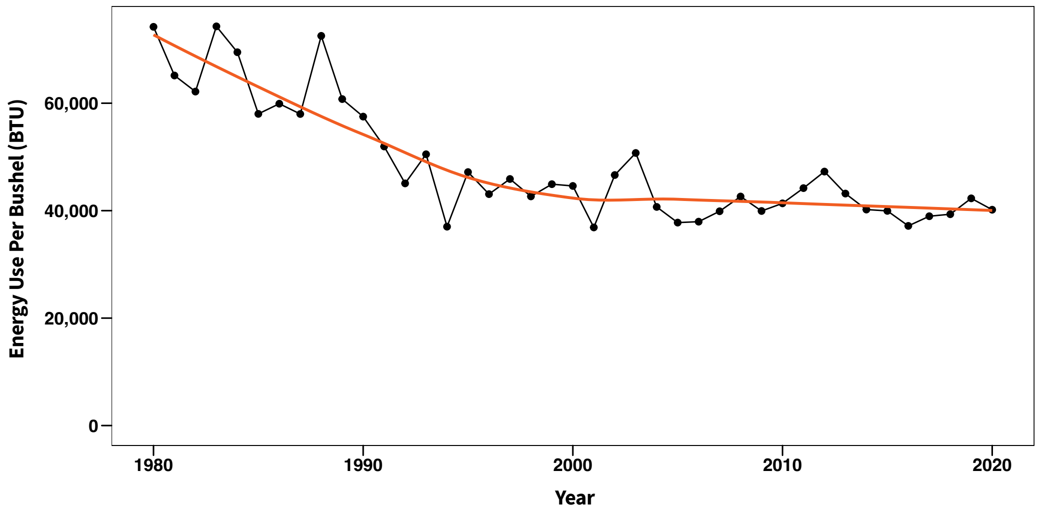
Figure 1.9.4. Land use efficiency (acres planted / bushel) for soybeans during 1980-2020



ENERGY USE

Energy use efficiency per bushel of soybeans showed improvement from 1980-2000, with a largely flat trend over the past two decades (Figure 1.9.5). The per acre energy use for soybeans has increased since around 2005 (Figure B.33), driven by increased use of fertilizers, herbicides and fungicides since 2000. Energy used for management has declined due to increasing rates of no till prior to, and through around 2005, when no-till systems reached 40% of soybean acreage, since which time the management energy has declined slightly (Figure B.34).

Figure 1.9.5. Energy use efficiency (BTU / bushel) for soybeans during 1980-2020



GREENHOUSE GAS EMISSIONS

Greenhouse gas emissions per bushel of soybeans improved substantially between 1980 and 2000 and have since followed a flat trend similar to energy use (Figure 1.9.6). Due to the slightly higher use of nitrogen fertilizer compared to previous years, there has been an increase in nitrous oxide emissions since around 2005, and this is reflected in the increase in per acre GHG emissions for soybeans, which were higher in 2020 than at any other time in the period of analysis (Figure B.35). Table 1.9.2 lists the top four contributors for energy use and GHG emissions for soybeans during 2010-2020.

Figure 1.9.6. Greenhouse gas emissions (lb. CO_2 Eq. / bushel) for soybeans during 1980-2020

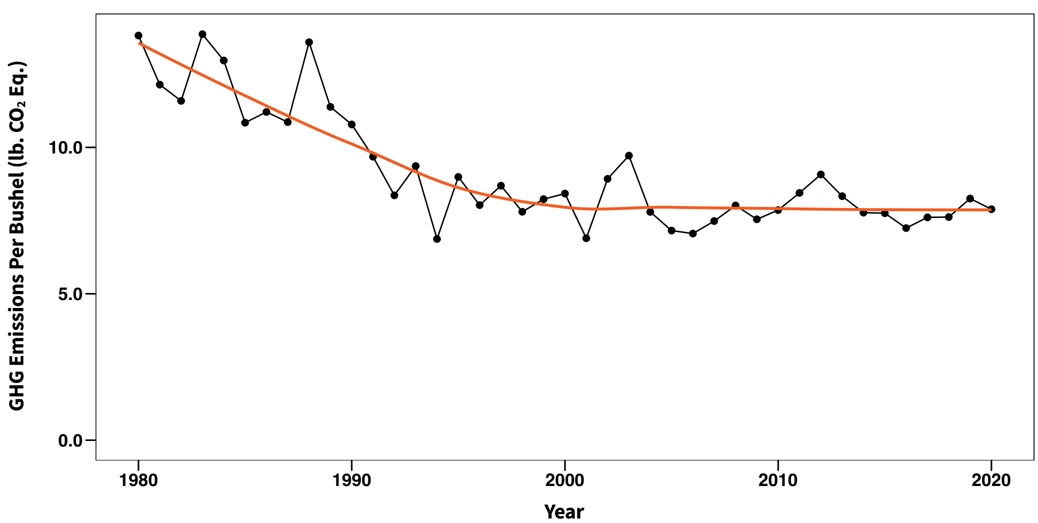


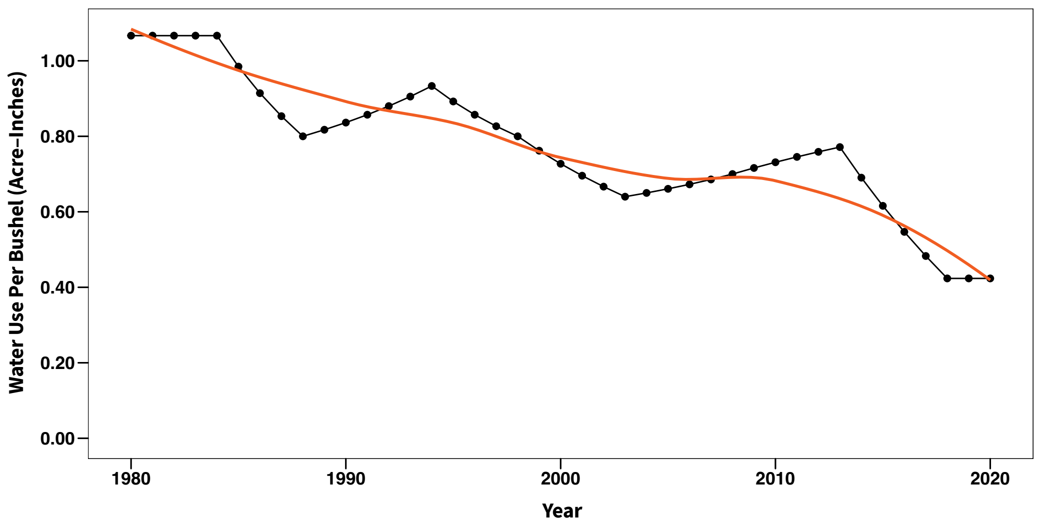
Table 1.9.2. Top four contributors for soybeans for the EU and GHG Emissions indicators during 2010-2020

ENERGY USE	GHG EMISSIONS
Management	Management
Fertilizer	Fertilizer
Crop Protection	Crop Protection
Transportation	Nitrous Oxide

IRRIGATION WATER USE

Irrigation water use efficiency for soybeans has overall improved from 1980-2020 (Figure 1.9.7), although substantial variability from the trend line is observed. A consistent trend of water use improvement up to the year 2000 was reversed until the early 2010s, likely a result of large scale rainfall deficit across large regions. Since 2013, the irrigation water use efficiency has improved. The average irrigated harvested acreage was approximately 9.5% across the 2008, 2013 and 2018 Irrigation and Water Management Survey for soybeans, when compared to the total harvested acres.

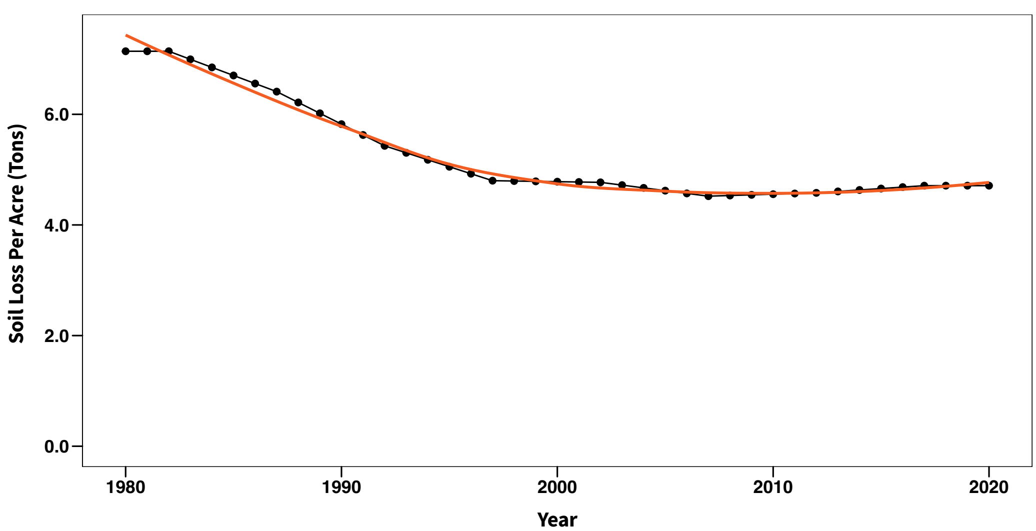
Figure 1.9.7. Irrigation water use efficiency (acre-inches / bushel) for soybeans during 1980-2020



SOIL EROSION

Soil erosion for soybeans also saw substantial improvement from 1980-2000, with additional slight reduction in the early 2000s (Figure 1.9.8). Since 2010, soil erosion has held largely steady for soybean-producing fields at just over 4 tons per acre per year.

Figure 1.9.8. Soil erosion (tons soil loss / acre / year) from fields producing soybeans during 1980-2020

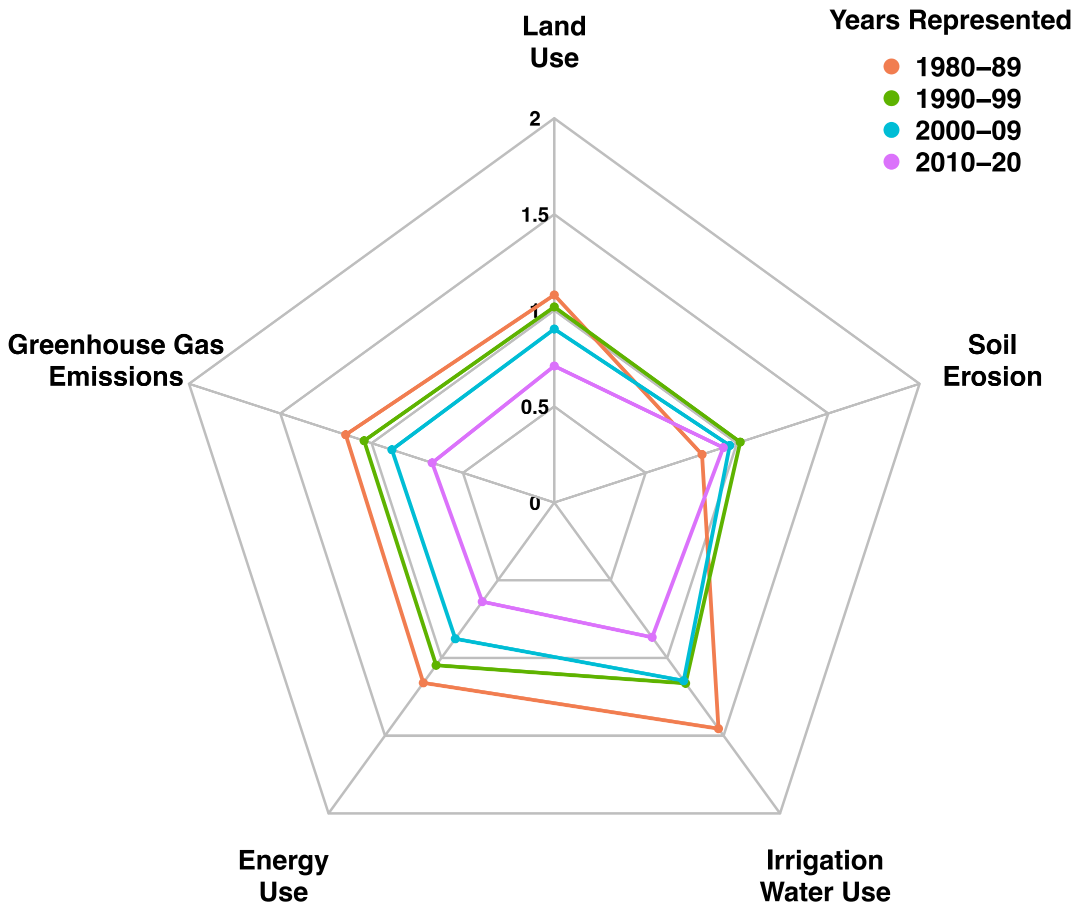


10. SUGAR BEETS

Sugar beets are a root crop grown predominantly in cooler climates. Areas of production are concentrated in northern states and the mountain west, with the largest acreage in Minnesota, Michigan, North Dakota and Idaho. The summary chart for sugar beets indicates steady improvement for land use, energy use and greenhouse gas emissions indicators, as well as improvement over the study period for irrigation (Figure 1.10.1). Table 1.10.1 presents a summary of all indicators for sugar beets for reference years. Unfortunately, there is a lack of key, up-to-date data for sugar beets. For example, crop protection and fertilizer usage were last surveyed in 2000. The late 2000s were an important time period as a new variety of genetically engineered sugar beet was introduced and adopted almost universally by U.S. sugar beet growers in 2009-2010 (USDA APHIS, 2020; USDA Economic Research Service, 2021). This variety requires fewer crop chemical inputs, however, no surveys on chemical use have been conducted after this transition period so we are unable to fully quantify environmental impacts related to sugar beet production. For this edition of the National Indicators Report, sugar beet yield units are expressed in tons of sugar rather than raw tons. The sucrose percent data reported by USDA was used to calculate this adjustment.

Figure 1.10.1. Summary chart of indicators for sugar beets during 1980-2020

Data are presented in index form, where all indicators have been scaled by indicator averages for the period 1998-2002. A 0.1 point change is equal to a 10 percent difference. Index values allow for comparison of change across indicators with different units of measure. A smaller area represents improvement over time.



Indicators averages for sugar beets for the period 1998-2002

Indicator	Value	Units
Land Use	0.293	Planted Acres Per Ton of Sugar
Irrigation Water Use	23.6	Acre-inches Per Ton of Sugar
Soil Erosion	9.56	Tons Soil Loss Per Acre
Energy Use	2,400,000	BTU Per Ton of Sugar
Greenhouse Gas Emissions	569	Pounds of CO_2 Eq. Per Ton of Sugar

Table 1.10.1. Summary of indicators for sugar beets

Year	Land Use	Irrigation Water Use	Energy Use	Greenhouse Gas Emissions	Soil Erosion
	Planted Acres Per Ton of Sugar	Acre Inches Per Ton of Sugar	BTU Per Ton of Sugar	Pounds of CO_2e Per Ton of Sugar	Tons of Soil Loss Per Acre
1980	0.3242	46.4644	2,885,250	666.1	7.5
1990	0.3083	26.9945	2,660,990	624.8	8.8
2000	0.2873	26.0884	2,353,609	558	9.8
2010	0.228	25.4731	1,745,775	426.6	8.8
2020	0.2001	16.8183	1,414,350	356.4	9.1

LAND USE

Acres planted to sugar beets increased from 1980-2000 before declining, and in 2020 is similar to that of the mid-1980s (Figure 1.10.2). The production of sugar beets has steadily increased over time, with some interannual variations (Figure 1.10.3). The land use efficiency indicator reflects crop yield increases, with significant improvements in the period from 2000-2010 (Figure 1.10.4). In recent years the land use efficiency has shown a gradual improvement.

Figure 1.10.2. Area planted (million acres) to sugar beets during 1980-2020

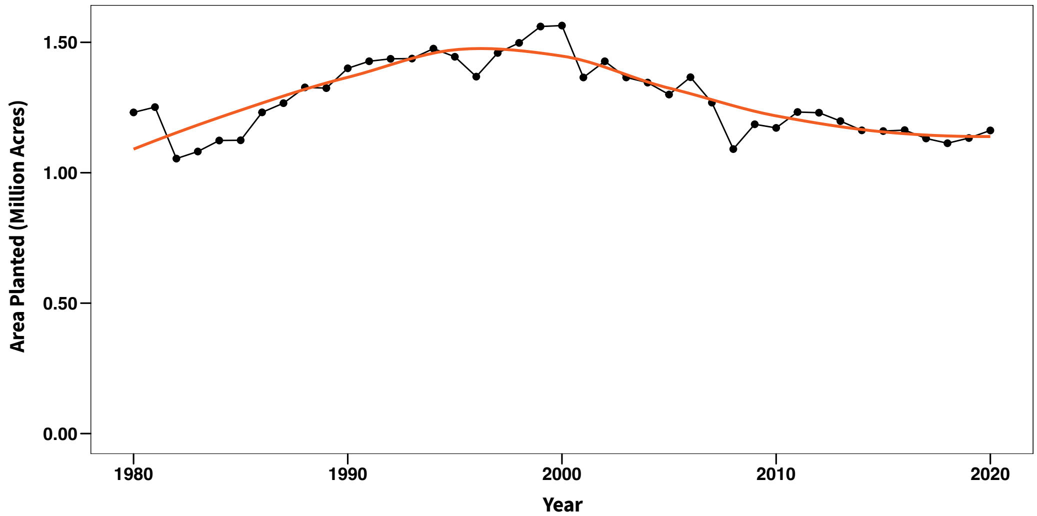


Figure 1.10.3. Total production (million tons of sugar) of sugar beets during 1980-2020

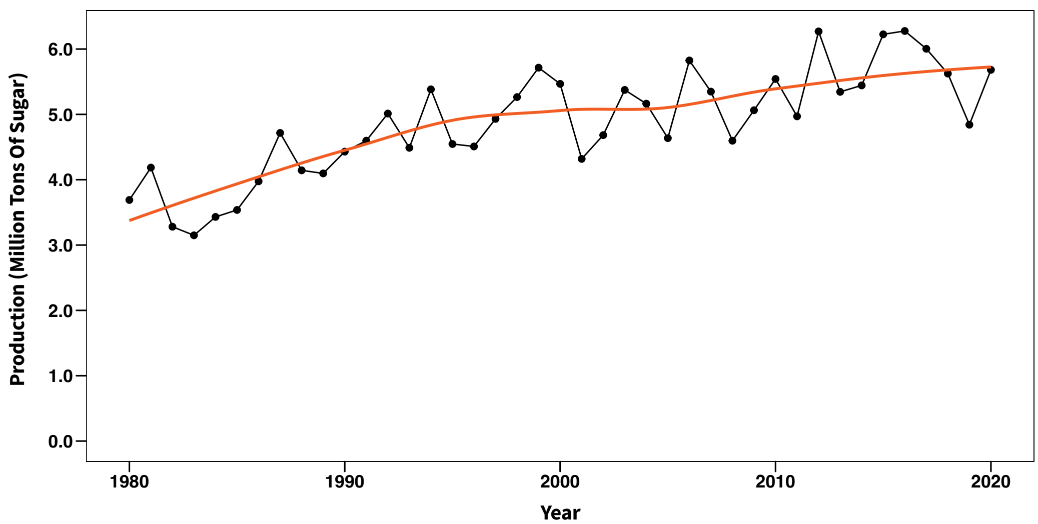
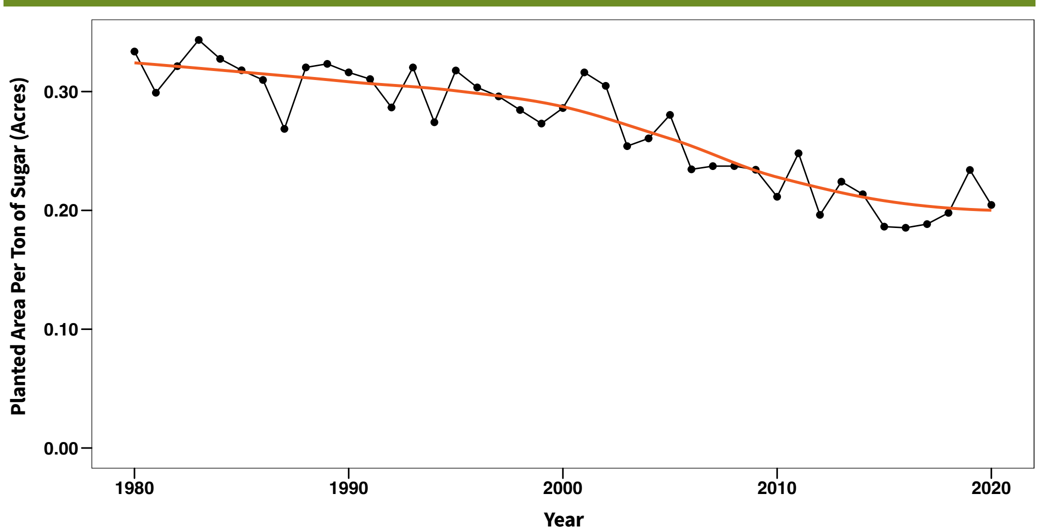


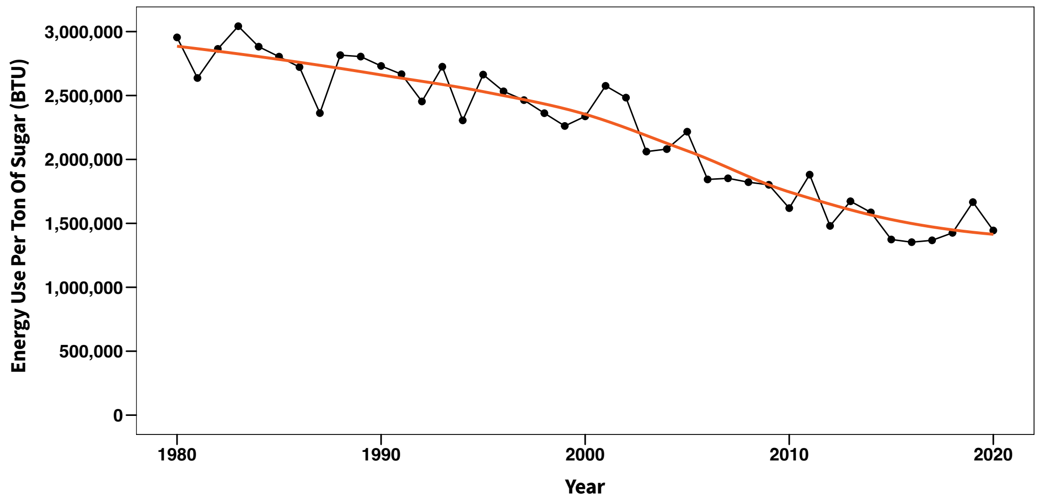
Figure 1.10.4. Land use efficiency (acres planted / ton of sugar) for sugar beets during 1980-2020



ENERGY USE

Energy use efficiency for sugar beet production has improved throughout the study period on both a per unit yield (Figure 1.10.5) and per acre basis (Figure B.37). This is driven by improvements in the energy efficiency of the manufacture of fertilizer and crop chemical inputs. Unfortunately, only one year of fertilizer and crop protectant data are available from USDA, therefore, application rates were assumed to be uniform throughout the study.

Figure 1.10.5. Energy use efficiency (BTU / ton of sugar) for sugar beets during 1980-2020



GREENHOUSE GAS EMISSIONS

Trends for GHG emissions for sugar beets follow the trends for energy use (Figure 1.10.6). The major factors for the GHG emissions indicator are nitrous oxide emissions from soil and emissions from the manufacture of fertilizers and and crop protectants (Figure B.40). Table 1.10.2 lists the top four contributors for energy use and GHG emissions for sugar beets during 2010-2020.

Figure 1.10.6. Greenhouse gas emissions (lb. CO_2 Eq. / ton of sugar) for sugar beets during 1980-2020

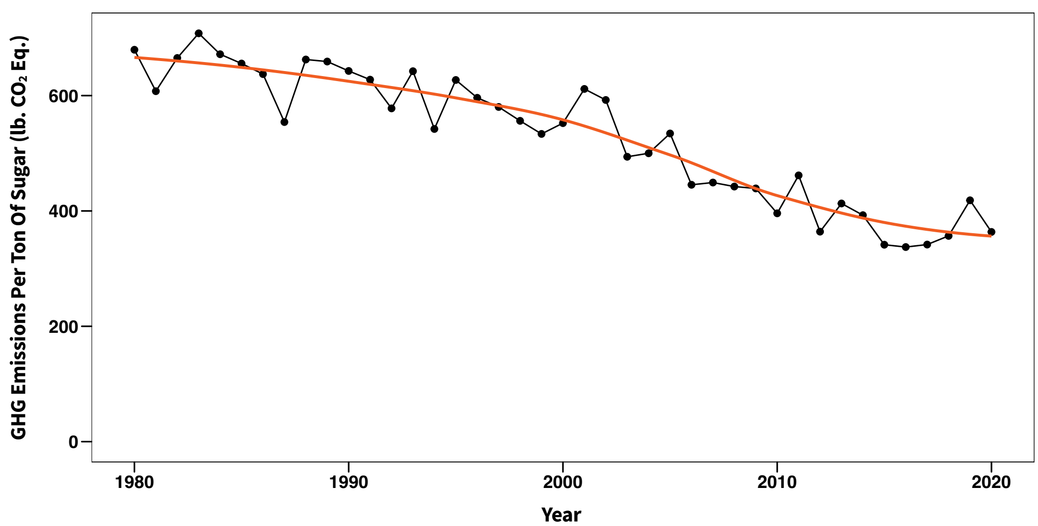


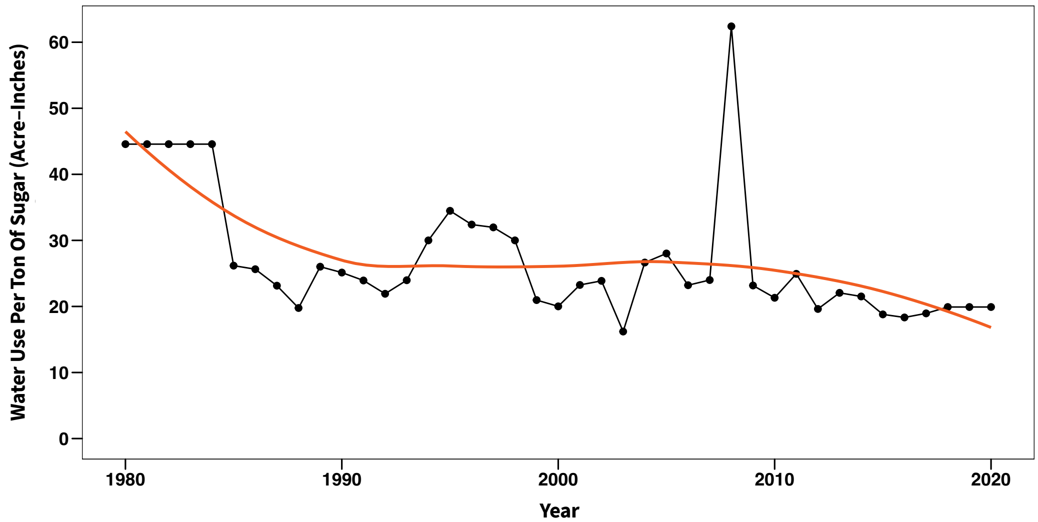
Table 1.10.2. Top four contributors for sugar beets for the EU and GHG Emissions indicators during 2010-2020

ENERGY USE	GHG EMISSIONS
Fertilizer	Nitrous Oxide
Crop Protection	Fertilizer
Management	Crop Protection
Irrigation	Management

IRRIGATION WATER USE

Irrigation water use efficiency for sugar beets improved during the 1980s (Figure 1.10.7). Lower irrigation water use efficiency and significant interannual variations were observed in the 1990s and 2000s, likely driven by weather. A small rate of improvement was observed in the 2010s. The last available Irrigation and Water Management Survey for sugar beets in 2008 indicated that approximately 38% of harvested acreage was irrigated.

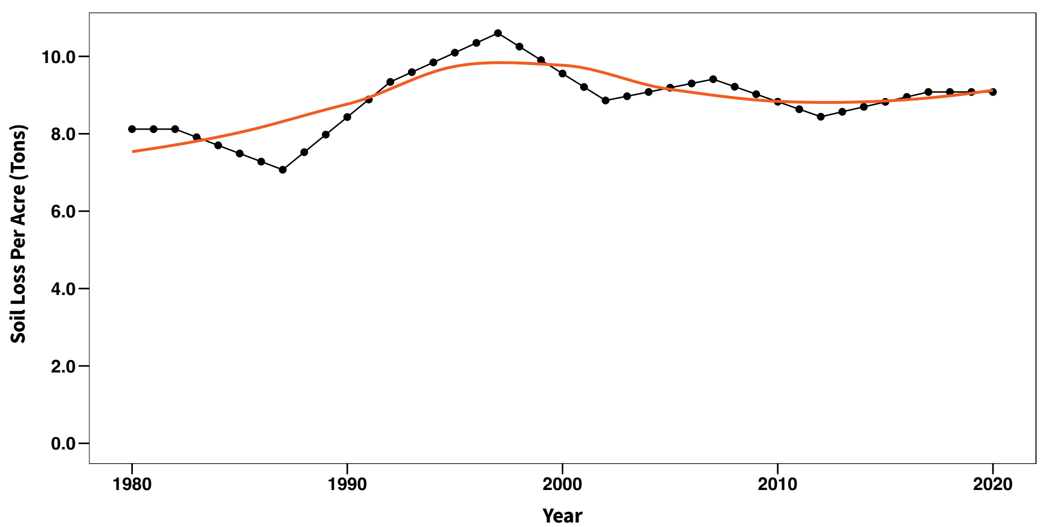
Figure 1.10.7. Irrigation water use efficiency (acre-inches / ton of sugar) for sugar beets during 1980-2020



SOIL EROSION

Soil erosion for sugar beet systems increased slightly from 1980 to 2000 and has since held largely steady at approximately 9 tons of soil loss per acre annually (Figure 1.10.8).

Figure 1.10.8. Soil erosion (tons soil loss / acre / year) from fields producing sugar beets during 1980-2020

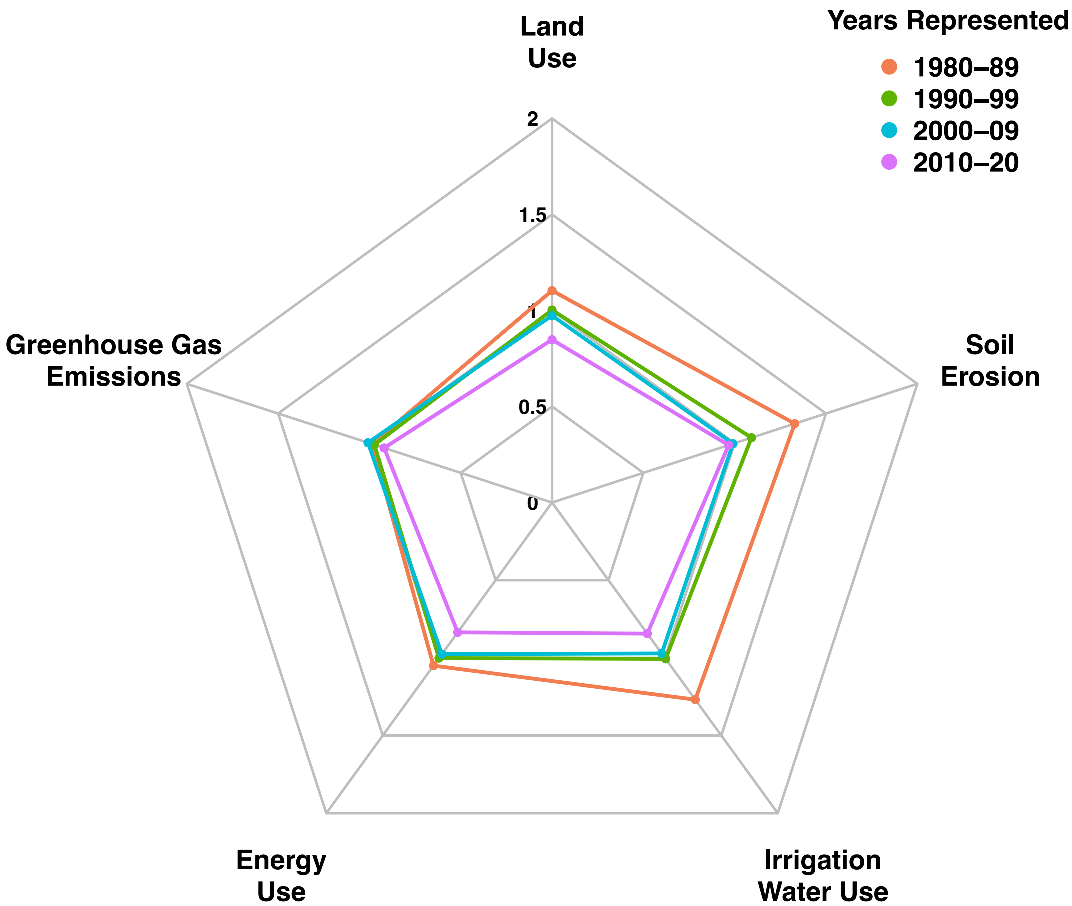


11. WHEAT

Wheat is grown in almost every state in the continental U.S. Here we calculate indicators for all wheat production, including both winter wheat, which is planted in fall and harvested in spring and spring wheat, including durum, which is planted in spring and harvested in summer. The type of wheat grown depends primarily on climate conditions. Across the U.S., wheat production acreage is greatest in the central plains, including Kansas, Texas, the Dakotas and Montana. The summary chart for wheat shows improvement in the 2010-2020 period compared to 1980-1990 for all indicators, with the greatest improvements in land use, irrigation water use and energy use (Figure 1.11.1). A summary of all indicators for wheat for reference years is shown in Table 1.11.1.

Figure 1.11.1. Summary chart of indicators for wheat during 1980-2020

Data are presented in index form, where all indicators have been scaled by indicator averages for the period 1998-2002. A 0.1 point change is equal to a 10 percent difference. Index values allow for comparison of change across indicators with different units of measure. A smaller area represents improvement over time.



Indicators averages for wheat for the period 1998-2002

Indicator	Value	Units
Land Use	0.0299	Planted Acres Per Bushel
Irrigation Water Use	0.5	Acre-inches Per Bushel
Soil Erosion	5.48	Tons Soil Loss Per Acre
Energy Use	99,200	BTU Per Bushel
Greenhouse Gas Emissions	23.6	Pounds of CO_2 Eq. Per Bushel

Table 1.11.1. Summary of indicators for wheat

Year	Land Use	Irrigation Water Use	Energy Use	Greenhouse Gas Emissions	Soil Erosion
	Planted Acres Per Bushel	Acre Inches Per Bushel	BTU Per Bushel	Pounds of CO_2e Per Bushel	Tons of Soil Loss Per Acre
1980	0.0322	0.7438	102,814	22.8	7.6
1990	0.032	0.5328	102,011	23.1	6.6
2000	0.0295	0.4971	100,417	24	5.5
2010	0.0271	0.4577	88,165	22.4	5.3
2020	0.024	0.3871	83,586	22.7	5.4

LAND USE

Land planted to wheat has steadily declined since 1980 (Figure 1.11.2), as has total production although at a slower rate (Figure 1.11.3). The land use efficiency indicator shows a modest improvement over time, reflecting increasing crop yields (Figure 1.11.4).

Figure 1.11.2. Area planted (million acres) to wheat during 1980-2020

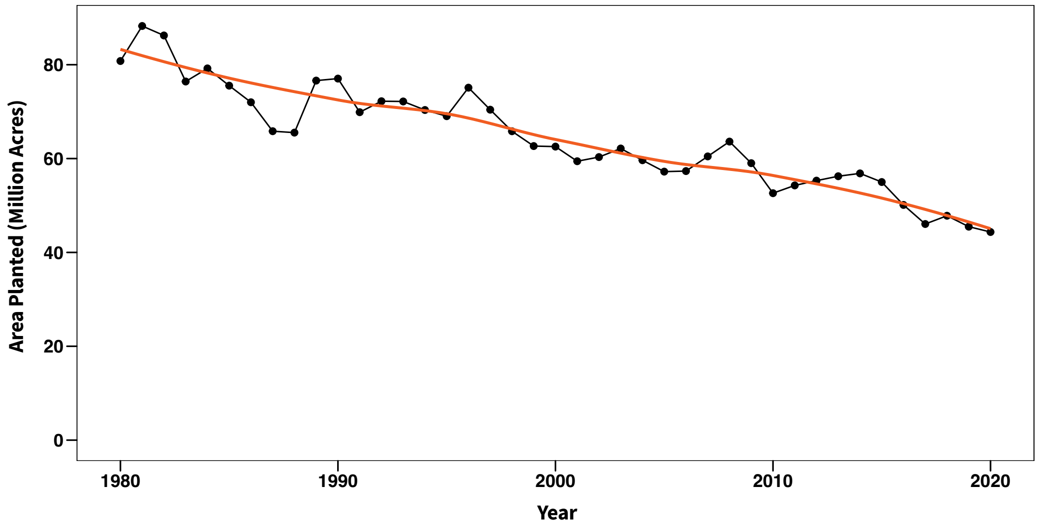


Figure 1.11.3. Total production (million bushels) of wheat during 1980-2020

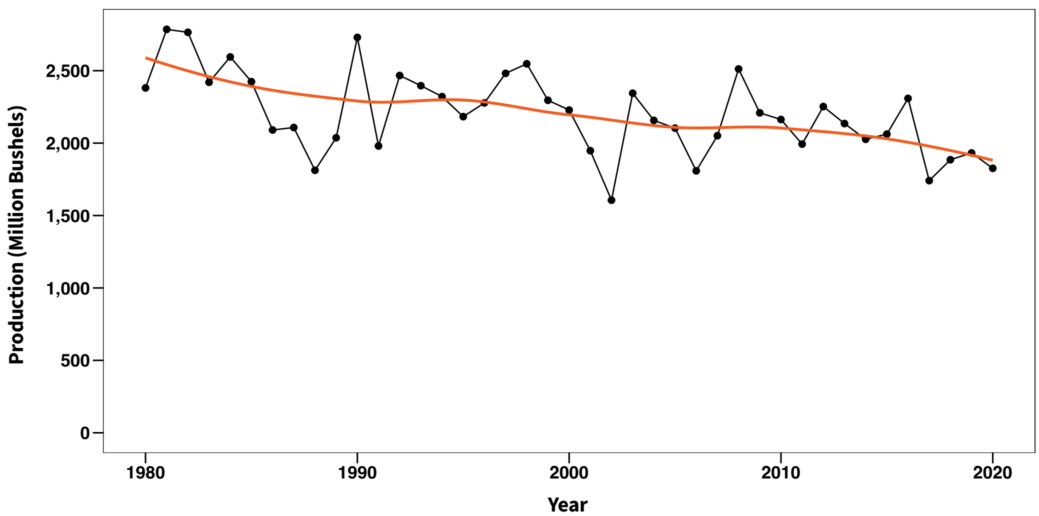
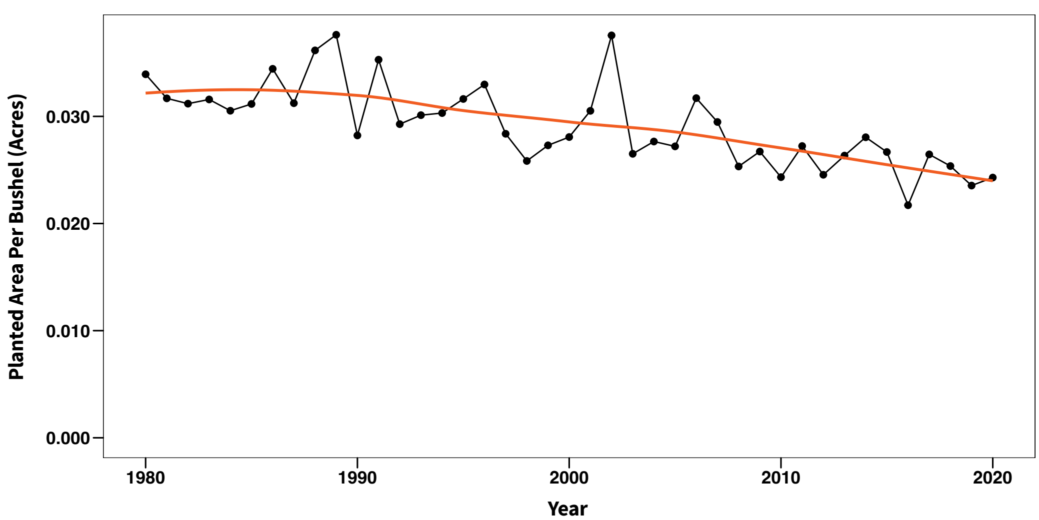


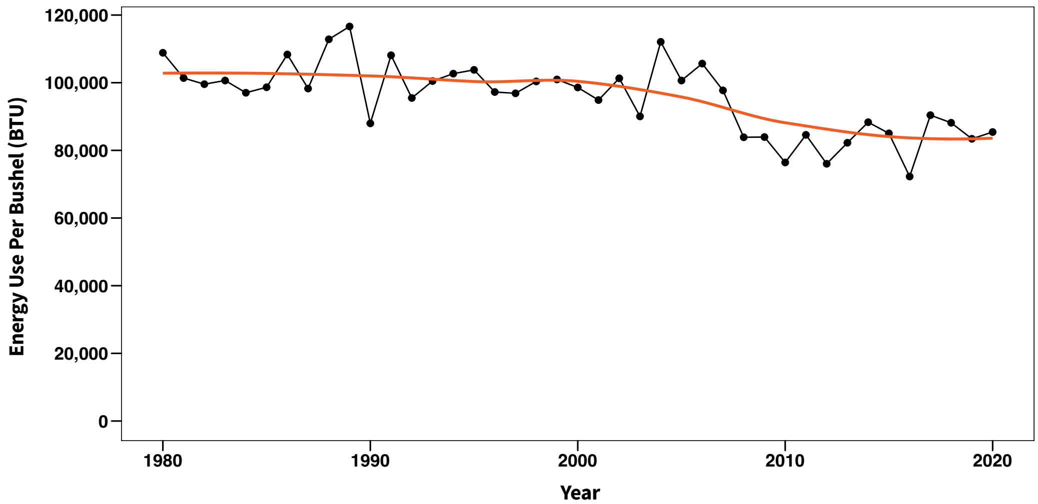
Figure 1.11.4. Land use efficiency (acres planted / bushel) for wheat during 1980-2020



ENERGY USE

Energy use efficiency for wheat improved somewhat in the early 2000s, following a level trend through the 1980s and 1990s, and again staying largely static since 2010 (Figure 1.11.5). A steady increase in no till adoption from 2000 through 2020 contributed to this improvement. Energy use per acre has increased during the years of this study (Figure B.41). There have been increases in nitrogen and phosphorous fertilizer use which has offset the reductions in management energy (Figure B.42).

Figure 1.11.5. Energy use efficiency (BTU / bushel) for wheat during 1980-2020



GREENHOUSE GAS EMISSIONS

Greenhouse gas emissions per bushel of wheat are largely flat across time with some interannual variations (Figure 1.11.6). Emissions per acre have increased, particularly since 2010 (Figure B.43). This is largely driven by increasing nitrous oxide emissions because nitrogen fertilizer applications have increased across this time period (Figure B.44). The top four contributors for energy use and GHG emissions for wheat during 2010-2020 are listed in Table 1.11.2.

Figure 1.11.6. Greenhouse gas emissions (lb. CO_2 Eq. / bushel) for wheat during 1980-2020

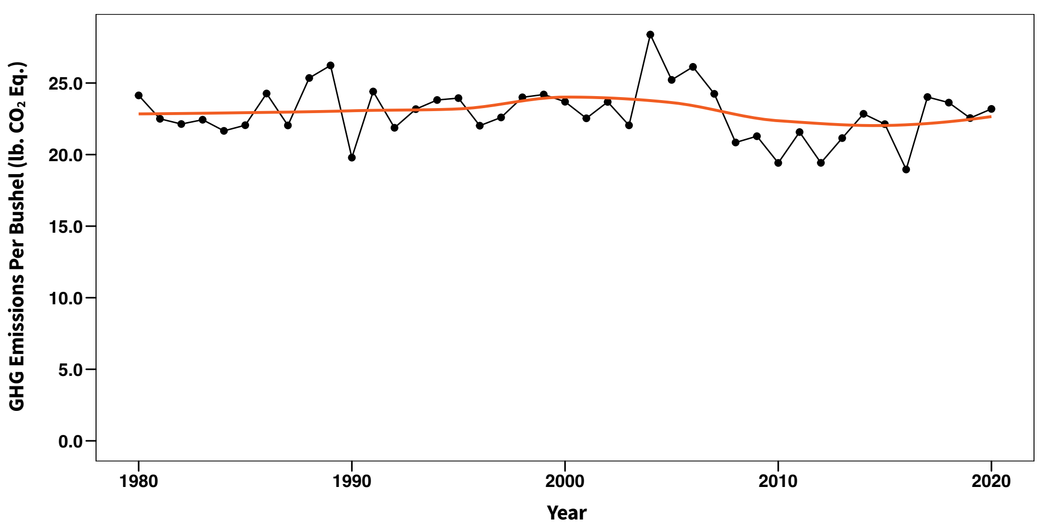


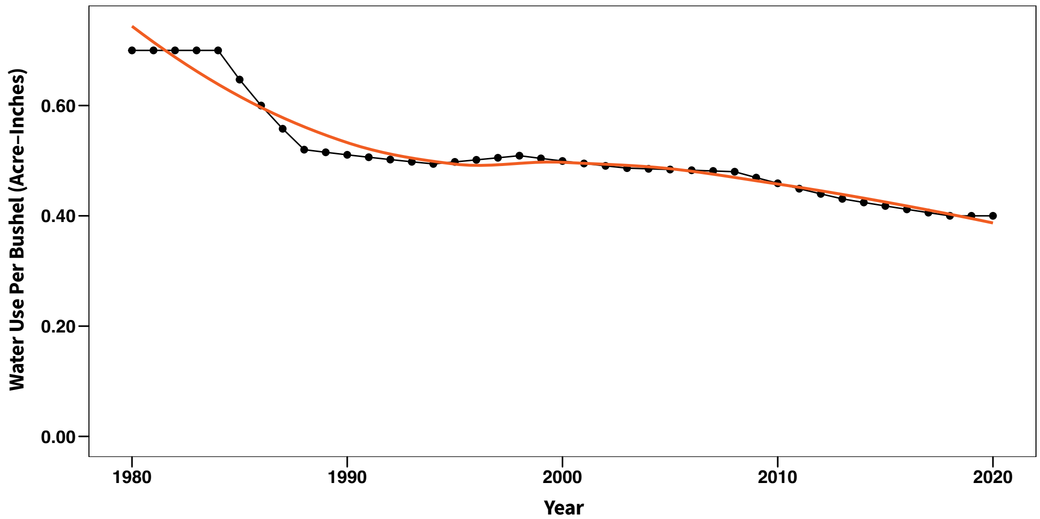
Table 1.11.2. Top four contributors for wheat for the EU and GHG Emissions indicators during 2010-2020

ENERGY USE	GHG EMISSIONS
Fertilizer	Nitrous Oxide
Management	Fertilizer
Seed	Management
Crop Protection	Seed

IRRIGATION WATER USE

Irrigation water use efficiency for wheat has improved over the study period (Figure 1.11.7), with a small reversal period in the 1990s followed by a steady improvement since 2000. Across the 2008, 2013 and 2018 Irrigation and Water Management Survey for wheat, the average irrigated harvested acreage was 6.7% of total harvested acres.

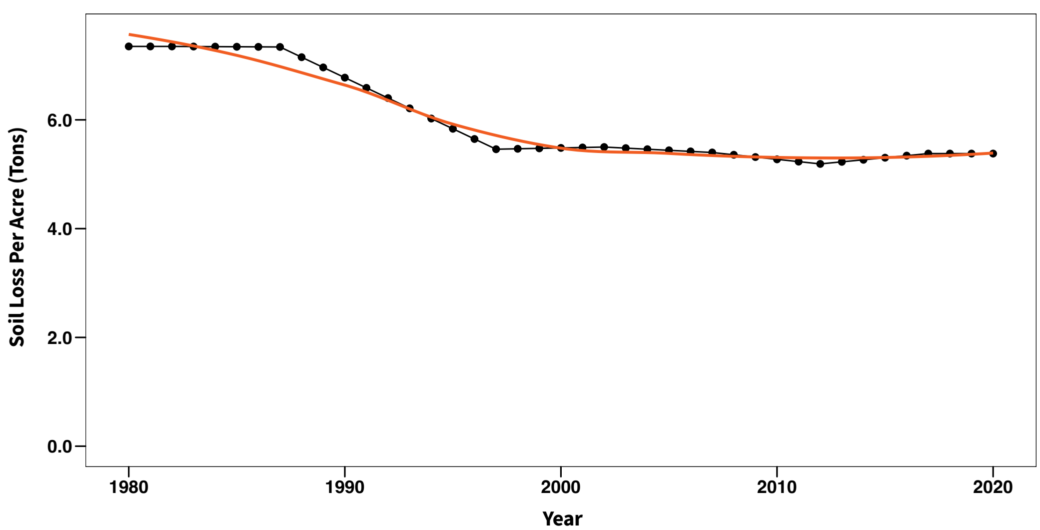
Figure 1.11.7. Irrigation water use efficiency (acre-inches / bushel) for wheat during 1980-2020



SOIL EROSION

Soil erosion for wheat decreased markedly in the 1990s, and erosion estimates since 2000 have been steady at approximately 5 tons of soil loss per acre per year (Figure 1.11.8).

Figure 1.11.8. Soil erosion (tons soil loss / acre / year) from fields producing wheat during 1980-2020



SUMMARY

While we break down the trends for each indicator and crop, there are some common themes that begin to emerge when looking across the full scope of the indicator results.

- Across crops, increases in fertilizer and crop protectant use in the past 10 years emerges as a key contributing factor to the increasing Energy Use and GHG Emissions trends. Efforts to improve on input use efficiency have not yet reached widespread effectiveness.
- Reductions in Greenhouse Gas Emissions per acre have only occurred for crops that are using less nitrogen fertilizer over time.
- Soil erosion improvements were greatest from 1990-2005, accounting for most of the gain for all crops. Soil loss uniformly increased or held steady in the 2010s. This may reflect the generally flat recent trend for adoption of no till and reduced till practices and the relatively modest adoption of cover crops to date. Understanding why conservation tillage adoption has plateaued will be key to understanding what is needed to drive greater adoption and future improvements in soil conservation.

As we have noted throughout this study, the trends identified are defined by available national scale data. In some instances, there are potentially important drivers of trends that cannot be incorporated into the analysis due to missing information. We discuss data limitations further in Appendix A.

Overall, the indicator findings extend the trend that was noted in the 3rd edition of the report (Field to Market, 2016) of a plateauing of the progress made in the 1990s and early 2000s. While the agricultural industry and research to develop new technologies is critical to success, it is increasingly clear that there are also social science and community level factors that contribute to sustained change. Ongoing work within Field to Market and member organizations is exploring what is necessary to accelerate the transition to sustainable practices including: exploring how social science research can inform effective strategies for sustained conservation practice adoption; considering how to incorporate and leverage innovative financial mechanisms to incentivize adoption; and collaborating across the value chain and full scope of agricultural stakeholders in the United States to identify and implement solutions. We remain committed to exploring all possible pathways towards achieving the goals of continuous improvement in environmental outcomes from agriculture.

PART 2: NATIONAL TRENDS IN ENVIRONMENTAL OUTCOMES FROM AGRICULTURE

2.1 BIODIVERSITY

Biodiversity, or the variety of plants, animals, fungi and microorganisms found in nature, is a critical natural resource for the health of the planet and human society, including agriculture. Supporting diverse organisms requires diverse habitats, many of which can be found in and around farms. Sustainable, productive farming systems ultimately rely on biodiversity. For example, native pollinators provide most of the crop pollination and support resilience where domesticated honeybee populations are facing threats. Integrated pest management is an agricultural management strategy that relies on ecosystems that support sufficient populations of natural pest predators to reduce threats to crops.

Society at large shares a vested interest in biodiversity. In fact, few sustainability issues are as visible and understandable to people than the preservation of wildlife habitat. Most farms are located in rural landscapes and tend to be near natural forests, prairies, wetlands or deserts that give wildlife a place to forage for food, breed and nest. Farms share these spaces with outdoor enthusiasts who value such areas for hunting, fishing and enjoying nature. Understanding how biodiversity in these regions has changed over time can inform strategies for preserving habitats and managing lands to support species and ecosystems at risk.

BIODIVERSITY METRIC

One of Field to Market's goals is to support diverse species and ecosystems by conserving and enhancing habitats across U.S. agricultural landscapes. The Fieldprint® Platform assesses biodiversity using the Habitat Potential Index (HPI). HPI scores the *potential for a given farm to provide wildlife habitat on land or in the water*. HPI scores range from 0-100 and measure the level of opportunity to improve or maximize habitat potential.

The metric provides separate scores for cultivated cropland, pastures and non-cultivated lands such as forests and wetlands, plus an aggregated score for the whole farm. Higher scores are desirable and indicate a greater potential to support wildlife habitat. Scores less than 50% represent significant opportunities for improving habitat potential, whereas values of 50-80% indicate moderate realized potential and scores greater than 80% demonstrate farms that have maximized opportunities for biodiversity to flourish. Guidance is provided to farmers and advisers on how to maximize the habitat potential of lands that they manage to improve on the score over time.

BIODIVERSITY INDICATORS

Biodiversity and habitat potential are inherently local and challenging to assess at the macro-scale. There is a wide diversity in management practices that influence habitat potential, and we currently do not have nationally available aggregate data that allow trends in such management to be tracked. In the previous edition of the

National Indicators Report (Field to Market, 2016) we reviewed change in land cover as an important indirect factor for consideration of habitat and biodiversity potential. We used the USGS Land Cover Trends report to assess changes in the 1980-2000 and additional scientific literature on land cover and land use change. We found increases in overall cropland in the early 1980s, followed by a loss of cropland in the 1990s to urban areas and grasslands, and finally with recent information indicating a new expansion of cropland in the years since 2008 at the expense primarily of grasslands (Field to Market, 2016).

Since 2016, new resources for assessing biodiversity trends directly have been released. The most authoritative scientific sources are from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) which has released a regional assessment for the Americas (IPBES, 2018) as well as a report on ecosystem services and food production (IPBES, 2017). IPBES is an independent, intergovernmental body established in 2012 to draw from expertise across scientific disciplines to catalyze the implementation of knowledge-based policies among governments, the private sector and civil society. Other sources of information for this section include scientific research articles and reports from the U.S. Department of Agriculture.

BIODIVERSITY IN NORTH AMERICA

North America supports a wide diversity of species, with approximately 13,000 species of plants, 650 birds, 450 mammals, 300 amphibians and 430 reptile species. However, the overall trends indicate that this diversity is threatened - across the Americas, one quarter of all species are threatened or face the risk of extinction. In North America, more than 75 species of freshwater fishes have become extinct since 1950 (IPBES, 2018).

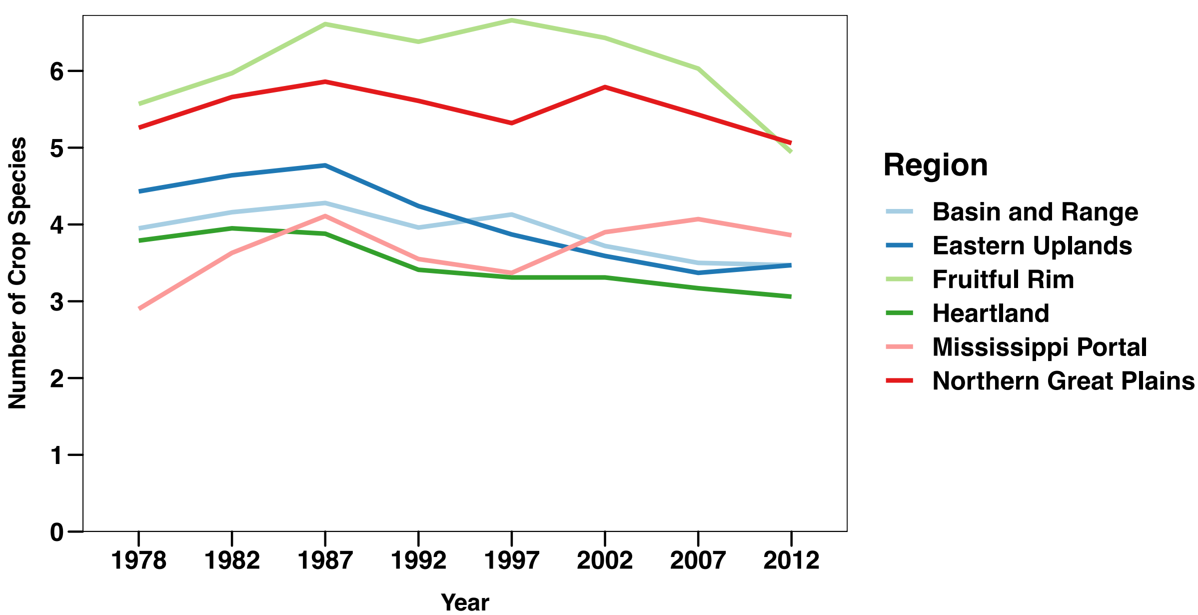
TRENDS IN CROP DIVERSITY

Agricultural lands can support biodiversity through growing diverse species for food production and taking other measures to support both habitat above ground and habitat for soil micro-organisms that are important for soil health. However, from 1978 to 2012, the diversity of crops grown in the United States dropped significantly (Figure 2.1.1). The lowest crop diversity is found in the American Corn Belt, where high-yielding corn and soybean varieties dominate the agricultural landscape. The trend toward corn and soy is also evident in the Eastern Uplands region of the U.S. which includes portions of Ohio, Pennsylvania, West Virginia, Virginia, Tennessee, Kentucky, Alabama, Mississippi, Oklahoma and Arkansas. Crop diversity remained fairly high and consistent in regions growing most of the fruits and vegetables in the country, as seen in California, Oregon, Washington, New York, Pennsylvania, New Jersey and Massachusetts. The Mississippi Portal region is the only region in the nation to record greater crop diversity over time, attributed, at least in part, to declines in cotton acreage, which may have opened to the door to more diverse crop rotations (Aguilar et al., 2015).

TRENDS IN BIRD ABUNDANCE AND DIVERSITY IN NORTH AMERICA

The conversion of lands to agriculture in North America has contributed to declines in bird species – between 1966 and 2013, populations of bird species associated with farmland declined by 74%. The most significant decline has been in populations of aerial insectivores, or birds that eat insects on the wing. No single factor has been identified for this decline, but important contributing

Figure 2.1.1. Number of crop species for six ERS Farm Resource Regions for Census of Agriculture years. Numbers represent county averages.



factors include inadequate insect prey populations on and around farms which is linked to several factors including agricultural insecticide use, compromised or insufficient surface water, and lack of suitable habitat and forage (Stanton et al., 2018).

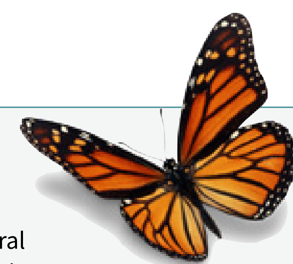
Lands fragmented by agriculture provide less suitable habitat for diverse bird populations. Smaller, discontinuous grassland habitats produce greater edge effects, which leads to greater pressure on bird populations by nest predation compared to larger continuous grassland areas (Stanton et al., 2018). In addition, shrinking wetlands has led to fewer habitats for riparian birds, such as red-wing blackbirds whose young depend on larger habitats to provide more available food. Rangeland or pasture lands, particularly when planted to multi-species grasses, offer better bird habitat than those cultivated in row crops. Farm operations can also cause direct harm to birds through pesticide exposure, soil preparation, planting, tillage, mowing and other harvest practices that can directly kill birds and destroy nests.

Farmers can reduce these risks and support avian biodiversity in their regions with the right information. For example, in soybean fields bird mortality can be almost eliminated by delaying planting by two weeks, which allows time for the young to fledge before the equipment destroys the nests. However, there are tradeoffs with production as such a delay may lower crop yields. Greater density and diversity of nesting birds can be found in no-till corn and soybeans, compared to those that are conventionally tilled, most likely because the standing vegetation offers greater cover from predators. In forage crop production, planning the timing of mowing to avoid cuttings during the breeding season can reduce the risk to birds. This can be a challenge in some systems, such as for cool season forages because they produce more biomass earlier in the season, sometimes necessitating mowing before young birds have fledged. Mowing exposes young birds to direct destruction from equipment and exposure to predators resulting from less plant dense plant cover. Wet years, though they depress yields, are associated with greater nest success in certain bird species due to fewer and later cuttings of forage crops (Stanton et al., 2018).

TRENDS IN POLLINATOR ABUNDANCE AND DIVERSITY IN NORTH AMERICA

Pollination is a necessary process for crop seed production and may be mediated by non-living factors such as wind or water, or by living pollinators, including bees, butterflies and birds. Due to this, pollination was the subject of a special report by IPBES (IPBES, 2017). Worldwide, approximately 75% of all cultivated crops depend on living pollinators. In 2012, the value of pollination for food production was estimated at $351 billion globally. Although some commodity crops commonly cultivated in North America self-pollinate, like cotton and soybeans, or are wind-pollinated like corn and sorghum, other crops such as alfalfa and many specialty crops depend on insect pollinators for reproduction.

In the United States, managed pollination by domesticated, non-native honeybees (European or Western honeybees and Asian or Eastern honeybees) is common. Commercial production of cherries, blueberries, almonds, tomatoes and watermelon are dependent on managed Western honeybee hives. These hives have been under threat of colony loss, which has been escalating since



SPECIES HIGHLIGHT: MONARCH BUTTERFLIES

The plight of the monarch butterfly (*Danaus plexippus*) is well known outside of the agricultural community. The butterfly is famous for long migrations and tendency to overwinter *en masse* in trees and structures along the coast in California and in the mountains of Central Mexico. Populations of the monarch have dropped precipitously since 1950, which has been directly linked to commensurate declines in the 10 milkweed species utilized as their larval host plants. Declines in milkweed populations are related to land use changes. For example, one of the monarch's preferred hosts, swamp milkweed (*Asclepias incarnata*), lives in wetlands which have been in decline in the U.S. A study in Illinois found a nearly 94% decrease in common milkweed populations (*A. syriaca*) after croplands were treated with glyphosate, but no significant losses in areas treated with non-glyphosate herbicides. In Iowa, that trend is replicated: milkweed populations dropped steeply since 2000, with some plant populations extirpated following glyphosate treatments (Zaya et al., 2017).

Weeds are loosely defined as a plant growing where it is not wanted by the land manager. Allowing milkweed and other weedy plant populations to become established in cultivated areas is not feasible for several reasons. Weeds can compete with crops for space, light, water and nutrients, may interfere with harvest operations and their seeds may contaminate harvests. Landowners and managers are encouraged to allow milkweeds and other pollinator host plants to grow and complete their lifecycles in non-cultivated areas of the farm and adjacent landscapes.

1990. These losses have been largely attributed to infestation by the parasitic varroa mite, which feeds on bee pupae and transmits viruses that compromise the bee's immune system leaving them vulnerable to other transmittable disease (IPBES, 2017).

Although a few species of domesticated honey and bumble bees are widely deployed to pollinate crops, there are at least 20,000 species of other organisms that provide pollination services, many of which are wild bees. Between 2008 and 2013, wild bee abundance decreased by 23% in the United States, mostly in the agricultural lands of the Midwest, Great Plains and Mississippi River valley. Threats to wild and domesticated bees are tied to land use changes, changing climate and pesticide toxicity, among others. IPBES (2017) also found that using an integrated approach to pest management can decrease the amount of insecticide applied and reduce the risk of exposing pollinators.

Land use changes lead to habitat fragmentation and loss for wildlife, including pollinators. A USDA report (Hellerstein et al., 2017) reviewed the impacts of these land use patterns on pollinators and found that the ability of a given area to support pollinators is highest in forests, rangeland, rural roadsides and certain farmland that produces sunflowers and berries. This ability is lower in lands producing cotton, soybeans, nuts and grapes, and further reduced in farmland producing corn, wheat, rice, barley and sorghum. While there is not a clear national trend, regional patterns in this ability as measured by a Forage Suitability Index (FSI) have been observed. Nationwide, from 2002 to 2012, FSI remained the same in 85.8% of land, improved in 6.9% and decreased in 7.3%. Decreases were concentrated in areas of Central California, Montana, North and South Dakota, Iowa, Illinois, Indiana, northeast Nebraska, northwest Kansas and along the Mississippi River, with the most significant decreases occurring in the Dakotas, which are primary summering grounds for honeybees. The greatest improvements from 2002 to 2012 were observed in Washington, Nevada, eastern Kansas, Oklahoma and eastern Texas (Hellerstein et al., 2017).

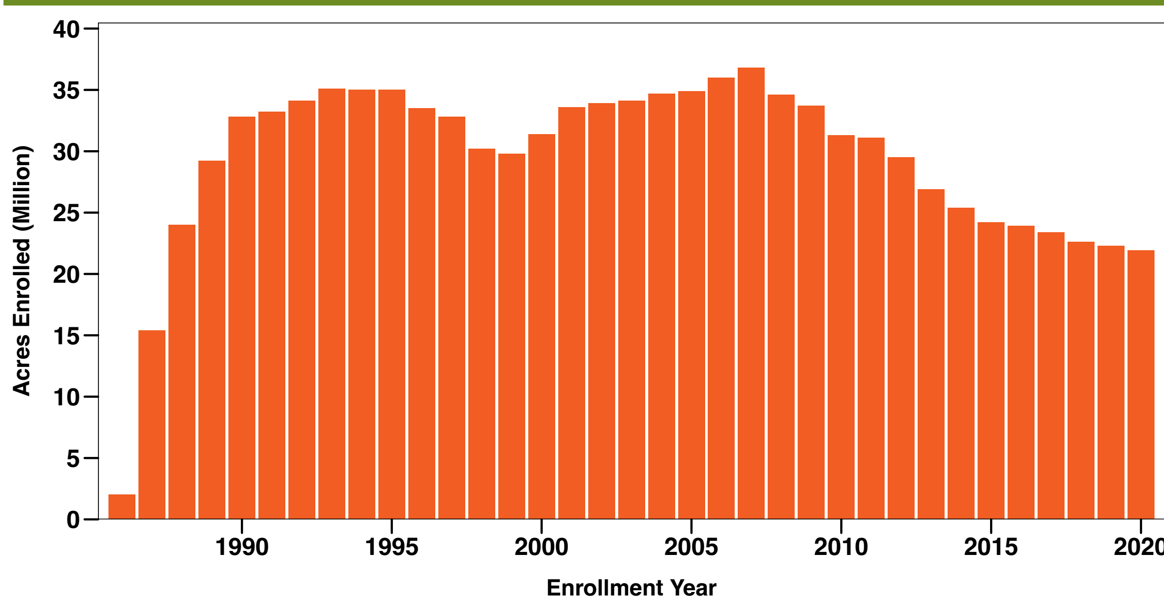
EFFECTS OF THE USDA CONSERVATION RESERVE PROGRAM ON BIODIVERSITY IN U.S. CROPLANDS

While there are ways in which agricultural lands can be managed to support biodiversity and reduce their impact on important species, setting aside sensitive lands out of production and providing areas in the agricultural landscape for diverse species to flourish can also be an option where it aligns with the needs and goals of a farm operation. Here we look at the trend over time in lands enrolled in the USDA's

Conservation Reserve Program (CRP) which was established in 1985 to "retire highly erodible and other environmentally sensitive cropland and pastureland" from production (USDA, 2020).

Farmers receive yearly rental payments from the USDA over a period of 10-15 years, during which time valuable land cover, such as prairie grass, is re-established. While the principal motivation is to reduce soil erosion, there are additional conservation benefits including supporting diverse plants and ecosystems. Land area in CRP rapidly increased in the early years of the program and stayed relatively constant from the early 1990s through the mid-2000s (Figure 2.1.2) however enrollment began to decline after 2007. This decline is partly attributed to higher crop prices, which serve as an incentive to bring the set aside lands back into production, as well as reductions in the funds available for the CRP program. As of November 2020, there were over 300 thousand farms enrolled in CRP, covering over 20 million acres with a total financial outlay of more than $1.8 billion in combined rental, cost-share and incentive payments.

Figure 2.1.2. Cumulative enrollment in Conservation Reserve Program



How CRP land is managed is important in determining how well it will be able to support biodiversity. For example, in the Southwest High Plains, lands enrolled in CRP are frequently seeded with non-native grasses, resulting in low plant species diversity and low-quality forage and habitat for pollinators. Patches of land in CRP that are greater in area than 100 acres and planted with diverse plant species have been shown to support pollinators and other wildlife (Begosh et al., 2020).

SUMMARY

No singular measure can provide an adequate understanding of the trend in biodiversity in and near agricultural fields. However, studies show that bird and insect populations in the U.S. have been declining for decades while at the same time native tallgrass prairies have been nearly eliminated. Further, the diversity of crops grown has declined overall, with the exception of the Mississippi Portal region. Together, these results signal an overall negative trend in biodiversity in and around farms.

Habitat loss continues to be a primary threat to biodiversity, not just in the U.S., but worldwide. The declining numbers of acres set aside in the Conservation Reserve Program over the past 10 years contribute to challenges of efforts to restore habitat and protect biodiversity on farms. With increasing reliance on chemical management with non-selective herbicides, populations of certain pollinator larval host plant, like milkweed, have been significantly reduced.

Agricultural landscapes across the U.S. have opportunities to support diverse and native species and ecosystems that provide important ecosystem services to humanity. Understanding the trends in both the diversity and abundance of species can help to identify what management practices lead to the greatest risk of further biodiversity loss and also what can be done to prevent loss and transform landscapes to support regeneration of biodiversity in agricultural landscapes. This section has highlighted some of the notable trends and what those imply for the risks to biodiversity associated with agriculture in the U.S. and begun to explore what management practices can reduce risk and support greater abundance and higher biodiversity of species. Biodiversity is a natural resource concern of national and global consequence, but it is inherently local. Farmers, with a deep understanding of their lands, are well positioned to identify both the risks and the best mitigation strategies that align with using the land to produce food, fiber, feed and fuel.

2.2 SOIL CARBON

Soils are the largest organic carbon pool on the land surface, and agricultural soils that have been disturbed by tillage and other practices for many years have lost carbon to the atmosphere. This historical loss, however, means that there is substantial opportunity to increase soil organic carbon (SOC) in agricultural soils by adopting practices that reduce soil disturbance and increase carbon from organic matter. These practices include conservation tillage, diverse crop rotations, residue retention and cover crops (Paustian et al., 2016). In recent years, many private sector efforts have begun to explore potential SOC sequestration as a strategy for meeting company and industry targets for climate change mitigation.

Carbon accumulation in the soil is difficult to measure because it occurs slowly over long time periods and does not follow a linear trend. While initial increase in carbon following a farm management change may be rapid, that rate will slow over time as the soil system begins to approach a new ecosystem equilibrium, or steady state (Paustian et al., 2016). For example, after conversion from conventional tillage to a continuous no tillage system, a field may approach a new equilibrium after 15-20 years with the largest sequestration rates occurring between 5-10 years (West and Post, 2003). Measuring soil carbon sequestration is complex; there are important dynamics occurring underground and out of range of direct observation. For example, studies have shown that SOC increases in the upper layers of soil following adoption of no tillage corresponds with a reduction of SOC in the lower layers. In effect, reduction in tillage reallocates carbon in the soil profile (Blanco-Canqui and Lal, 2008). This dynamic is attributed to how the shift to no-tillage reduces the incorporation of crop residues and root material into soils (Baker et al., 2007). Regardless of the climate mitigation benefit, SOC is an important sustainability indicator as a measure of soil health that supports many of the functions and ecosystem services vital to agricultural production (Lal, 2016).

Field to Market's goals include recognizing the critical importance of soil carbon both to mitigate climate change and to improve soil health and the resilience of agricultural lands to extreme climate events. To incorporate soil carbon into the Field to Market program, we have adopted two field-level assessment tools that provide farmers with an annual snapshot of their soil's health and assess the potential to increase SOC by adopting conservation practices.

SOIL CARBON METRIC

The primary Soil Carbon metric in the Fieldprint Platform is the Soil Conditioning Index (SCI), a conservation planning tool developed by USDA NRCS to provide guidance to users on probable directional change in soil carbon as a result of practice adoption and change. SCI has three main components – soil organic matter (SOM), field operations and erosion. SOM contains approximately 58% carbon, and therefore the SCI provides an indication of whether a soil is gaining or losing carbon. SCI is calculated from the Revised Universal Soil Loss Equation 2 (RUSLE2) and is a unitless, relative and crop-specific measure with an output range of -1 to +1. Very small values (- 0.05 to +0.05) represent index levels where there is little or no confidence that soil organic matter (SOM) is changing in either direction. As the SCI value moves further away from zero, it indicates greater confidence that the soil carbon is changing; therefore, higher values approaching +1.0 indicate greater confidence that SOC is increasing and lowest values, approaching -1.0 indicate greater confidence that soil carbon is decreasing. The advantages of the SCI are that it is relatively simple to use and can be applied with just one year of information about a farm operation. Note that this method only captures the dynamics of soil carbon in the surface layer of the soil.

Field to Market has also integrated a second tool – COMET-Planner – as an optional scenario planner to assess how recent or planned changes in practices might impact carbon in their soils (Swan et al., 2020). This feature allows producers and their advisers to quickly and simply estimate the quantity of carbon various conservation practices might sequester in their fields. Together, these tools provide both a high-level assessment of soil health and a starting point for understanding the potential benefits to a producer and farm from engaging with private sector carbon markets before committing to the extensive testing and modeling requirements of market entry.

NATIONAL TRENDS IN SOIL CARBON FROM 1990-2015

Given the complexity of soil organic carbon measurements described above, understanding how the SOC content of agricultural soils in the United States has changed over time requires application of sophisticated simulation models. As a party to the UN Framework Convention on Climate Change, the United States produces annual inventories of all greenhouse gas emissions sources and sinks (U.S. EPA, 2021a), including those from agriculture. To support this reporting, the USDA publishes a quadrennial greenhouse gas inventory, focused on agriculture, forestry and land use change, which contains detailed national- and state-scale modeling of all greenhouse gas sources and sinks for agricultural lands. The most recent USDA Agriculture and Forestry Greenhouse Gas Inventory assesses these changes from 1990-2015 (USDA, 2021) and provides the most comprehensive estimate of SOC change on U.S. croplands available. Here we examine the results for major cropping systems grown on mineral soils, which are low in organic matter. It is important to note that organic soils, while small in area in the U.S., are very vulnerable to soil carbon loss when cultivated.

The USDA uses a simulation model called DayCent to estimate soil carbon using detailed data on land management, weather conditions, soil characteristics and land use history. The modeling is conducted for 400,000 National Resources Inventory (NRI) survey points that represent a statistical sampling of land use and management practices on all non-federal lands in the United States. DayCent models plant-soil nutrient cycling by simulating key processes occurring in the soil including plant growth, senescence, decomposition of dead plant matter and other organic matter and nitrogen mineralization (DelGrosso et al., 2001b; a). Because the simulations run for multiple years, they are accounting for whole crop rotations so results are available for entire cropping systems rather than just individual crops. The analysis defined 10 major cropping systems based on five-year rotations as determined by the NRI survey data. Six of the cropping systems contain results for the commodity crops considered in this report.

- **Row crops**: At least three of five years in corn, soybean and/or sorghum;
- **Small grains**: At least three of five years in barley, wheat and/or oats;
- **Low residue crops**: At least three of five years in cotton, potatoes, sugar beets, dry beans, onions and/or tomatoes;
- **Hay (legume)**: five continuous years in legume hay;
- **Flooded rice**: At least three of five years in flooded rice production;
- **Other**: agricultural lands that did not have three of five years in any of the other definitions. Contains a mix of crops and diverse rotations.

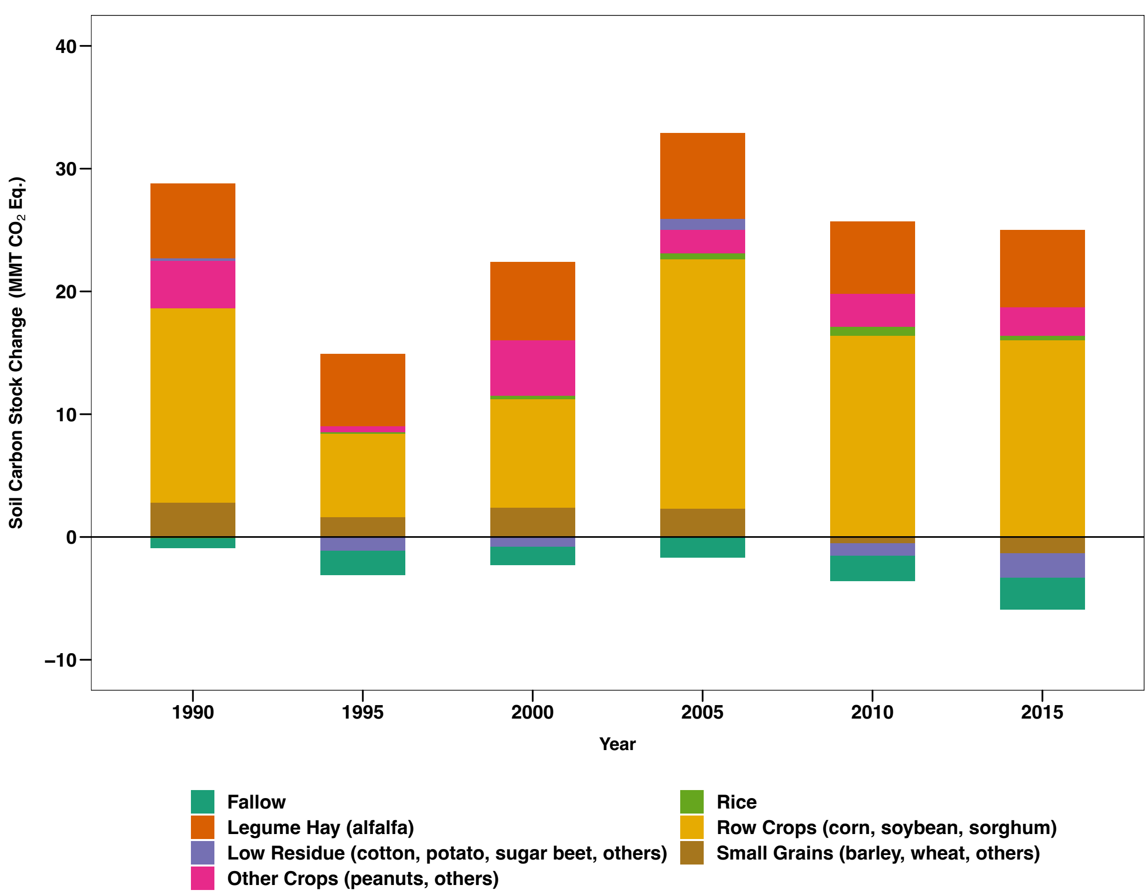
We also include in our discussion the soil carbon change in land enrolled in the Conservation Reserve Program (CRP). This land has been identified as environmentally sensitive and set aside from active crop production, typically planted to grasslands or other perennial vegetation.

SOIL CARBON TRENDS BY CROPPING SYSTEM

The results presented here are taken from the USDA analysis (USDA, 2021) and represent the change in SOC stock in one year from all lands in the U.S. in a particular cropping system (as defined above). The results are displayed in units of million metric tons of carbon dioxide equivalent (MMT CO_2e). We display carbon sequestration (gain) in soils as a positive stock change and carbon emissions (loss) from soils as a negative stock change.

Overall, soils actively managed under the six cropping systems considered here have increased soil carbon stock throughout the last 25 years (Figure 2.2.1). The amount of carbon gained fluctuates over time with both the area in production for each of the cropping systems and changes in management practices and weather. Lands that are left fallow are also included and illustrate the importance of living plants to maintaining and increasing soil carbon. Overall, the amount of carbon gained has varied and the most recent two years of analysis available – 2010 and 2015 – indicate losses of soil carbon from small grains and low residue crops, and relatively steady gains in the other cropping systems.

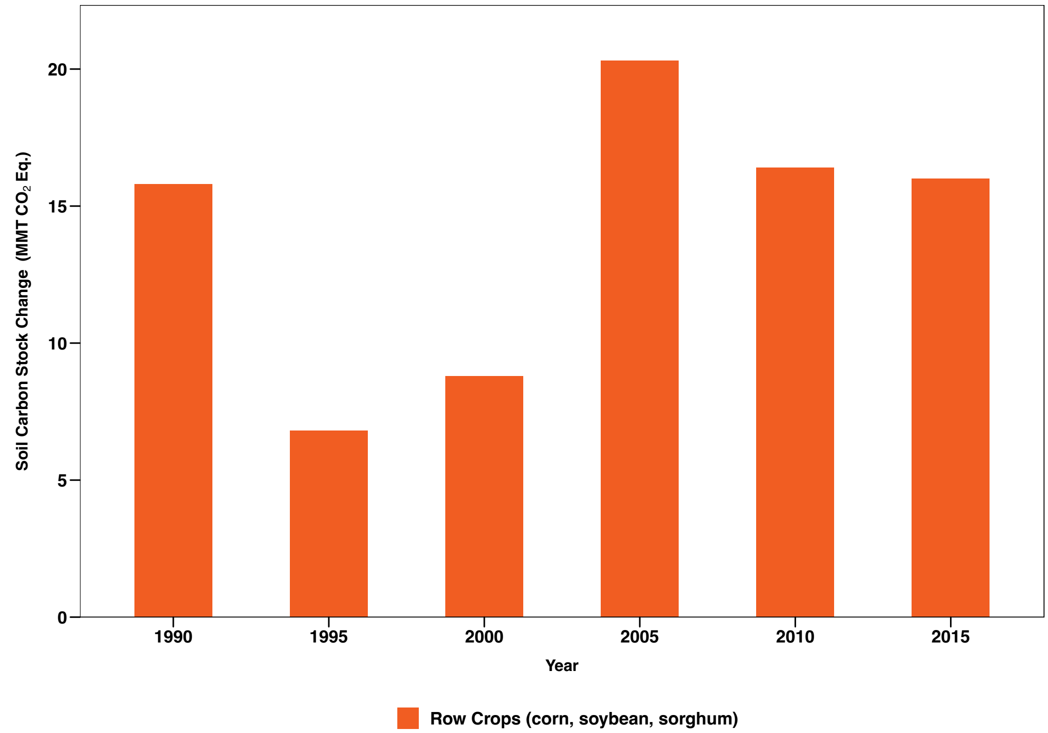
Figure 2.2.1. Soil organic carbon stock change in major U.S. commodity crop systems from 1990-2015 (MMT CO_2e per year)



ROW CROPS

USDA modeling of soil carbon stock change for row crop systems considers croplands that have been in production of corn, soybean and/or sorghum in at least three years of a five year period. This definition captures most lands in corn and sorghum production. Row crop rotations typically contain some high residue crops. These lands have consistently added carbon to the soil over the past 25 years. The increase in soil carbon can be attributed both to increases in the acreage used for production of these crops, as well as shifts toward reduced and no tillage that have occurred since 1990 (Figure 2.2.2).

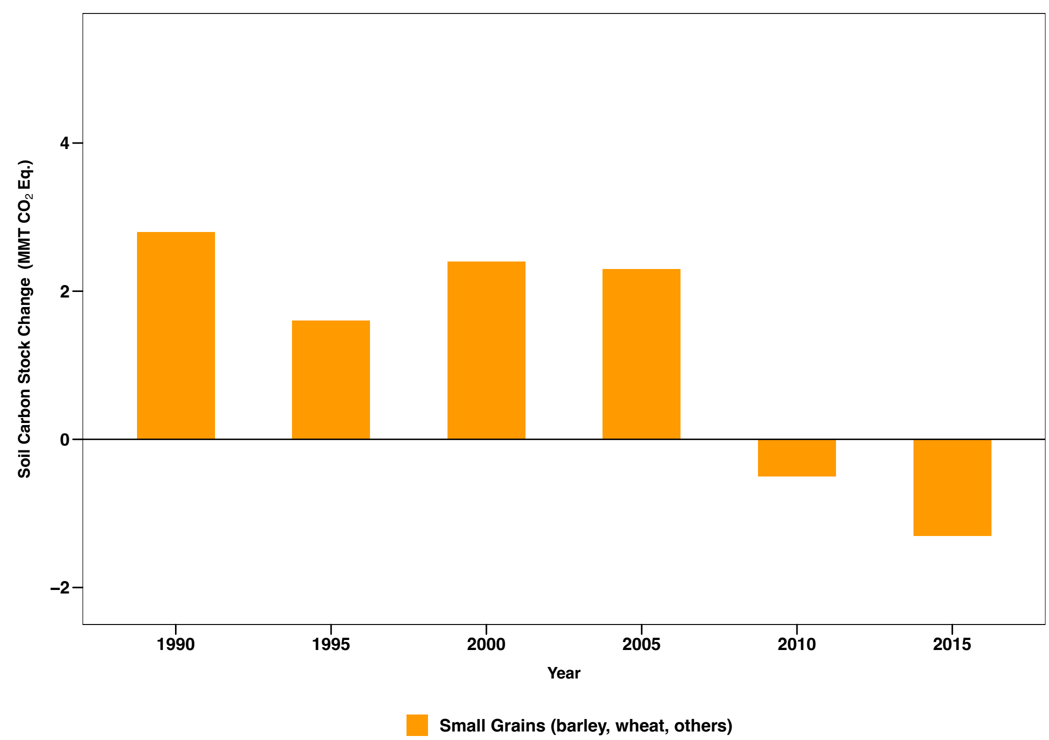
Figure 2.2.2. Soil organic carbon stock change in row crop systems from 1990-2015 (MMT CO_2e per year)



SMALL GRAINS

Small grain systems are defined as lands that are in production of wheat, barley and/or oats in at least three years of a five year period. Land area dedicated to small grain systems has been declining over the past 25 years. In addition, these crops are prevalent in western regions of the country which may be water limited, and wheat is frequently grown in a wheat-fallow rotation small grain systems, which produce lower amounts of crop residues, were responsible for a modest amount of soil carbon gain from 1990-2005, however in 2010 and 2015 these lands have seen reduction in soil carbon stock, representing an emission of carbon dioxide from the soil (Figure 2.2.3).

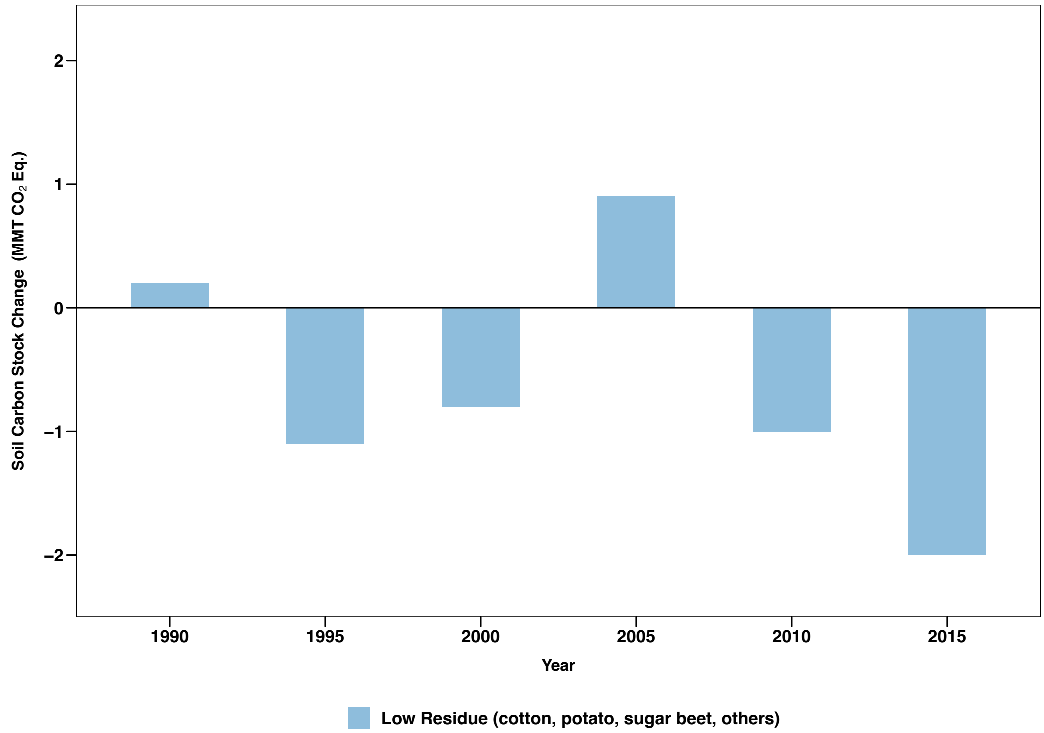
Figure 2.2.3. Soil organic carbon stock change in small grain crop systems from 1990-2015 (MMT CO_2e per year)



LOW RESIDUE CROPS

Cotton, potatoes and sugar beets are included in the USDA modeling category of Low Residue crops due to their plant characteristics and harvest practices leaving little residue on the soil after harvest. Harvesting root crops like potatoes and sugar beets requires a greater amount of soil disturbance. Together, low crop residue and necessary soil disturbance contribute to the soils in these cropping systems typically emitting carbon rather than gaining carbon. Their overall acreage and contribution to the total soil carbon storage on croplands is small and has typically gained or lost less than 1 MMT CO_2e in the years considered. The exception is a greater loss of soil carbon occurring in the most recent analysis year of 2015 (Figure 2.2.4).

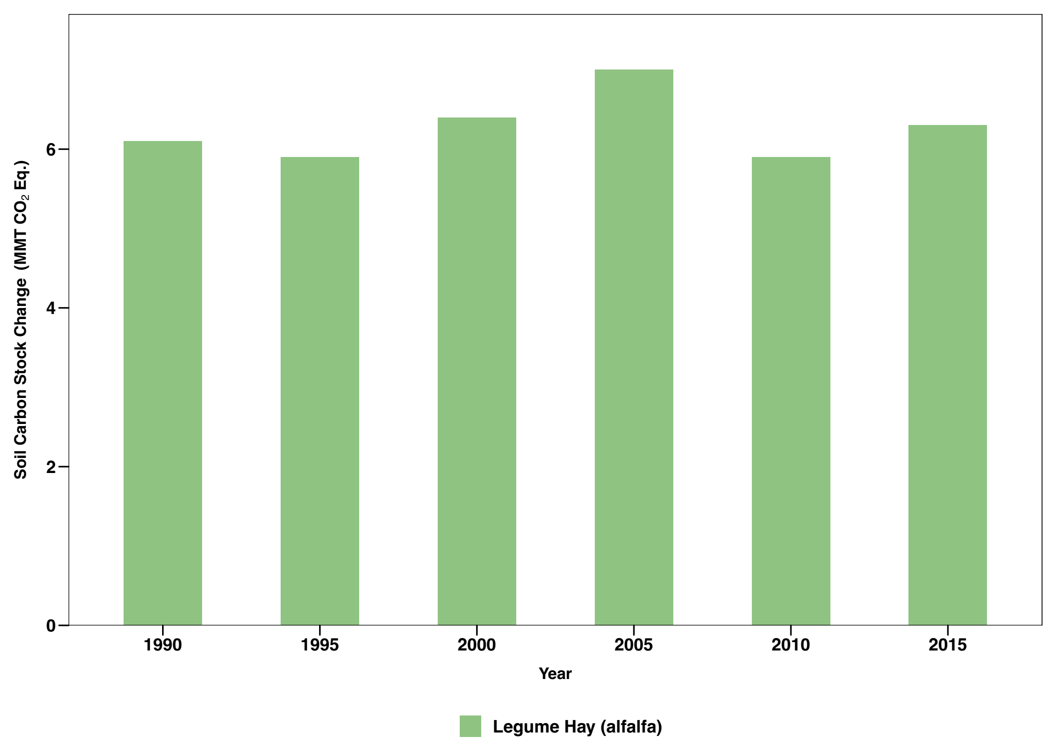
Figure 2.2.4. Soil organic carbon stock change in low residue crop systems from 1990-2015 (MMT CO_2e per year)



LEGUME HAY

Perennial hay crops have greater potential to increase carbon in the soil as they require less disturbance of the soil in most years. Alfalfa is the most common legume hay grown in the United States, and the combination of reduced disturbance and nitrogen fixation contribute to lands growing alfalfa consistently gaining soil carbon stock throughout the time period analyzed here (Figure 2.2.5).

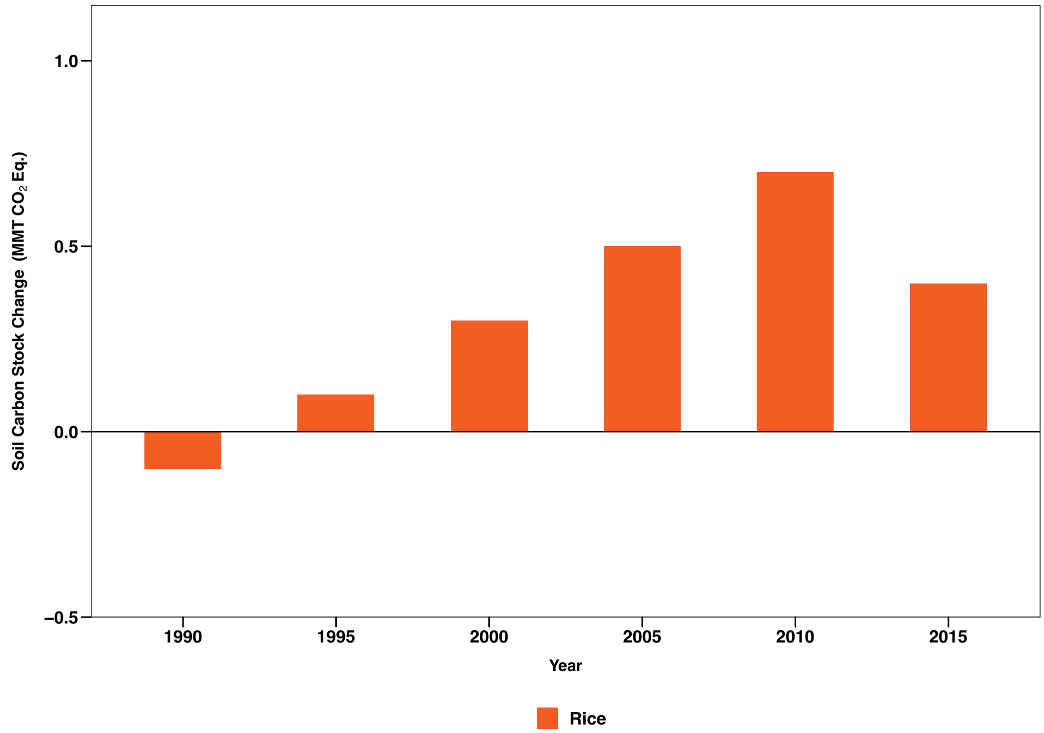
Figure 2.2.5. Soil organic carbon stock change in legume hay crop systems from 1990-2015 (MMT CO_2e per year)



RICE

Rice systems are considered separately in the USDA modeling analysis as the crop is typically grown on flooded fields and the biogeochemical cycles that determine the carbon and nitrogen balance in the soil operate differently in the oxygen-deficient flooded environment. In the United States, the acreage in rice production is small, so the contribution to overall soil carbon stock is small. Rice has consistently demonstrated a gain in soil carbon stock over the past 25 years (Figure 2.2.6).

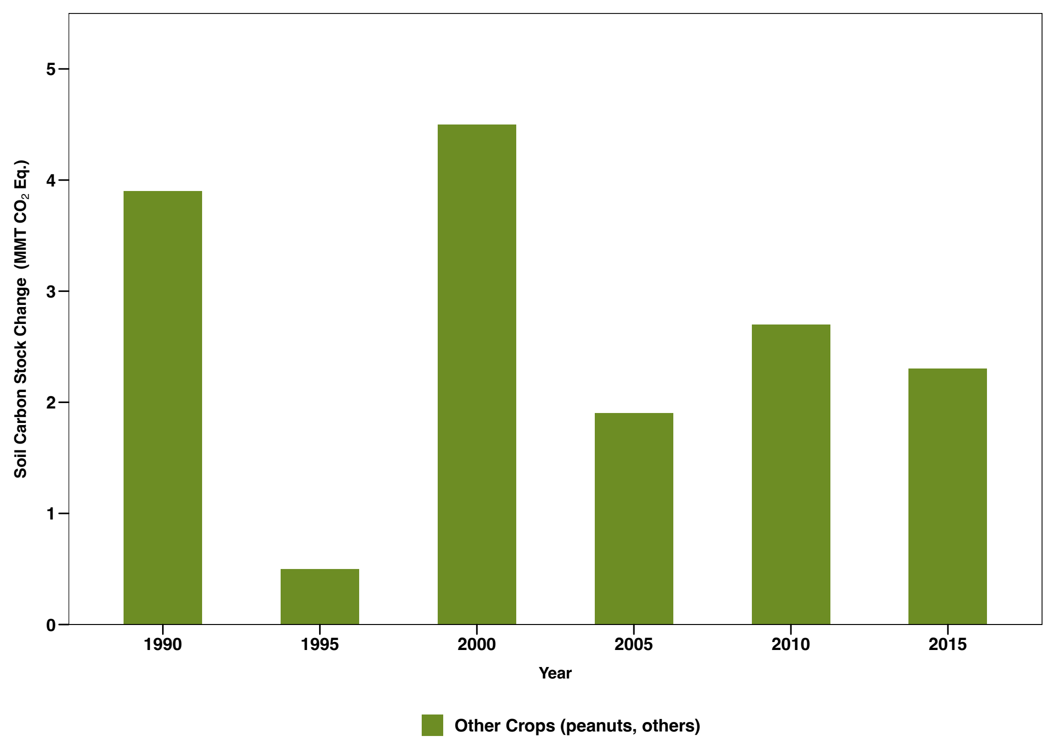
Figure 2.2.6. Soil organic carbon stock change in rice crop systems from 1990-2015 (MMT CO_2e per year)



OTHER CROPS

The "other crops" category refers to cropping systems that did not fall under the more specific categories considered above and typically represent more complex rotations. These lands also demonstrate consistent increase in soil carbon stock over the study period (Figure 2.2.7).

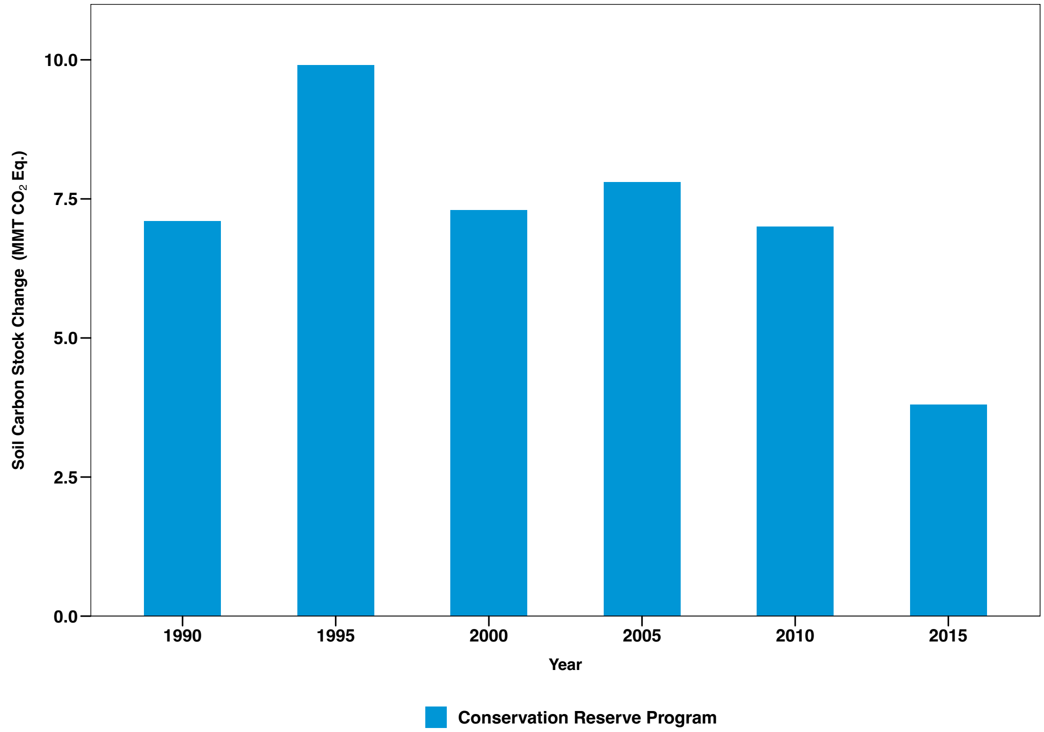
Figure 2.2.7. Soil organic carbon stock change in other crop systems from 1990-2015 (MMT CO_2e per year)



SOIL CARBON TRENDS FOR LANDS IN THE CONSERVATION RESERVE PROGRAM

Lands in the Conservation Reserve Program (CRP) are removed from active crop production for a period of time, and are included here as these lands were previously, and are likely to be again, in active production of crops. Setting aside land in a perennial grassland can increase the carbon in the soil and improve the overall soil health. These lands consistently provide a sink for soil carbon throughout the study period, with fluctuations in the carbon stock change determined by the extent and location of land set aside in any given period (Figure 2.2.8).

Figure 2.2.8. Soil organic carbon stock change in Conservation Reserve Program lands from 1990-2015 (MMT CO_2e per year)



SUMMARY

Overall, soils actively managed under the cropping systems considered in the Field to Market program have increased soil carbon stock during the last 25 years. The greatest soil carbon gain was observed in 2005 and in later years less carbon gain and some increases in carbon losses is observed. These findings are consistent with the analysis of Soil Conservation in Part 1 of this report, which indicate that reductions in reducing soil erosion have largely plateaued as total acres in reduced and no tillage practices has stayed steady. The adoption of conservation tillage is the most significant factor influencing the soil carbon gains observed here, with additional contributions from manure management and including perennial hay in rotations (USDA, 2021).

While cover crops are included in the USDA analysis, they do not correspond to a significant increase in soil carbon. This is due to a limitation in the data available for the modeling, which does not include details on cover crop termination practice and, as a result, the models assume termination using tillage (USDA, 2021). Better information is needed from surveys on the methods of termination, such as through herbicide application or mechanical rolling, that do not involve soil disturbance. Under those conditions, cover crops are associated with increasing soil carbon (USDA, 2021). While cover crop acreage is currently relatively small, it is increasing and this detail will become an important consideration for assessing trends in soil carbon over time.

Other conservation practices that increase soil carbon sequestration on a farm are not included in the USDA analysis. For example, conservation practices that convert small areas of sensitive and low productivity cropland within a crop field to grasslands are also increasingly part of the toolkit available to farmers. These include grassed waterways, buffer strips at the edge of fields and prairie strips, as well as using economic and spatial analysis to identify where land can be taken out of production without negatively impacting the profitability of a farm operation. These practices have multiple environmental benefits, including soil carbon storage, erosion control and creating habitat to support diverse ecosystems.

Over the past decade there has been increasing awareness of the importance of soil organic carbon for agricultural productivity, soil health and climate mitigation. Public and private sector efforts to improve climate outcomes hold promise to accelerate adoption of agronomic practices that improve soil health and store soil carbon. The development of incentives and market programs for these benefits hold promise to accelerate adoption of agricultural management practices through financial and technical assistance to farmers. Future soil carbon sequestration in croplands will depend both on the adoption of SOC sequestering practices as well as on changes in weather conditions from ongoing climate change. Continuing to track trends over time is important for understanding agriculture's potential to contribute to climate mitigation and meeting domestic and international goals and commitments.

2.3 WATER QUALITY

Farming activities have a significant impact on water quality across the United States as soil and water are inextricably linked. Nutrients and other substances applied by the farmer or deposited on the land in other ways, like dry deposition or dissolved in rainwater or irrigation water, contribute to the total loading of the nutrient or substance on a field. Most crop inputs, including organic and inorganic fertilizers and soil-applied crop chemicals, must be activated by water to be taken up by plant roots. In a perfect system, any soil-applied agricultural inputs would only be taken up by the root systems of target plants, be that the crop absorbing nutrients or weeds imbibing herbicides. Unfortunately, crop inputs and soil particles (sediment) are often lost from farm fields during periods of high rainfall or irrigation. Eroded soil and lost inputs leaving the farm make their way into shared water resources through surface runoff, tile drainage and infiltration through the soil profile to groundwater, with numerous negative consequences for the downstream people and wildlife that rely on that water.

A primary barrier to understanding the impacts of conservation measures intended to improve the quality of water leaving farm fields through surface runoff, tile drainage and infiltration through the soil profile is the confounding effect of variable rainfall. Intense rainfall and flooding accelerate soil erosion and the movement of sediment, crop nutrients and protectants into surface waters and increases the volume of water (and the crop inputs dissolved within) moving through, and discharged from, tile drainage. In coarse, sandy soils, high precipitation may dissolve soil-bound inputs, causing them to be leached and lost to groundwater. Despite concerted efforts to optimize input applications and protect soil from erosion, extreme precipitation events can overwhelm those efforts, leading to downstream water quality impairment.

A WORD ABOUT PHOSPHORUS

Phosphorus is generally considered "immobile" in the soil, meaning it does not readily move from where it was applied. Over many years of farming and applying phosphorus to fields, the nutrient can accumulate in the soil, and may be flushed out during significant precipitation events. Most phosphorus in the soil is in the particulate form or occluded within soil granules. This has led to the misconception that controlling soil erosion will effectively control phosphorus export from agricultural land (Baker et al., 2014), but recent developments have shown that a significant portion of phosphorus losses can be in the dissolved form (Baker et al., 2007; Joosse and Baker, 2011).

This "legacy" phosphorus can make it difficult to demonstrate the efficacy of ongoing phosphorus reduction strategies, as it may enter waterways several years after it was applied.

Conversely, during relatively dry years, precipitation may not exceed the water-holding capacity of the soil. In this case, very little water will leave the farm, thereby naturally reducing the amount of sediment and crop inputs entering surface and groundwater. For this reason, it is important to consider water quality outcomes in terms of longer-term trends and indicators rather than measuring success of any interventions from single-year measurements.

Although there is no shortage of examples of crop protectant chemicals such as herbicides being found in municipal drinking water supplies, excess nutrients in the water, principally nitrogen and phosphorus, have led to decades-long efforts to reduce losses from farm fields. Nitrogen and phosphorus stimulate the growth of photosynthetic organisms, which is why they are so valuable to crop production and yields. But, when lost to aquatic systems such as rivers, lakes, bays and gulfs, nitrogen and phosphorus stimulate the growth of photosynthetic algae, which leads to a cascade of negative impacts, including hypoxia (severely depleted oxygen levels). Hypoxic waters cannot support diverse aquatic populations. Fish and other mobile, aquatic animals can flee hypoxic areas, but stationary wildlife such as mussels, clams and oysters have no such escape and die, creating "dead zones".

FIELD TO MARKET WATER QUALITY METRIC

Water quality is a complex environmental metric to measure and model, as it is affected by many site-specific factors, such as soil properties and topography. Further, it is influenced by both short- and long-term management decisions such as timing of fertilizer application and the type of tile drainage system installed. In 2014, Field to Market adopted a simple index model to include water quality resource concerns as a sustainable agriculture component, and in 2021 implemented a more detailed field specific tool that provides a detailed assessment of the risk of nutrient loss from a field and how well existing practices are mitigating the risk.

The metric uses the USDA NRCS Stewardship Tool for Environmental Performance (STEP) to calculate each field's specific risk of nutrient loss. The estimate is based on soil and field physical properties, such as field slope and soil texture, and assesses the effectiveness of conservation practices at mitigating loss for four specific pathways - surface nitrogen loss, surface phosphorus loss, subsurface nitrogen loss and subsurface phosphorus loss. The metric helps growers and Field to Market Continuous Improvement Projects identify the practices that can have the greatest impact at reducing nutrient loss in critical areas of concern. In 2021, STEP was adopted as Field to Market's Water Quality metric.

WATER QUALITY INDICATORS

Field to Market's goals include improving regional water quality through reduction in sediment, nutrient and pesticide loss from U.S. cropland. In the previous edition of this report (Field to Market, 2016), we summarized findings from USDA's Conservation Effects Assessment Program (CEAP) to understand how adoption of conservation practices has impacted major watersheds in the U.S. Here we will further examine water quality trends of three large waterbodies in the United States that have been profoundly affected by agriculture: the Chesapeake Bay, the Gulf of Mexico and the Gulf's primary tributary, the Mississippi River. Trends analyses were drawn from meta-analyses of scientific research papers published by Chesapeake Progress, America's Watershed Initiative and Virginia Marine Research Institute and government reports from the the Environmental Protection Agency (EPA) and National Oceanic and Atmospheric Administration.

WATER QUALITY IN THE CHESAPEAKE BAY

Two-hundred miles long, the Chesapeake Bay is the largest estuary in the United States. Connected to the Atlantic Ocean at its mouth in Norfolk, Virginia, the bay is fed by 50 rivers originating in New York, Pennsylvania, West Virginia, Maryland, Delaware, Virginia and the District of Columbia. The Chesapeake Bay Program, in partnership with the EPA, other federal, state, non-profit and other organizations, monitor the water quality of the Chesapeake Bay, which has been on the EPA's Impaired Waters List for decades. Agricultural runoff is a primary non-point source of nutrients affecting water quality in the Bay. Since the Clean Water Act was implemented in 1972, efforts have been underway to clean up the Chesapeake Bay. Progress toward clean water goals is determined by measuring dissolved oxygen, nutrients and chlorophyll (an indicator of algal abundance) in water at different depths along the bay. Other variables are also measured, such as oyster and aquatic grass abundance. Results indicated slower than desired progress in reducing nutrient pollution from agriculture and urban areas in the early 2000s (Chesapeake Bay Program, 2019). In response, in 2010 the EPA embarked on its largest cleanup effort to date: it established the Chesapeake Bay Total Maximum Daily Load (TMDL), a comprehensive and explicit limit on the amount of nitrogen (185.9 million pounds), phosphorus (12.5 million pounds) and sediment (6.45 billion pounds) permitted to reach the waters of the Bay each year by 2025. To achieve these TMDL reductions, each of the six states on the Chesapeake Bay and the District of Columbia have implemented their own Watershed Implementation Plans (WIP). Figures 2.3.1, 2.3.2 and 2.3.3 illustrates modeled nitrogen, phosphorus and sediment loads to the Chesapeake Bay, by source (Chesapeake Progress, 2019). Although agriculture is the primary source of nitrogen loading in the Chesapeake Bay, runoff from forests is the primary source of sediment.

Using regulatory frameworks for nutrient management and voluntary incentive programs, such as Maryland's Cover Crop Program, these states are expanding agricultural best management practices (BMPs) to reduce loading of sediment, nitrogen and phosphorus into the many rivers and streams that empty into the Chesapeake Bay. Among these BMPs are cover crops, eliminating or reducing tillage, nutrient management plans and edge of field practices like grassed waterways and bioreactors, which are proven to reduce soil and input losses. Between 2012 and 2017, cover crop adoption in Maryland grew 6%, with about 33% of farmland planted in cover crops (Wallander et al., 2021). As a result of implementing these BMPs across the Chesapeake Bay watershed, nitrogen loads from agriculture were reduced by 3% between 2009 and 2020, phosphorus was reduced by 7% and sediment by 19% (Chesapeake Progress, 2021).

Figure 2.3.1. Annual nitrogen loads in the Chesapeake Bay

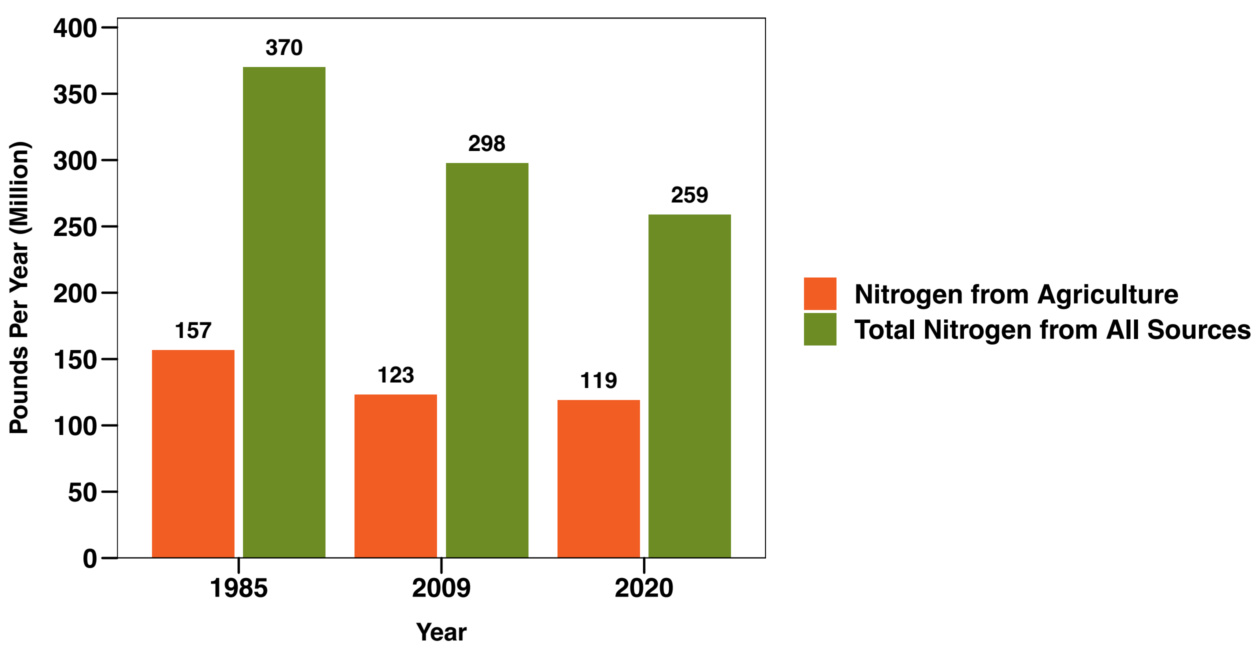


Figure 2.3.2. Annual phosphorus loads in the Chesapeake Bay

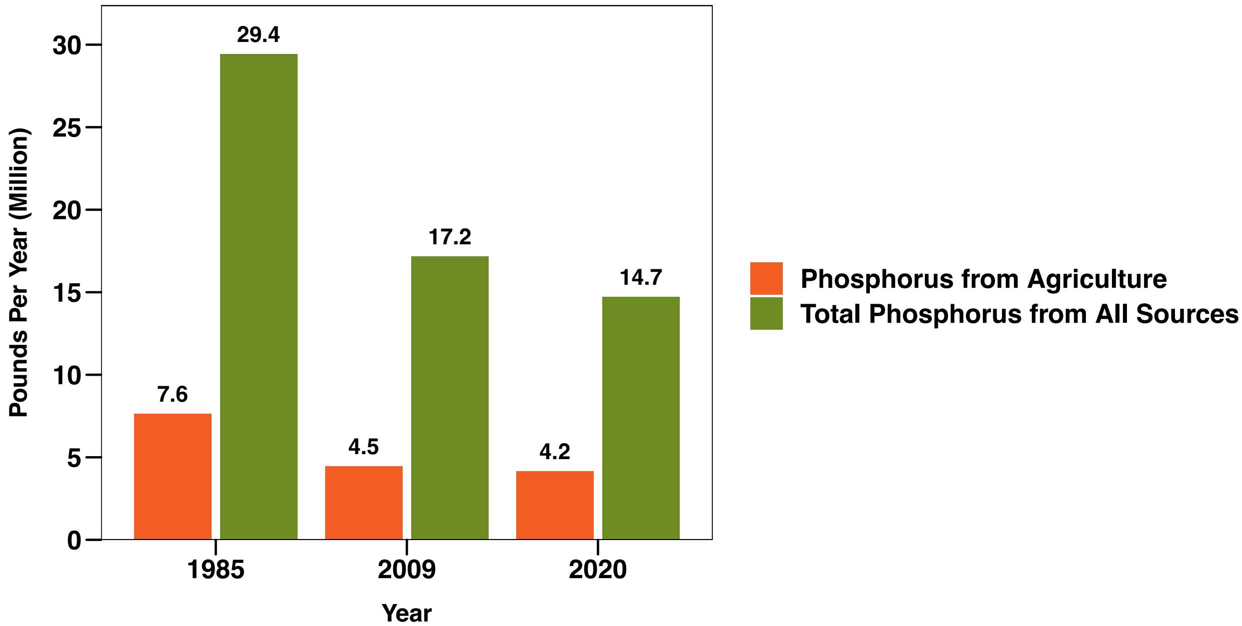
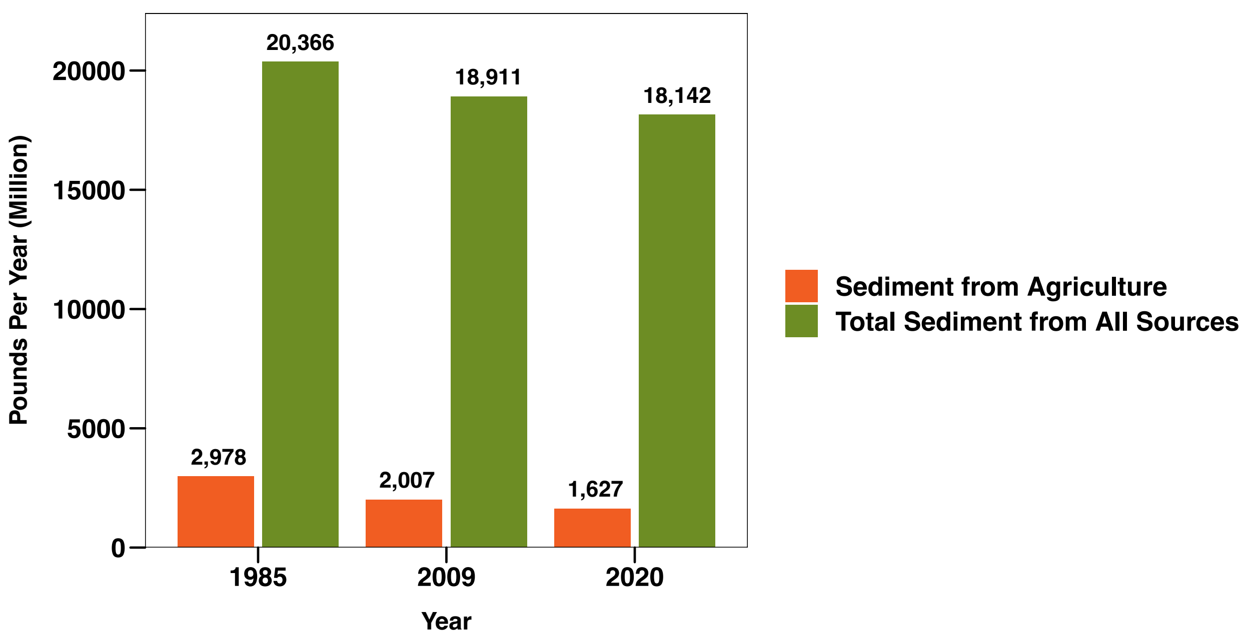
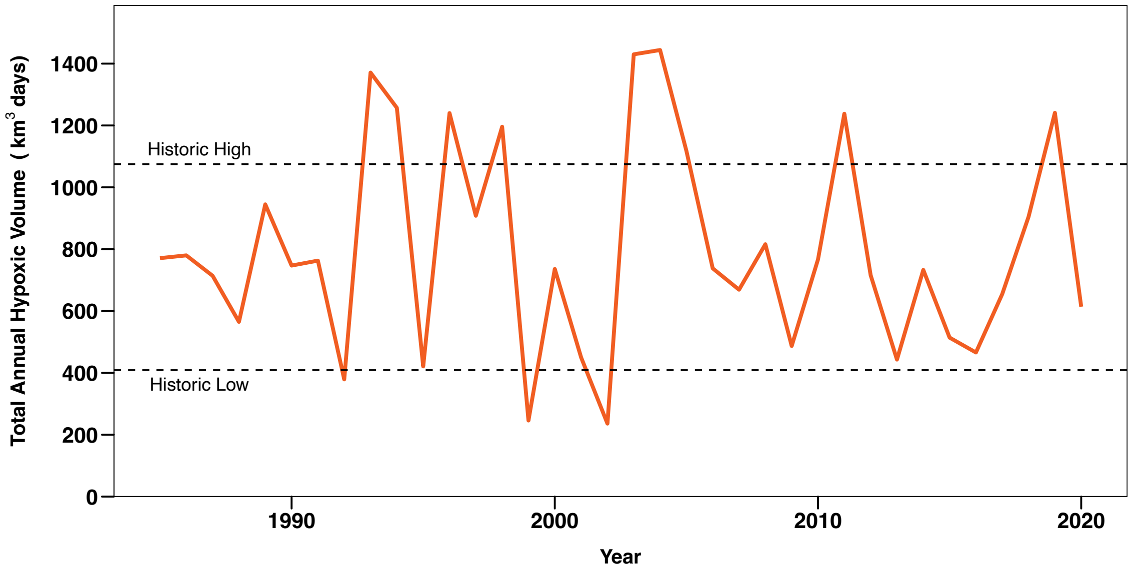


Figure 2.3.3. Annual sediment loads entering the Chesapeake Bay

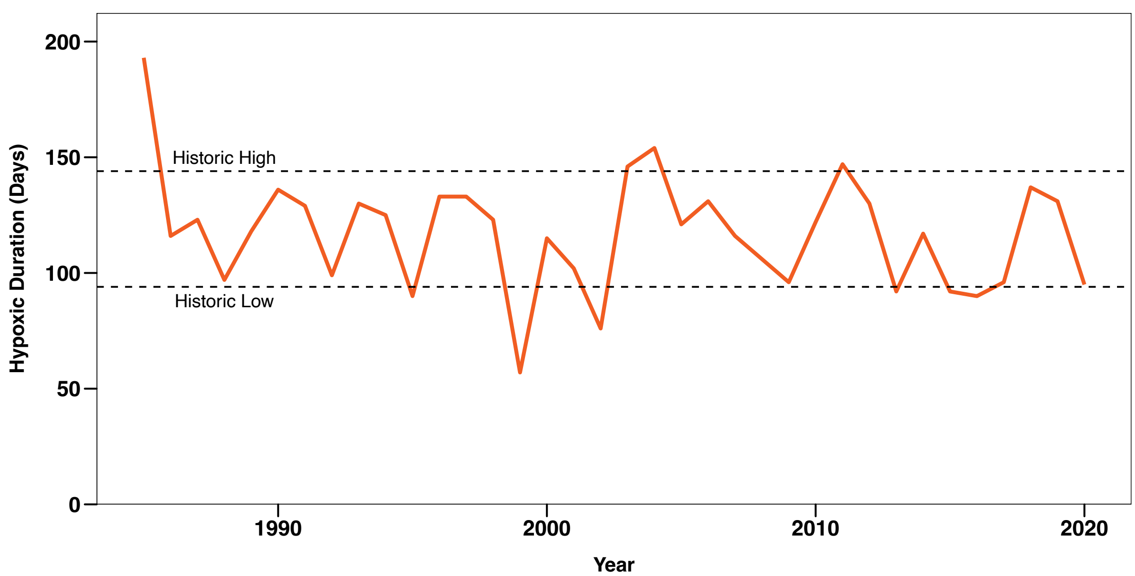


In 2020, the volume of the hypoxic zone in the Chesapeake Bay was the seventh smallest ever recorded and lasted for a fairly short duration (Figure 2.3.4, 2.3.5).

Figure 2.3.4. Historic volume of the Chesapeake Bay Hypoxic Zone. Historical values represent the normal based on a 35-year simulation.



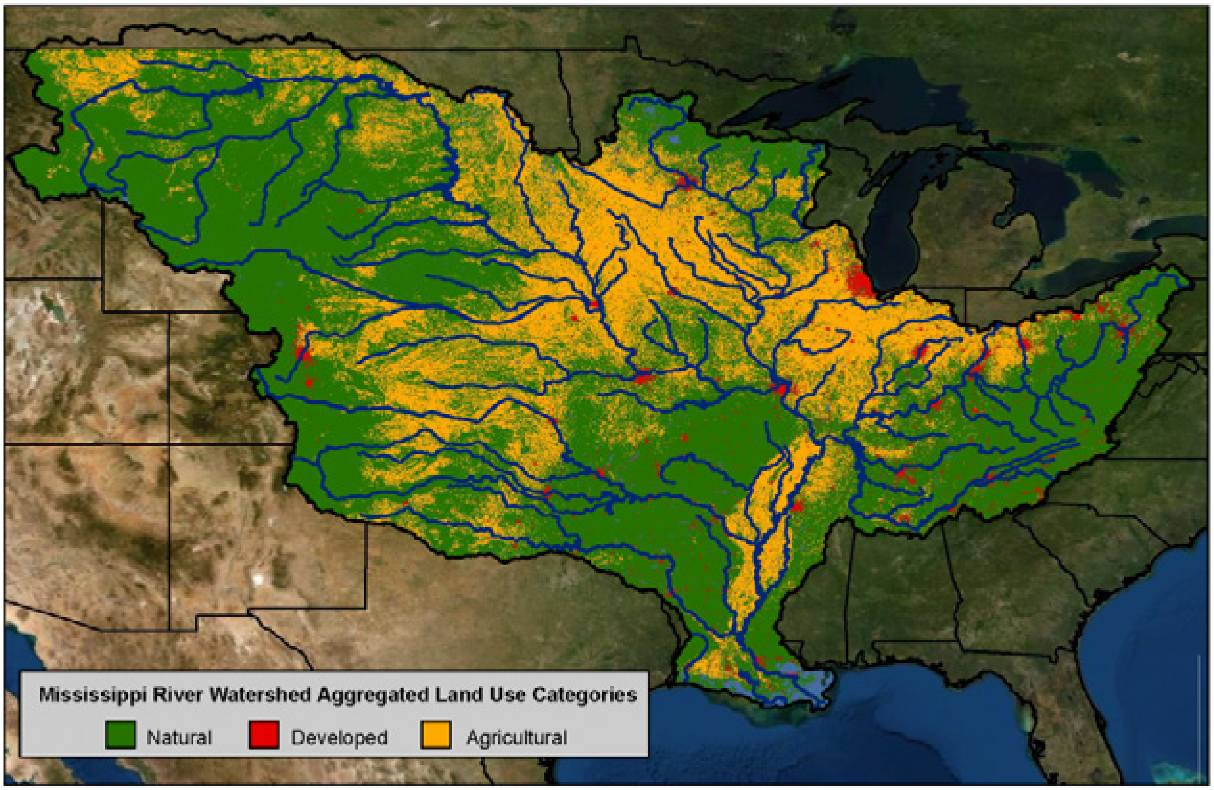
Figures 2.3.5. Historic duration of the Chesapeake Bay Hypoxic Zone. Historical values represent the normal based on a 35-year simulation.



WATER QUALITY IN THE MISSISSIPPI RIVER AND GULF OF MEXICO

The Mississippi River watershed is the largest drainage area in North America, originating in Canada and emptying into the Northern Gulf of Mexico, 2,350 miles south. The watershed covers 1,245,000 square miles, which is 41% of the contiguous U.S. across 31 states. Fed by the Ohio and Missouri Rivers, plus hundreds of smaller tributaries that cut across agricultural lands, the Mississippi River has been significantly impacted by sediment and agricultural runoff containing fertilizer and chemicals. The National Oceanic and Atmospheric Administration (NOAA) monitors the hypoxic zone in the Gulf of Mexico and publishes annual reports on the zone's anticipated size and duration(National Oceanic and Atmospheric Administration, 2020).

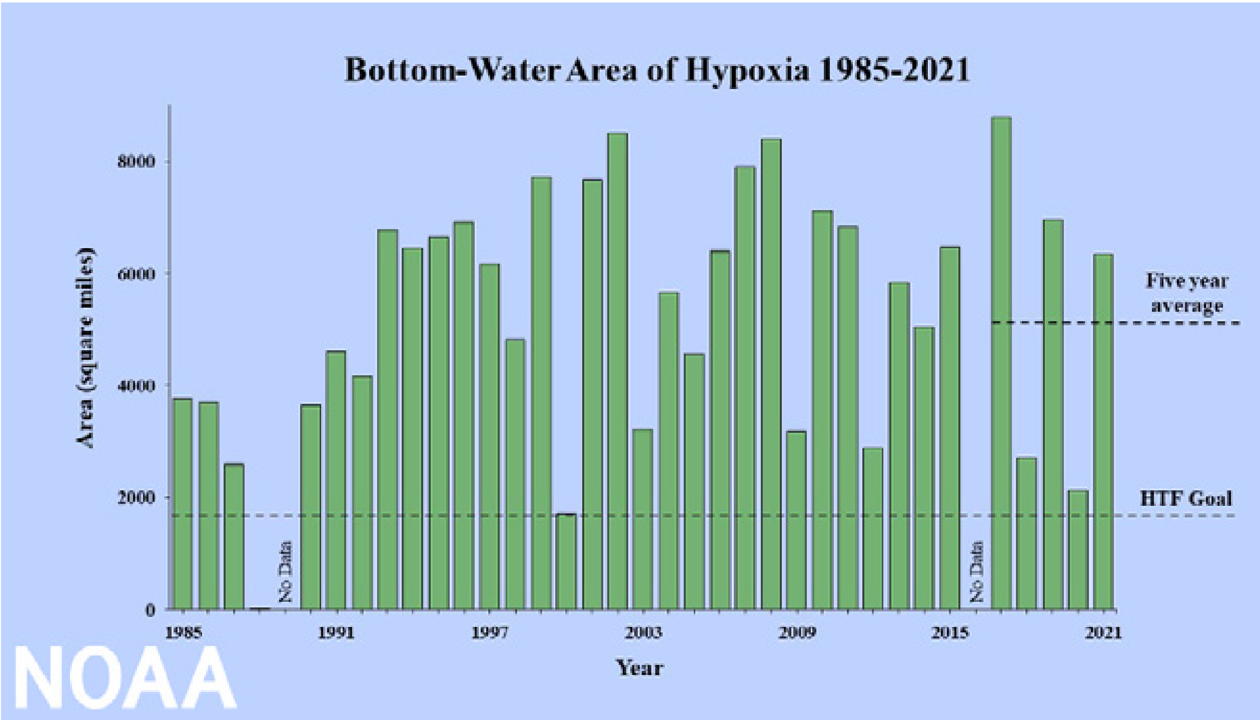
Figure 2.3.6. Mississippi River watershed land use categories



In 2020, the non-profit America's Watershed Initiative scored the Mississippi River watershed a "D", a downgrade from their 2015 assessment that earned a "C" (America's Watershed Initiative, 2020). Nutrient concentrations, primarily nitrogen and phosphorus, increased over that time period, and it is estimated that more than 1.5 million tons of nitrogen enter the Gulf of Mexico via the Mississippi River every year, with the majority of the excess nutrients coming from agricultural fields. Irregular weather patterns in the watershed, particularly flooding and drought, have strong influence on the volume of water in the river, which also impacts the amount of sediment, nutrients and other agricultural inputs carried within that water. Because of this relationship between weather and river water volume, it can be difficult to definitively tie water quality outcomes to upstream agricultural practices except over the long term.

Water quality in the Gulf of Mexico is impacted by the quality of water flowing down the Mississippi River. Nutrients entering the Gulf feed large algal blooms, which ultimately result in hypoxic zones, just as occurs in the Chesapeake Bay. In 2017, the hypoxic zone reached a record 8,776 square miles, the largest ever recorded. It should be noted that the hypoxic zone in the Gulf of Mexico is still largely measured and reported in units of area, rather than volume, although volume offers insight into the depth of the zone which has impacts on aquatic wildlife (Scavia, et al 2019). This is likely due to the large amounts of water traveling down the Mississippi River. Mixing of surface and bottom waters as a result of tropical storms distributes oxygen throughout the water column and decreases hypoxia. Thus, a direct annual relationship between agricultural nutrient management and hypoxic zones is not expected, rather it's important to consider the trends over longer times, and include consideration of other nutrient sources and hydrologic and weather conditions for the rivers as well as the coastal waters.

Figure 2.3.10. Area of the Gulf of Mexico hypoxic zone from 1985-2021



The outcome of the reductions in nutrient and sediment loading on the size and duration of the hypoxic zone has not shown a clear trend (Figure 2.3.10). The area of the Gulf hypoxic zone was 2,116 square miles in 2020 (U.S. EPA, 2021b), the third smallest recorded in the 34 years the size has been tracked but still larger than the 1,950 square mile goal set by the Hypoxia Task Force. The smaller size has been attributed in part to water mixing caused by the strong winds from Hurricane Hanna. Given the impact of weather variability from rainfall patterns across the Mississippi watershed on sediment and nutrient loads to the Gulf, and intensity and timing of tropical storms on the hypoxic zone extent, it is important to look at the long-term trend when determining whether progress is being made.

GAUGING THE EFFICACY OF CONSERVATION PRACTICES ON WATER QUALITY

The Conservation Effects Assessment Project (CEAP) was created in 2003 as a partnership between USDA-NRCS, NIFA, other federal offices and private entities to quantify the water quality impacts of government conservation practices and programs on a watershed, regional and national scale (Moriasi et al., 2020). The 2016 National Indicators Report (Field to Market, 2016) relied heavily on CEAP to identify progress in reducing nutrient loss from agriculture.

Table 2.1. Efficacy of successful implementation of various best management practices to improve water quality outcomes from agriculture (Moriasi et al. 2020)

REGION	CONSERVATION PRACTICES	OUTCOME
Mississippi Delta	Conservation Reserve Program (CRP)	90% decrease in sediment runoff 50%-100% reduction in total nitrogen and total phosphorus in runoff
Mississippi Delta	Vegetated drainage ditches Sediment retention pond	69% decrease in sediment runoff 30%-50% decrease in total nitrogen and total phosphorus runoff
Mississippi Delta	Constructed wetland	Reduced herbicide losses to surface runoff by 58-95%
Georgia	Winter cover crops Strip tillage	Rain lost as runoff decreased 8% Infiltration increased by 10% Sediment losses reduced every year
Ohio	Drainage water management	Reduced N losses by 8% Reduced P losses by 40%
Arkansas	Cover crops	Reduced suspended sediment by 39% Reduced nitrate-N losses by 86% Reduced phosphate-P losses by 53%
Missouri	No tillage Cover Crops 3-year rotation	Increased organic soil carbon by 32% in the topsoil Reduced soil losses by 85%
Iowa	Riparian buffer	Removed 110 – 551 pounds of N per year via denitrification

Conservation efforts to improve water quality focus on reducing sediment, nutrient and crop protectants lost from agricultural fields and therefore reduce these components entering surface and groundwater through runoff, infiltration and tile drainage. In-field practices, including cover cropping and reducing or eliminating tillage were evaluated, as were edge-of-field practices like drainage management and grassed waterways, singly or in combination. Table 2.1 summarizes a synthesis by Moriasi et al. (2020) focusing on CEAP assessments at the plot, field and edge-of-field scales during the program's first 15 years.

SUMMARY

Agricultural lands play a critical role ensuring clean water for society and ecosystems throughout the country. Complex weather factors, and the complexity of the biogeochemical cycling of nutrients and the fate and transport of chemicals in the soil, make it particularly challenging to quantify water quality and to attribute changes to any specific cause. Tracking water quality change is therefore a long-term endeavor. Fortunately, there is ample evidence from research at field and watershed scales that certain agricultural practices retain nutrients and soil in the field and thereby reduce the risk of losing nutrients and chemicals to waterways.

Research at the plot, field and landscape scales analyzing the effects on water quality of in-field practices like cover crops, reduced tillage and edge-of-field practices including riparian buffers and constructed wetlands demonstrates measurable improvements in nitrogen, phosphorus and sediment losses from farms. Although there has been a steady increase in the number of acres receiving NRCS CSP support for these practices between 2017 (728,607 acres) and 2020 (1,701,880 acres), this still only represents 1% of the total U.S. cropland (897,400,400 acres) (NRCS 2021). For these practices to reduce the negative impacts from agriculture on a watershed scale, they need to be implemented ubiquitously, according to local physical conditions and cropping systems.

Overall, the trends in water quality for economically important watersheds like the Chesapeake Bay and Gulf of Mexico over the past five years do not suggest improvement. Hypoxia in both areas remains problematic and is closely linked to precipitation patterns that either increase or decrease flow in the tributaries and the amount of nutrients, crop protectants and sediment dissolved within.

HOW TO CITE THIS REPORT

Field to Market: The Alliance for Sustainable Agriculture, 2021. Environmental Outcomes from On-Farm Agricultural Production in the United States (Fourth Edition). ISBN: 978-0-578-33372-4.

While the National Indicators Report may be cited or referenced, the 2009, 2012, 2016 and/or 2021 reports should not be used to make individual sourcing or performance claims for a given commodity. In addition, any mentions of the findings from the Field to Market report "Environmental Outcomes from On-Farm Agricultural Production in the United States" should be explicit regarding the timeline of study, the source of data, the units of analysis, and the fact that results represent national averages rather than individual performance.

Field to Market does not authorize or endorse claims that equate or compare Field to Market's national average results with the results of specific individuals or geographies. It also does not support claims that equate past performance with future performance or that overlook and/or are not explicit regarding the relevance of units of analysis.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APPENDIX A: ENVIRONMENTAL INDICATORS METHODOLOGY

1. OVERVIEW

The environmental indicators presented here build on the previous three reports (Field to Market, 2009b, 2012b, 2016c) as well as ongoing development of the field and farm level metrics used in the Fieldprint® Platform. Five indicators – Land Use, Soil Conservation, Irrigation Water Use, Energy Use and Greenhouse Gas Emissions – are calculated for a 41-year period, from 1980 through the 2020 (inclusive) growing season. The methodology is detailed in this section, with emphasis on new data sources and methodology changes, along with highlighting where there are significant gaps in data availability. Moreover, we include one additional crop in this 4th version of the report, sorghum, to align with the expansion of Field to Market's program. All data were downloaded for the entire 1980-2020 period anew in 2021. This ensures that we are using the most updated information, as data from government sources are subject to recalculations when models are changed, algorithms revised, and/or corrections implemented.

Field to Market first produced a National Indicators Report in 2009 to explore the broad environmental trends in commodity crop production. The calculations developed for that initial report then served as the foundation for the field-level metrics in the Fieldprint Platform. The methods for both the report and the Platform were substantially revised in the 2012 National Indicators Report. While the overall methodology has similarities, the Platform's sustainability metrics are intended for use at a field scale and were developed with the ability to handle field specific physical environment (weather, soils) and management information. For example, the national level indicators calculated here consider the average of tillage systems for a given crop for the whole country, while the metrics can account for the actual tillage system on an individual field. With field-specific information, the Platform can use environmental models to calculate specific sustainability metrics. This is the case with Soil Erosion, which is calculated in the Platform using the NRCS models WEPP and WEPS. The Soil Erosion indicator reported here is based on simulation results provided by the USDA National Statisticians office (Personal communication, Patrick Flanagan, USDA NRCS, February 2021).

Field to Market's programs and goals focus on eight environmental outcomes. In this report, we calculate national level crop specific indicators for five of those outcomes in Part 1 and provide status and progress reports based on government reports and scientific synthesis publications for the other three in Part 2.

The five environmental outcomes with crop-specific trends presented in Part 1 are:

- Land Use Efficiency (acres per unit of production)
- Irrigation Water Use Efficiency (acre-inch of water applied per additional unit of production)
- Soil Erosion (tons of soil loss per acre)
- Energy Use Efficiency (BTU of energy used per unit of production)
- Greenhouse Gas Emissions (pounds of carbon dioxide Eq. per unit of production)

Table A.1: Crops included and unit of production for analysis

CROP	YIELD UNIT	DESCRIPTION
Barley	bushel	Bushel, 48 lb. of barley grain per bushel (14.5% moisture)
Corn (grain)	bushel	Bushel, 56 lb. of corn grain per bushel (15.5% moisture)
Corn (silage)	ton	2000 pounds (lb.) (65% moisture)
Cotton	lb. of lint	Pounds (lb.) of lint (5% moisture)
Peanuts	lb.	Pounds (lb.) (7% moisture)
Potatoes	cwt	Hundredweight, (100 lb.)
Rice	cwt	Hundredweight, (100 lb.) (12.5% moisture)
Sorghum	bushel	Bushel, 56 lb. of sorghum grain per bushel (14% moisture)
Soybeans	bushel	Bushel, 60 lb. of soybean seed per bushel (13% moisture)
Sugar beets	ton of sugar	2000 pounds (lb.)
Wheat	bushel	Bushel, 60 lb.of wheat grain per bushel (13.5% moisture)

Calculations for the efficiency indicators (irrigation, energy and GHG emissions) are also available on a per-acre basis for purposes of understanding underlying drivers of the trends. These indicators are calculated for the eleven crops listed in Table A.1, including sorghum for the first time.

The three outcomes reviewed and discussed in Part 2 are:

- Biodiversity
- Soil Carbon
- Water Quality

Each is explored through available scientific synthesis documentation and, where available, government reports at the national level. Information is generally not crop specific but is discussed in terms of regions and relevant U.S. commodity cropping systems.

The methods for calculating the indicators are standardized as closely as possible across crops and use publicly available data sources. By focusing on the national average, we capture trends both in management practices as well as in regional shifts in the location of production.

The methods described below follow the 2012 and 2016 report methods in using planted acres, rather than harvested acres, to account for land in production (Field to Market, 2012b, 2016c). The use of planted acres accounts for any land planted but not harvested as a result of extreme weather (e.g. flood, drought) or other variable impacting yield or farm economics. Therefore, it is a more comprehensive measure, particularly at the national scale, where crop abandonment is an important means of understanding the overall efficiency of input usage and the relationship between environmental impacts and productivity. The impacts of intentional land fallowing or double cropping are not explicitly captured here.

Changes in the 4th Edition: With each edition of the National Indicators Report we seek to identify data resources that can help to fill important gaps in our understanding of trends. For this edition, we were able to acquire additional data resolution for manure and crop protectants and incorporate energy efficiency and clean energy trends in the electricity sector into the calculations. Specifically, differences from the 3rd edition include:

- Additional detail on manure applications amounts by crop. This has allowed us to be more specific about manure as a source of nitrogen. This is most significant as a fraction of the nitrogen for corn silage.
- Introducing information on trends in energy efficiency of input production and emissions from the electric grid now provide credit for these society-wide energy sector changes that were previously uncredited.
- Improved accounting of crop protectants by allocating uncategorized pesticides into herbicides, insecticides, and fungicides, and the creation of two additional categories: growth regulators and fumigants.

1.1 CORN FOR GRAIN AND SILAGE

As with the 2016 National Indicators Report (Field to Market, 2016c), we distinguish between corn for grain and corn for silage. While these represent two different crop production systems, the data collection and reporting for USDA does not always distinguish between them. Adjustments are made based on the harvested area estimates, which are provided for corn for grain and silage separately. Estimated corn for silage planted area was subtracted from USDA's total planted area for corn for all purposes and the estimated percent abandonment for corn for silage and corn for grain are assumed to be equal. Data on manure application rates and acres treated with manure for silage and grain production were requested and obtained from USDA ERS. This allowed the analysis to specifically account for the Energy and GHG emissions differences associated with fertilizer and manure (Personal Communication, Laura Dodson, USDA ERS, July 2021).

Due to the nature of the USDA National Resources Inventory (NRI) datasets used by NRCS to model Soil Erosion, soil erosion rates are generated for all land planted to corn, regardless of whether it is harvested for grain or silage. However, considering silage is typically harvested earlier than grain, and more residue is retained on the fields during grain harvest – it is expected that, on average, erosion from corn silage would be higher than that from corn grain, all other things being equal (Roth and Heinrichs, 2001).

1.2 SUGAR BEETS

Sugar beet yield is expressed in tons of sugar, calculated by multiplying the raw weight of beets by the percent sugar. This unit reflects the management goals of sugar beet growers as the amount of sugar, rather than raw beet weight, is what harvest payments are based on. This is also how sugar beet production is defined in the Fieldprint Platform.

1.3 CO-PRODUCTS FOR COTTON

As with the previous edition of this report (Field to Market, 2016b), the methodology for cotton accounts for allocating the proportion of impact for the fiber (cotton lint) based on economic share of cotton lint and seed. Cotton seed is an economically important co-product of cotton and is a consistent component of income for all U.S. cotton producers. The economic allocation formula determines the share of the primary product as a proportion of the total dollar value. The share of the lint value divided by the value of lint plus seed was determined to be 83%. This factor is applied to the Irrigation Water Use indicator and to the Energy Use and GHG Emissions indicators expressed in per unit of production. The indicators expressed on a per acre basis were not adjusted.

1.4 DATA RESOURCES

The following data were batch downloaded using USDA National Agricultural Statistics Service (NASS) Application Programming Interface (API) (U.S. Department of Agriculture, 2021) for all crops and available years at the national level:

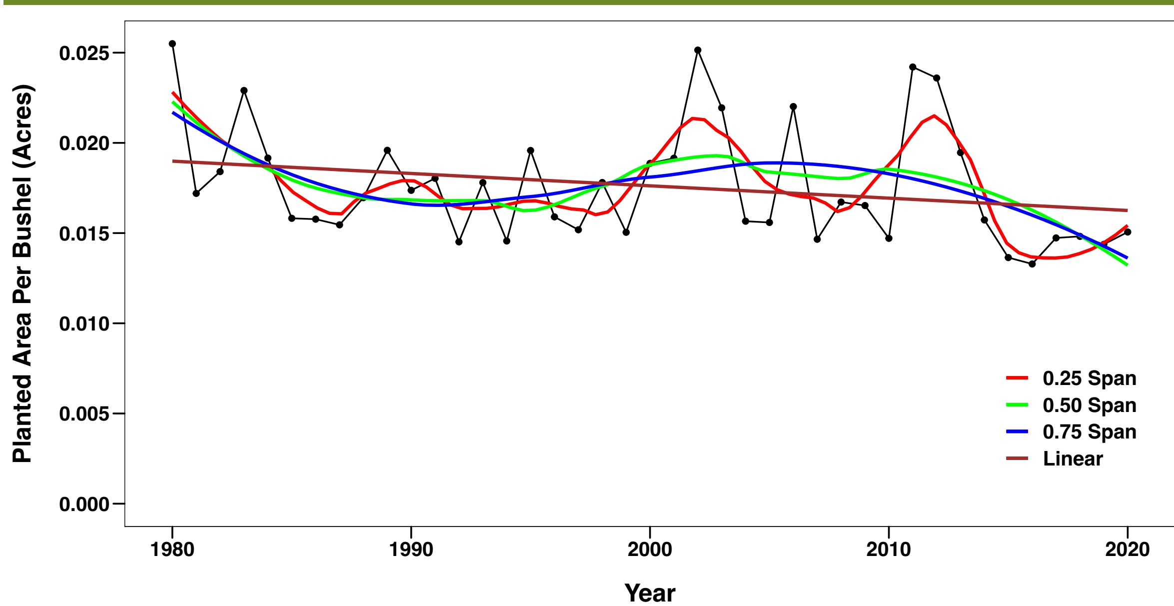
- For synthetic fertilizers (nitrogen, phosphate and potash) and crop protectants (herbicide, insecticide, fungicide, all others), the data items *Applications*, *Measured in Number*, *Average and Applications*, *Measured in Pounds*.
- The data items *Acres Harvested*; *Acres Planted*; *Production*, *Measured in [Units of Production]*; and *Yield*, *Measured in [Units of Production] / Acre*.
- For sugar beets, the data item *Sucrose*, *Measured in Pct*.

1.5 INDICATOR TREND LINE

For the previous edition of the National Indicators Report (Field to Market, 2016b), linear trends were plotted in the indicator graphs and were also used to extract estimates to create graphs and tables. Other tables in the 2016 report used summary data estimated from five year moving averages.

For the current report, we have relied on locally estimated scatterplot smoothing (loess) functions both to plot indicator trends in all the graphs and to extract estimates for the summary tables. In broad terms, the loess function takes overlapping slices of data along the X-axis and estimates a line for the data in that slice; the resulting lines are then connected in a smooth curve (Ott and Longnecker, 2001). An input of the loess function is the span (also called the bandwidth or smoothing parameter), a value between 0 and 1 which controls the width of the slice, i.e., the proportion of observations used for local regression at each point of the X-axis (Ott and Longnecker, 2001). The span has been set at 0.75, the default for the package stats in R (R Core Team, 2021). This value provides a robust smoothing that decreases the influence of year-to-year variability on the indicator trends. Figure A.1 plots a comparison of the output from three loess functions with increasing span values (0.25, 0.50, and 0.75 span values)

Figure A.1. Demonstration of three loess functions and a linear function



and a linear trend line, in which it is shown that as the span value increases so does the degree of curve smoothing.

Due to the nature of the data in this report, a loess function is a nearly ideal choice, given that we are describing past trends for various indicators from biological systems without assuming that any model (linear, quadratic, etc.) is better. It is important to note that this study does not attempt to predict any future trends for the indicators, a task for which loess functions are not designed.

In this report, we observed many reversals of the direction of indicator trends, which rules out the application of a linear function. Although some crops do exhibit close-to-linear yield improvements due to better crop technology, hybrids, or increased nutrient and crop protection usage, the holistic way the indicators are calculated results in indicators influenced not only by crop yield, but by weather conditions, shifts in crop growing regions and tillage regimens, usage changes in agricultural inputs, non-constant technology adoption, among many other factors. When these factors are aggregated by the indicator calculations, a linear trend is not complex enough to capture the changes that have occurred in U.S. commodity crop production in the past 40 years.

2. LAND USE EFFICIENCY INDICATOR

The Land Use efficiency indicator is the amount of land required to produce a unit of production (e.g. acre/bu), and is the inverse of standard crop yield calculations. We report on the trends in total area planted and crop production for each crop. The Land Use indicator follows the same methodology as the Land Use metric result from the Fieldprint Platform.

Data used in this analysis are on a planted area basis to account for abandonment of acres that are planted but not harvested. This abandonment can occur due to adverse weather or other conditions that result in a harvest not being economically viable. By considering planted acres, we capture the overall resource use efficiency per unit of production at the aggregate national scale.

3. SOIL EROSION INDICATOR

The Soil Erosion indicator is obtained from custom modeling conducted by the USDA National Statisticians office and follows the methodology used for estimates of erosion included in the USDA NRI. The modeling relies on data available in five-year increments from 1982-2017 collected through the NRI's statistical survey of non-Federal land use and natural resource conditions and trends. Erosion results represent both water and wind erosive properties according to simulation model results. Each successive report provides a consistent methodology across the time series; thus, if changes are made to methodologies for aggregation, all previous years are re-calculated.

The soil erosion estimates in this report are based on the 2017 NRI methodology (U.S. Department of Agriculture, 2020). NRI erosion prediction models provide an estimate of average expected rates of erosion based on inherent soil and climate conditions as well as farm management. The NRI 2017 release used the Revised Universal Soil Loss Equation ver. 2 (RUSLE2) to estimate water erosion and the Wind Erosion Equation (WEQ) to estimate wind erosion for selected states. Note that the NRI soil erosion estimates do not account for gully erosion or movement and re-deposition of soil within a field. The full results are presented in the 2017 report (U.S. Department of Agriculture, 2020) by state. The Soil Conservation metric in the Fieldprint Platform also applies the NRCS models for individual fields; it applies the Water Erosion Prediction Project (WEPP) model for water erosion, and the Wind Erosion Prediction System (WEPS) model for wind erosion[2].

The primary Soil Erosion indicator reported here is in units of tons of soil lost to erosion per acre per year for each crop, which is the unit of simulation for the wind and water erosion models. This is in agreement with the Soil Conservation metric in the Fieldprint Platform.

4. IRRIGATION WATER USE EFFICIENCY INDICATOR

The Irrigation Water Use efficiency indicator is intended to reflect yield gains attributed to irrigation, versus non-irrigated production. This indicator only applies to irrigated production. Irrigated agriculture in the U.S. varies across different cropping systems, climate regions and economic and regulatory environments. The indicator was developed to normalize yield gains due to irrigation across all these variables. The equation, therefore, accounts for the viability of rainfed production and applied water use efficiency.

Irrigation water use is defined here as the anthropogenic application of water to crop land to support crop growth and development. We confine our focus to irrigation water applied as a primary resource over which growers have direct control. To the extent that irrigation source and delivery mechanism (e.g., gravity fed vs. pumping) drives energy use, these practices are captured in the Energy Use indicator.

The Irrigation Water Use (IWU) efficiency indicator is calculated as:

$$IWU = \frac{\text{Irrigation Amount (acre - inches)}}{\text{Irrigated Yield} - \text{Non-Irrigated Yield}}$$

Irrigation amount, irrigated yield and non-irrigated yield are self-reported by growers receiving the survey, and data are tabulated by USDA (USDA National Agricultural Statistics Service, 2019). It is worth mentioning that, following USDA's definitions, non-irrigated yield does not refer to the yield from rainfed cropping systems, but rather to the non-irrigated yields on irrigated farms only (U.S. Department of Agriculture, 2019). The resulting value from the irrigation water use efficiency indicator represents the

[2] Field to Market Metrics Documentation

amount of water for each incremental gain in crop yield. Data used in the calculation of the national indicator are taken from the USDA Irrigation and Water Management Survey (IWMS) (formerly called FRIS, Farm and Ranch Irrigation Survey), a component of the Census of Agriculture that is produced at five-year increments. These data are available for 1984, 1988, 1994, 1998, 2003, 2008, 2013, and 2018 and include national scale estimates by crop of the amount of irrigation water applied per acre, irrigated crop yield and non-irrigated crop yield. The non-irrigated crop questions were removed from the 2018 survey, thus that data are only available through the 2013 survey (U.S. Department of Agriculture, 2019). To obtain a non-irrigated yield estimate for 2018, we first calculated the average ratio of irrigated to non-irrigated yield for the last four available censuses for a given crop, then we multiplied the irrigated yield of 2018 by this ratio. As defined by IWMS, non-irrigated yield is from crops grown under the same conditions as the irrigated yield on farms equipped for irrigation. Thus, non-irrigated yield is distinct from rainfed yield, which refers to crops grown on farms with no irrigation systems. In the United States, rice is assumed to be grown in irrigated systems only, and the non-irrigated yield is set to 0.

Linear interpolation between IWMS census years was used to estimate the amount of irrigation water applied in non-census years, along with irrigated and non-irrigated yield for all crops, except sugar beets. For sugar beets, a different methodology was needed due to anomalous data in the last census available for this crop (2008), where irrigated and non-irrigated yield values at the national level were very close to each other and deviated from the expected trend. We first calculated the relationship between the average yield from NASS, which represents both irrigated and rainfed production, and the irrigated and non-irrigated yields from IWMS. This relationship was then used to estimate the irrigated and non-irrigated yields for the intervening years, by adjusting the NASS average yield, which is available annually (U.S. Department of Agriculture, 2021).

The Irrigation Water Use metric in the Fieldprint Platform uses the same equation as the indicator reported here, using field specific information input by individual users.

5. ENERGY USE EFFICIENCY INDICATOR

The Energy Use efficiency indicator was developed to provide a consistent method for evaluating the efficiency of energy used in a farm operation. The data used to calculate this indicator also feeds into the Greenhouse Gas Emissions indicator, described in the following subsection. The boundaries defined for the Energy Use indicator start at pre-planting and include all farm activities for the cultivation of the crop, ending at the first point of sale or when the harvested crop is transferred to a processing or storage facility. The primary indicator is represented in units of energy use expressed as British thermal units (Btu) per unit of crop production. We also consider the energy use per acre by crop.

The indicator considers the major energy-intensive areas of on-farm crop production. It includes two components: direct and indirect energy. Direct energy is used to operate farm equipment, pump irrigation water and to dry and transport crops. Direct energy use accounts for the fuel type used (diesel, electricity, gasoline, natural gas and liquefied petroleum gas) when data were available. Indirect energy is the energy embedded in fertilizer, crop protectant and seed production. Our analysis does not quantify the energy associated with manufacturing farm equipment, fuel used on farm or structures such as grain bins. To the extent data are available, trends in the energy used to manufacture fertilizers and crop protectants are included. For example, energy needed to manufacture nitrogen fertilizer has been significantly reduced over time (International Fertilizer Association, 2018).

The Energy Use Metric in the Fieldprint Platform likewise considers the energy used from pre-planting to the first point of sale. The metric is field-specific and relies on user input to determine the direct energy; then, it combines user inputs on chemical and fertilizer applications with the data sources mentioned below to calculate the indirect energy components.

The primary data source for calculating this indicator at the national level is the USDA Agricultural Resources Management Survey (ARMS) (U.S. Department of Agriculture Economic Research Service, 2021), which captures many on-farm practices including tillage and number of applications of crop protectants and fertilizer. Additional data were acquired from USDA Agricultural Chemical Usage reports (U.S. Department of Agriculture, 2021), which provide application amounts for fertilizers and crop protectants, and parameter datasets used in the Greenhouse Gas Regulated Emissions and Energy Use in Transportation (GREET) model (Wang et al., 2020). All energy requirements are converted into British Thermal Units (BTU) for comparison purposes. Greenhouse gas emissions and embedded energy values for pesticides are taken from Audsley et al. (2009).

5.1 IRRIGATION ENERGY

Irrigation energy calculations are based on standard engineering methodologies (Hoffman et al., 1990) using national-level data in the Agricultural Resource Management Survey and the Irrigation and Water Management Survey for the years of this study. These reports provided data on average operating pressure for irrigation pumps, based on share of irrigated fields using sprinkler, pressure and gravity systems; average lift of water, based on share of irrigated fields using well water and surface water; average depth to irrigation wells; and amount of water applied. These four main data points are used to calculate a national average of the energy required to pump irrigation water for each crop.

5.2 MANAGEMENT ENERGY

One major factor determining equipment energy use is the intensity of tillage for a crop. For this, data from the ARMS was supplemented with national level data from the Conservation Technology Information Center (Conservation Technology Information Center, 2008) and a tailored data report from USDA ERS on tillage and residue management (Personal Communication, Steven Wallander, USDA ERS, April 2021). Energy and carbon dioxide (CO_2) emissions levels by crop and tillage system (no-till, reduced till, and conventional tillage) are estimated from West and Marland (2002). For crops where this study does not provide specific data on tillage energy, a similar crop or corn was frequently chosen as a proxy, and it is also well defined for all tillage systems in West and Marland (2002). Assumptions were made for:

- Barley: Tillage energy for barley was based on wheat.
- Cotton, Peanuts, Potatoes, Sorghum and Sugar beets: Assumed tillage energy equal to that for corn.
- Rice: USDA estimates for fuel consumption for rice and corn were used to develop an index value that was then used to adjust the corn tillage energy contribution. This resulted in a national average for a conventional tillage program for rice that is 54% that of corn.

The portion of planted acreage using each tillage system comes from ARMS, CTIC and ERS, and is available for all crops.

Fuel efficiency of farm equipment is assumed to be constant over time. While it is likely that fuel efficiency has increased, nationally averaged data on such changes over time are lacking. Thus, this analysis may underestimate efficiency improvements associated with equipment technology. For management energy, the GHG emissions factors for conventional tillage, reduced tillage, and no-till from West and Marland (2002) are converted to gallon of diesel equivalents, and then to BTU.

Energy associated with manure application is calculated using ARMS data on application rates and treated acreage to estimate the loading and application energy used for all crops, and added to the management energy component. Using engineering data on fuel use for tractor loading and spreading, a factor of 0.0862 gallons of diesel fuel per ton of manure applied is used. A tailored data report from USDA ERS for manure treated acres and application rates for corn grain and silage allowed us to differentiate the indicators for these two crops. No useful manure application data were found for potatoes and sugar beets at the national scale.

A new component for this 4th edition of the National Indicators Report includes accounting for the energy required by equipment used to apply fertilizer and crop protectants. Due to the nature of the data available for this category from USDA, several data processing steps were implemented. For protectants, the five active ingredients with the highest number of applications per category, crop and year were averaged. Each protectant category contributed its own average to the overall number of applications. For fertilizers, the number of applications for phosphorus and potassium were averaged, while the number of nitrogen applications was kept as-is. The number of applications per category were then summed. In farm operations, fertilizer and crop protectant applications are often combined in the same trip. To account for this efficiency, the summed number of applications was divided by 1.5. This factor assumes that 66% of all applications are combined in the same trip. The number of applications was multiplied by a factor of 17,796 BTU per pass; this component typically represented < 1% of total energy use for a given crop and year. Including this factor allows us to observe and consider trends over time in the frequency of application trips as those change in response to new crop varieties and management recommendations.

5.3 POST-HARVEST TREATMENT ENERGY USE

The boundary of the present analysis considers energy used up to the first point of sale. This can vary considerably by crop, due to differences in storage or use of the harvest. Grain drying energy use was drawn from USDA reports and Cooperative Extension resources (Sanford, 2005). The amount of moisture removed from grain, shown in Table 2, and the efficiency assumptions of drying operations were considered constant over time.

Distances from farm to the first point of sale were estimated and are provided in Table 2. These were used in conjunction with literature on fuel consumption by heavy trucks to develop the transportation estimate of 6.5 miles per gallon of diesel (Office of Energy Efficiency, 2000; Cai et al., 2015). Estimated distances are provided in Table 2, based on consultation with commodity group experts. Transportation energy is held constant over time due to the lack of time series-specific data.

Table A.2: Estimated drying and transportation requirement based on expert assessments

CROP	POINTS OF MOISTURE REMOVED	ONE-WAY DISTANCE TRANSPORTED - MILES
Barley	1.5	45
Corn (grain)	3	30
Corn (silage)	0	3
Peanuts	12.5	45
Rice	5.0	30
Sorghum	3	45
Soybeans	1.4	45
Sugar beets	0	15
Wheat	1.4	45

Cotton drying is handled differently from other crops. Cotton harvest moisture uses a qualitative measure that ranges from very dry to very wet rather than percentage moisture; for this analysis, cotton harvest was assumed to have a normal amount of moisture (which assigns 593 BTU per pound of lint), as defined in the Energy Use metric in the Fieldprint Platform, and with a transportation distance of 10 miles. These factors are held constant over the study period.

Potatoes, as a fresh-market crop, also are handled differently. The first point of sale may occur on or off the farm, depending on the arrangement a grower has with the buyer. To achieve year-long supply for fresh market and to make efficient use of capital investment in processing facilities, much of the fall potato crop is stored on-farm after harvest. Energy is used to cool the storage facility and circulate air to preserve quality. Time in storage is highly variable, from a few weeks to 10 months. Here, we assume storage of 120 days on farm and no transportation energy requirement. Energy for ventilation ranges from 3-13 kWh/1000 cwt/day, which typically represents < 10% of total energy use for potato production.

5.4 SYNTHETIC FERTILIZER

USDA provides national level data on the total amounts of fertilizer applied. Application rates, expressed as pounds per acre, were estimated by linear interpolation for years lacking data from USDA. By dividing the total fertilizer applied by planted acres, we calculated pounds of fertilizer per planted acre. Fertilizer application rates for nitrogen, phosphate and potash are multiplied by energy conversion factors provided in the GREET model (Wang et al., 2020); these factors include embedded energy and transport energy for fertilizer. Values used for all crops are:

- 27,119 BTU per pound N
- 13,212 BTU per pound P_2O_5
- 3,484 BTU per pound K_2O

The production efficiency of synthetic fertilizer has improved over time with less energy required to produce a unit of fertilizer. To account for this, the BTUs estimated for nitrogen manufacture were adjusted using a multiplier that accounted for an approximately 30% improvement in energy use efficiency during the period of this study (International Fertilizer Association, 2009). A similar adjustment was made to the energy use embedded in the production of phosphorus and potassium fertilizers, using global data from the International Energy Agency (2019). This multiplier assumed an efficiency improvement of approximately 20% over the years in this study, which is approximately half the efficiency rate reported by IEA (40%). This conservative reduction considers the uncertainty about locations where the fertilizers were manufactured and where the efficiency improvements were observed.

5.5 CROP PROTECTANTS

As with fertilizers, data on the quantity of agricultural chemicals used by crop are available from USDA. USDA utilizes four categories for pesticides: herbicides, insecticides, fungicides and "all other." All data are reported as total pounds of active ingredient applied. For data before 1994, the pounds of active ingredients were summed up by protectant category; starting in 1994, we used the total value per protectant category provided by USDA. Then, for the "all other" category for all years, we matched active ingredients to a reference database that classified them into herbicides, insecticides, fungicides, growth regulators and fumigants. The reference database for pesticide types was built from multiple sources (Fournier et al., 2012; U.S. EPA, 2014; Brown and Sandlin, 2019; National IPM Database, 2021). After pesticide type classification, the pounds of each protectant category were added to the primary USDA categories (herbicides, insecticides, fungicides); in addition, two new pesticide categories were created for growth regulators and fumigants. After exploratory data analysis, we discovered that the sum of all active ingredients for the "all other" category by crop and year was typically a smaller number than the total value given by USDA; although the embedded crop protectant energy and greenhouse gas emissions may be underestimated using this method, we improved the value of these data by assigning active ingredients to their crop protectant category. By applying this methodology, we gained valuable insights about crop protectant trends; for example, learnings about fumigant use in potatoes and peanuts and growth regulators in cotton would have been hidden had we left the "all other" category unexplored.

Values for embedded energy in pesticides are taken from Audsley et al. (2009), which provided factors for energy and greenhouse gas emissions for herbicides, insecticides, fungicides and growth regulators. For each category, the average energy per pound of active ingredient was multiplied by the application rates.

Weighted average values taken directly from Audsley et al. (2009) were as follows:

- 165,947 BTU per pound of Herbicides (386 MJ/kg)
- 117,797 BTU per pound of Insecticides (274 MJ/kg)
- 181,854 BTU per pound of Fungicides (423 MJ/kg)
- 118,657 BTU per pound of Growth Regulators (276 MJ/kg)
- 165,947 BTU per pound of Fumigants (same as herbicide due to lack of data) (386 MJ/kg)

The IEA multiplier to account for the efficiency of global electricity generation was also applied to the embedded energy use of crop protectants (International Energy Agency, 2019a).

5.6 SEED

The energy required to produce the crop seed is based on industry and expert judgement regarding the more intensive level of management and use of inputs to produce seed, since there are no satisfactory data sources on this topic. The energy use value for each crop is multiplied by a factor of 1.5 and used as the assumption for energy embedded in seeds planted. Seeding rate data from ARMS are multiplied by the energy factor corresponding to each crop. Seeding rates for potatoes and sugar beets were obtained from a different source (Becker and Ratnayake, 2010) than the rest of the crops due to lack of data from ARMS. Seed usually accounts for < 5% of the total energy to produce the crop.

6. GREENHOUSE GAS EMISSIONS INDICATOR

The Greenhouse Gas Emissions indicator shares the same system boundaries as the Energy Use efficiency indicator and uses much of the same data. The major sources of emissions include energy use, emissions from residue burning, nitrous oxide emissions from soils and methane emissions from flooded rice production. The Greenhouse Gas Emissions indicator does not account for soil carbon stocks or fluxes. We consider national level trends in soil carbon in Part 2 of this report.

6.1 EMISSIONS FROM ENERGY USE

Energy use, as described in the previous section, is converted to GHG emissions by considering the source of energy (fuel type). Emissions are reported as pounds of carbon dioxide equivalents (CO_2e). CO_2e is a common measure for assessing total greenhouse gas emissions that accounts for the relative strength of the Global Warming Potential (GWP) of different greenhouse gases. Thus, CO_2e provides a method to combine emissions of carbon dioxide with emissions of methane and nitrous oxide in a common unit for comparison. A factor of 22.4 pounds CO_2 per gallon of diesel combusted was used. It is expected that actual emissions associated with combustion of diesel through agricultural engines has improved over time but time series data for these emissions are lacking.

The carbon emissions from equipment operation for the three tillage systems considered in this study are listed in Table 3 and were taken from West and Marland (2002).

Table A.3: Emissions from tillage operations from West and Marland (2002)

CARBON EMISSIONS FROM MACHINERY OPERATION	CORN	SOYBEANS	WHEAT
		kg C per hectare	
Conventional Till	72.02	67.45	67.45
Reduced Till	45.27	40.70	40.70
No Till	23.26	23.26	23.26

The three tillage systems are consistent with the definitions used by the Conservation Technology Information Center (CTIC) and USDA's ARMS data: conventional till, reduced-till and no-till. CTIC provides the percentage of each crop under the different tillage practices over time. Conventional tillage uses the most energy for machinery, and hence produces the largest carbon emissions of the three practices, while the opposite is true of no-till. For crops not included explicitly in West and Marland (2002), the same substitutions made for the Energy Use indicator were used here.

The analysis in this report assumes that these emissions factors have not changed over time. While it is likely that energy efficiency has improved and emissions have been reduced from farm equipment over time, data documenting the extent of any improvements are lacking. Efficiency gains due to increased adoption of no-till and reduced-till practices are captured through the share of each crop under each tillage system.

Emissions from irrigation water pumping and application are estimated from the energy use calculation. The IWMS provides data on energy source for irrigation; from those data, we learned that in the period of this analysis the share of acreage using electricity for pumping increased from 54 to 68%, while the share of acreage for diesel-fueled pumps increased from 17 to 22%. The remaining acreage uses a mix of pumps powered by natural gas, propane and gasoline, the share of acreage using these three fuel sources have declined from a combined 29% at the start of this study to 9% in the latest IWMS. The emissions from irrigation have been partitioned using the share of acreage where irrigation is powered by each fuel source. In addition, the reductions in emissions from the national electrical grid (U.S. EPA, 2021c) are taken into consideration for the share of irrigation emissions from electricity-powered pumps. The overall carbon emission intensity of the national electrical grid has improved approximately 39% since 1996 (the first data point available), according to historical data (U.S. EPA, 2021c). The emissions from grain drying and crop storage for potatoes are likewise calculated in a consistent manner with the energy used for these activities, with the national grid adjustment applied to the GHG emissions from the electricity share of the energy use for crop drying and storage operations. No drying or storage was estimated for corn silage and sugar beets. The amount of fuel combusted and electricity consumed are used to estimate greenhouse gas emissions. Diesel is assumed as the fuel used for transport.

The embedded greenhouse gas emissions in seed are estimated in the same manner as for energy – as a fraction of the total greenhouse gases to produce the crop, using the same factors described in the previous section.

6.2 EMISSIONS EMBEDDED IN CROP PROTECTANTS AND SYNTHETIC FERTILIZERS APPLIED

Emission factors for product-embedded carbon dioxide were taken from the GREET model (Wang et al., 2020) for fertilizers and from Audsley et al. (2009) for crop chemicals.

As with energy use, emissions from fertilizer and crop protectant manufacture were adjusted to account for global improvements in carbon intensity of electricity generation (International Energy Agency, 2019b; c) and nitrogen production (International Fertilizer Association, 2018) during the period of this study.

6.3 NITROUS OXIDE EMISSIONS FROM SOILS

Nitrous oxide is a greenhouse gas with a 100 year global warming potential (GWP) of 298 times that of CO_2 (Solomon et al., 2007).

Nitrous oxide released from soil microbial activity in association with nitrogen fertilizer application is an important source of emissions. The range of estimates for nitrous oxide as a percent of nitrogen applied is very wide depending on the source of nitrogen, application method, and soil conditions at the time of application.

The updated methodology for estimating nitrous oxide emissions from managed soils across a region was adopted here (Intergovernmental Panel on Climate Change, 2019). The methodology applied for the nitrous oxide estimate included Eq. 11.1 *Direct N_2O emissions from managed soils* (Tier 1), Equation 11.9 *N_2O from atmospheric deposition of N volatilized from managed soils* (Tier 1), and Equation 11.10 *N_2O from N leaching/ runoff from managed soils*. For Eq. 11.1, the aggregated default value (0.01) was used instead of the disaggregated values by climate or irrigation type for all crops except rice, for which the flooded rice value (0.004) was used. The products of these equations were summed to obtain a value for each crop and year; nitrogen content from both synthetic and organic sources were included. Direct emissions account for nitrogen fertilizer lost due to nitrification and denitrification, while indirect emissions account for denitrification of volatilized ammonia (NH_3) deposited elsewhere, and from nitrate (NO_3) lost to leaching and runoff as the nitrogen cascades through other ecosystems after leaving agricultural fields. To convert the emissions from applied nitrogen into CO_2e, we have accounted for the ratio of the molecular weight of nitrous oxide to nitrogen (44/28) and the GWP of nitrous oxide.

USDA conducts periodic, detailed national modeling of GHG emissions and soil carbon sequestration from all U.S. agricultural lands; this is discussed in more detail in Part 2 of this report.

6.4 EMISSIONS FROM FIELD BURNING AND RESIDUE REMOVAL

Emissions from field burning surface residue make up a relatively small share of total emissions from agricultural production in the United States. Levels of residue burning are taken directly from the EPA's report on GHG emissions and sinks (U.S. EPA, 2021a). The quantity of surface residue available to be burned is calculated as a proportion of the crops' yield. The final calculation determines the amount of greenhouse gases released into the atmosphere. The release of carbon dioxide is not counted as it is considered part of the natural annual uptake and emission of CO_2 from plant growth rather than an anthropogenic emission. Among the crops in our analysis, burning of rice residue is the most prevalent with 6% of acres burned for the latest data point available (U.S. EPA, 2021a). Emissions from residue burning account for < 0.5% of total emissions for rice.

Residue removal from an annual crop field results in a smaller GHG impact by reducing emissions from residue breakdown. We include this factor for wheat and barley where a measurable share of cropland has residue removed after grain harvest. The emissions reduction is calculated using a value of 0.3 lb. of nitrogen for wheat and 0.24 lb. of nitrogen for barley per bushel of grain harvested. Wheat straw is removed from 6-13% of acres (Ali et al., 2000; Ali, 2002; Wright et al., 2009), while barley straw is removed from 23% of acres (Wright et al., 2009); we assume 50% of residue is being removed. At the national level, barley and wheat straw removal reduces GHG emissions by approximately 0.78% and 0.23%, respectively.

6.5 METHANE EMISSIONS FROM FLOODED RICE

Methane emissions are produced by anaerobic bacteria that live in rice fields that are flooded for continuous periods of time during the growing season. Emissions for rice are based on the levels reported in the EPA's report of GHG emissions and sinks (U.S. EPA, 2021a).

Data points for only three years (1990, 2005, and 2010) were complete to estimate CH_4emissions. Although there are methane emission estimates for years 2015 to 2019, we lack denominator data in the form of acreage reported by USDA National Resources Inventory, which may be added to a later edition of EPA's report (U.S. EPA, 2021a). Methane emissions vary in the period 1990-2019 mostly due to differences in acreage of rice production, which has been in a downward trend since 2000. The report (U.S. EPA, 2021a) also states that methane emissions have been reduced 6% in 2019 compared to 1990; however, this trend has not been captured in this edition of the National Indicators Report due to lack of NRI rice acreage data for the years 2015-2019. Years prior to 1990 were set to the 1990 level while years after 2010 were held constant at the 2010 level. Methane emissions from other crops due to flood irrigation are not considered in this report due to the limited number of acres flooded and the short duration of flooding periods. The source material for this calculation uses the common units of carbon dioxide equivalents and these are not converted.

7. DATA AVAILABILITY

This report relies heavily on annual and periodic surveys conducted by USDA National Agricultural Statistics Service (NASS) and Economic Research Service (ERS). Over the study period, there have been changes in both the frequency of surveys and the questions asked of farmers. While there is a long-term consistent record of major variables including crop yield, planted area and total production, surveys of farming practices are not conducted annually. Here we summarize some of the main characteristics of data availability and the limitations they pose to this analysis.

- *Inconsistent survey period*: Surveys on crop inputs are led by ERS and conducted periodically since 2000. This includes details of fertilizer and crop chemical applications, including type of products applied, number of applications per year, volumes of products, the rate and type of manure application and the seeding rate. Several crops are surveyed each year in a time and labor-intensive process. As a result of funding and staffing limitations, the return interval for major crops has been irregular.
- *Limited crops captured*: While statistics are captured for the major cropping systems in the country, a number of smaller crops are missing or collected less frequently. A particularly challenging example is that agronomic practice data for sugar beets were collected in the early 2000s, however the last data collection year for fertilizer and crop chemical information was 2008. In 2009-2010, a new variety of genetically engineered sugar beet was introduced and almost universally adopted. However, with no further data points from USDA, we are unable to confirm anecdotal reports from farmers on the difference this has made in their practices.
- *Changes in data collected over time*: Over time, survey questions may be added, removed or adjusted, which can make tracking specific data points over a long period challenging and necessitate alternate data sources or assumptions for a long-term analysis. A specific example is the irrigation survey conducted every five years as a companion to the Census of Agriculture. One survey data point important to our calculation of the Irrigation Water Use indicator is "non-irrigated yield" defined as crop yield on land equipped for irrigation but not receiving irrigation in that year. This data point was eliminated with the most recent irrigation survey (2018).
- *Available literature*: Another type of data limitation is in the available scientific literature summarizing key energy and GHG emissions information. For example, for tillage energy and GHG emissions we rely on a publication from 2002, as no more recent information is available. Energy and GHG emissions associated with crop chemical production likewise are taken from a 2009 publication, with no additional information available.

In discussions with stakeholders over the 12 years since the first report was published (2009) we have hypothesized that several additional factors may influence energy and GHG emissions trends over time, however, we lack the necessary data to incorporate them into the analysis. These include changes over time in farm equipment fuel efficiency, the country of origin and share of domestic versus imported fertilizer and crop protectants applied in the U.S., and the share of rice acreage employing alternate management such as dryland row rice or alternative flood management techniques like alternate wetting and drying.

Finally, Table A.4 shows how much data we were able to procure for each crop before applying data processing steps such as linear interpolation to fill-in the time series. Because many data sources are surveys that occur with both regular and sporadic frequency, data processing methods to fill-in the data series were necessary to calculate all indicators for each year during 1980-2020.

Table A.4. Initial data availability for each crop

CROP	DATA AVAILABILITY (%)
Barley	26.4
Corn, grain	38.1
Corn, silage	38.1
Cotton	38.7
Peanuts	28.2
Potatoes	34
Rice	27.8
Sorghum	29.9
Soybeans	38.6
Sugar beets	24
Wheat	35.6

While many datasets are currently available for the crops evaluated, the expansion of these methods to other crops is limited by data availability. One notable exception is that this report does not include alfalfa, a crop in the Field to Market program but one which is not included in ERS surveys; therefore, too few of the necessary data resources were available to calculate indicator trends. In addition, access to data over time on the efficiency of farm equipment, including use of alternative and renewable energy sources, would greatly improve the accuracy of trends reported. Where necessary, we have reached out to commodity and industry groups to gather insights and data for use in refining some assumptions, regarding prevalence of certain management practices that impact energy use and GHG emissions.

The methodology described here has been developed and refined since the initial 2009 report. As additional data, and new methods are developed, we will continue to provide updates to these environmental indicators every five years. The ability to continue and improve on these analyses is dependent on the availability of the public data sources which provide a transparent, accessible and fundamental means of understanding sustainability trends.

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APPENDIX B: SUPPLEMENTARY FIGURES FOR PART 1

BARLEY

Figure B.1. Energy use (million BTU / acre) for barley during 1980-2020

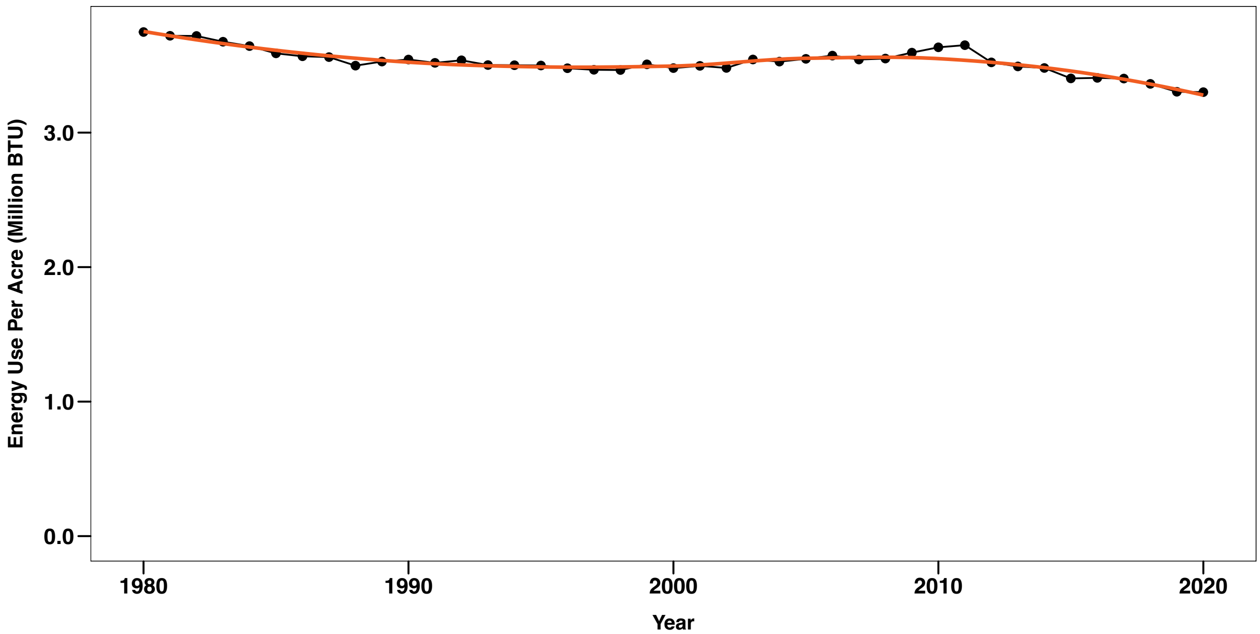


Figure B.2. Energy use efficiency (BTU / bushel) for barley during 1980-2020 colored by component

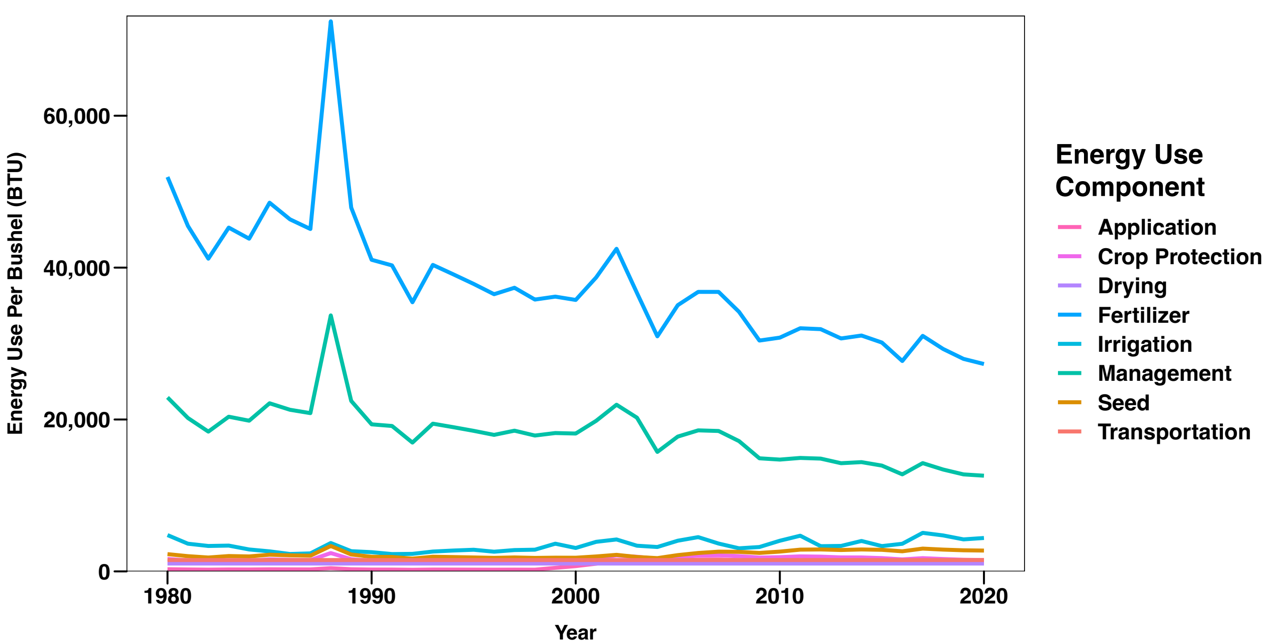


Figure B.3. Greenhouse gas emissions (lb. CO_2 Eq. / acre) for barley during 1980-2020

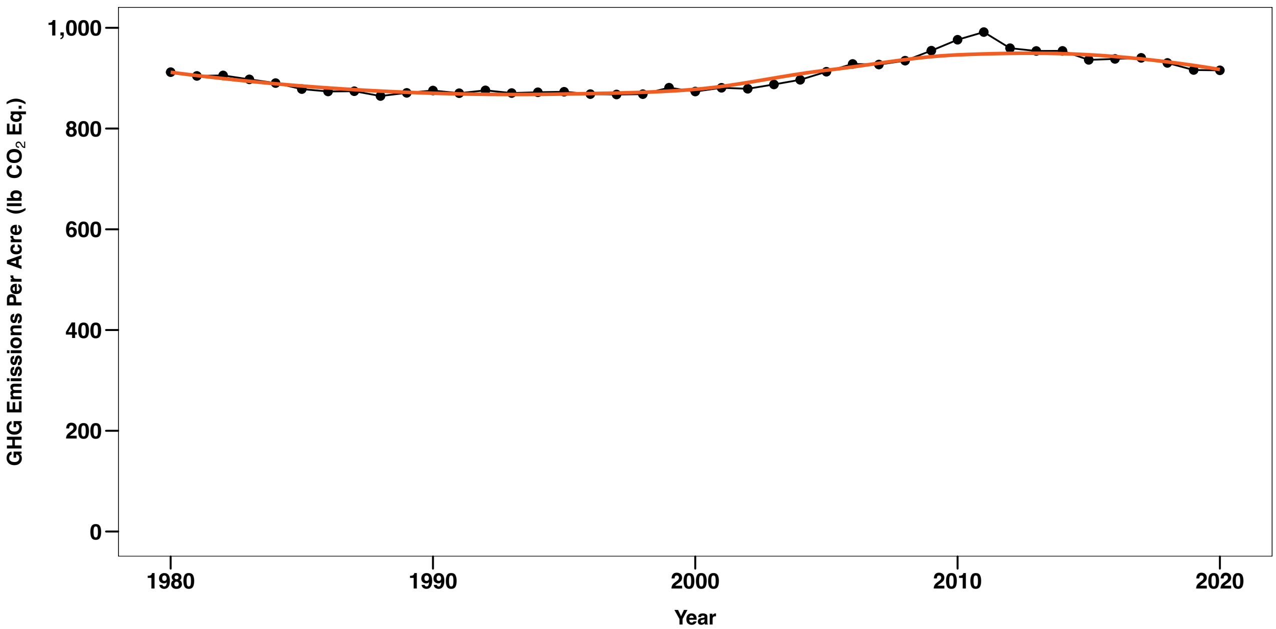
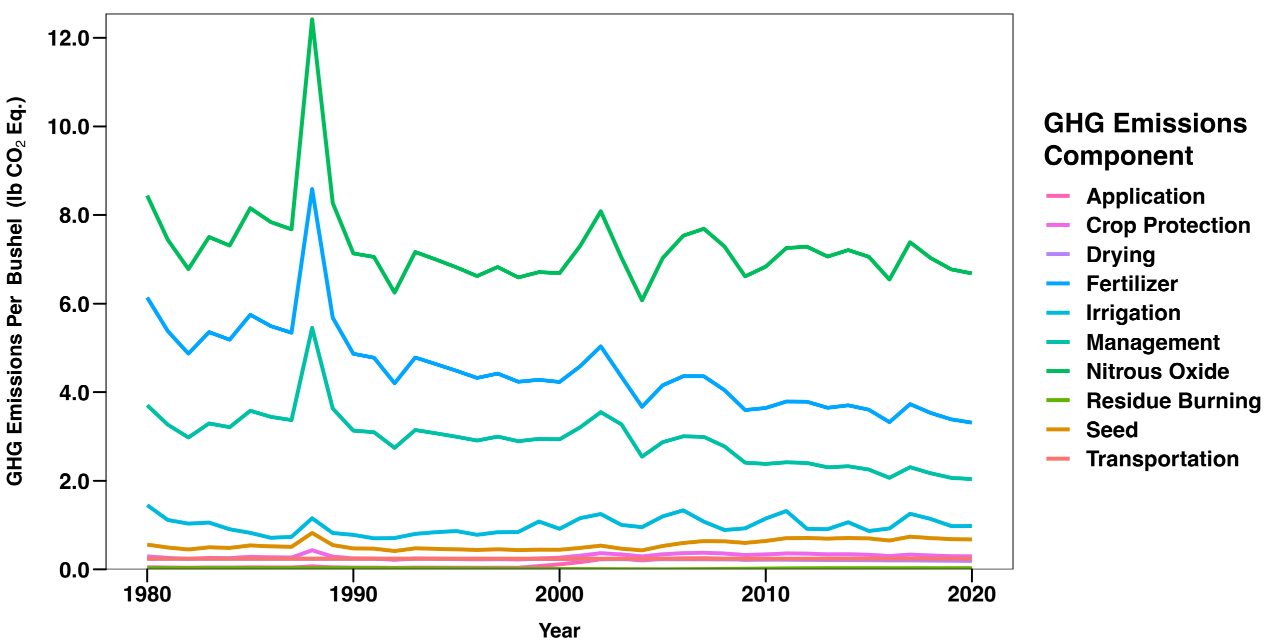


Figure B.4. GHG emission efficiency (lb. CO_2 Eq. / bushel) for barley during 1980-2020 colored by component



CORN (GRAIN)

Figure B.5. Energy use (million BTU / acre) for corn grain during 1980-2020

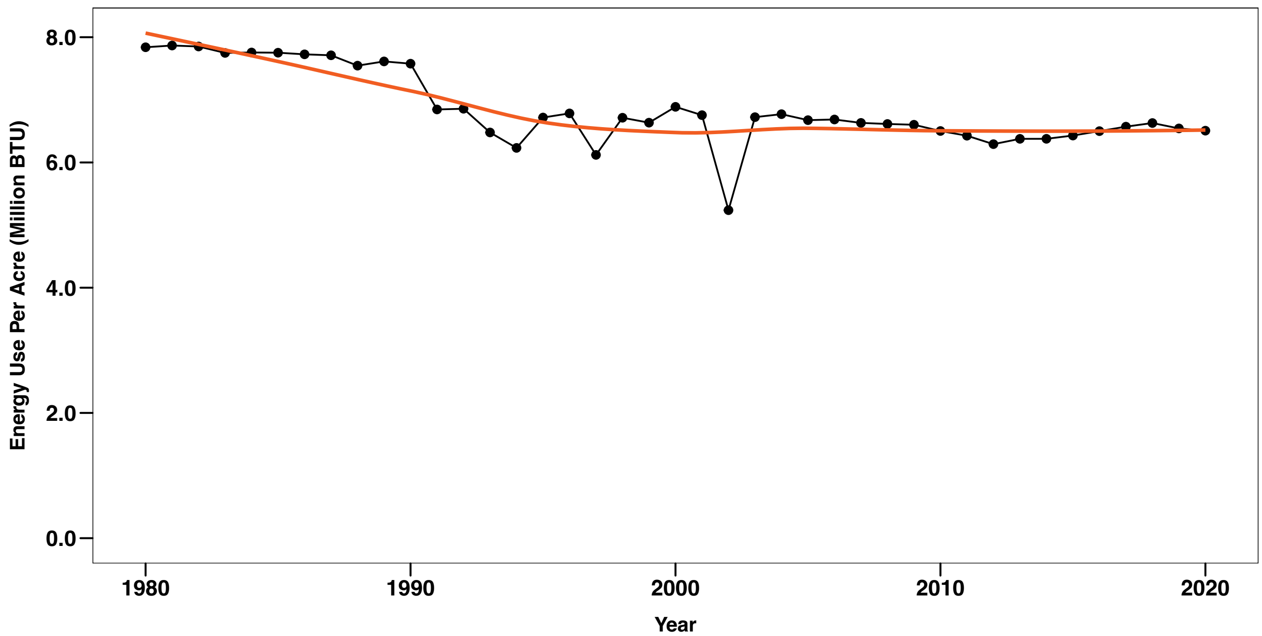


Figure B.6. Energy use efficiency (BTU / bushel) for corn grain during 1980-2020 colored by component

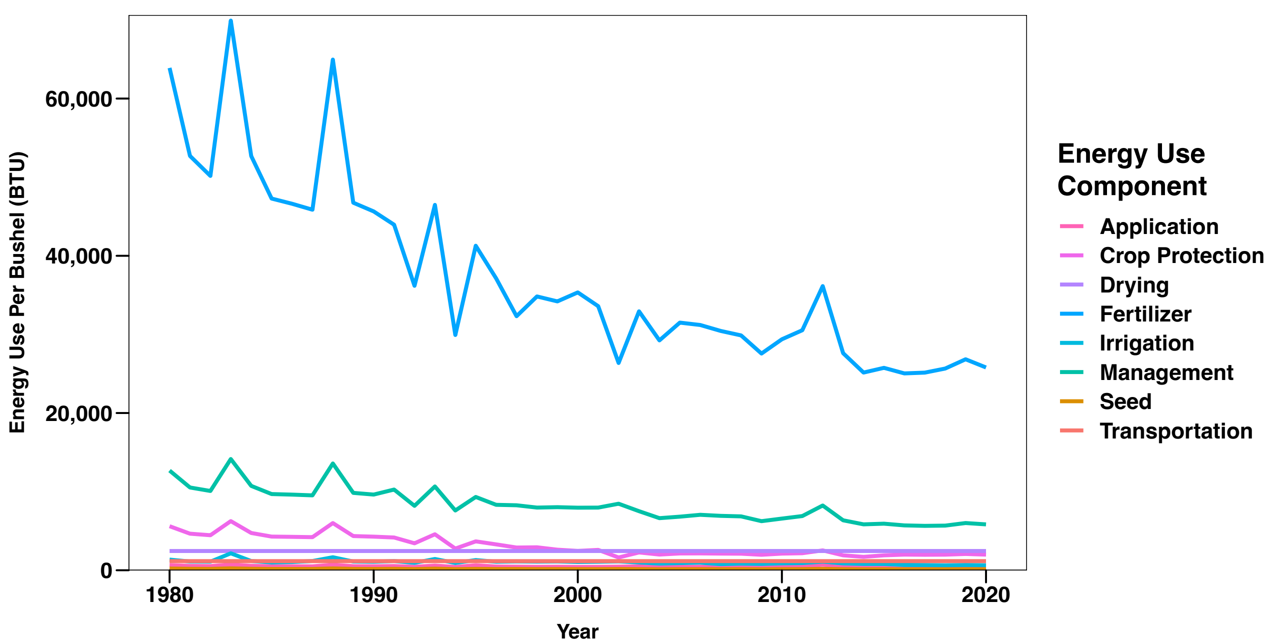


Figure B.7. Greenhouse gas emissions (lb. CO_2 Eq. / acre) for corn grain during 1980-2020

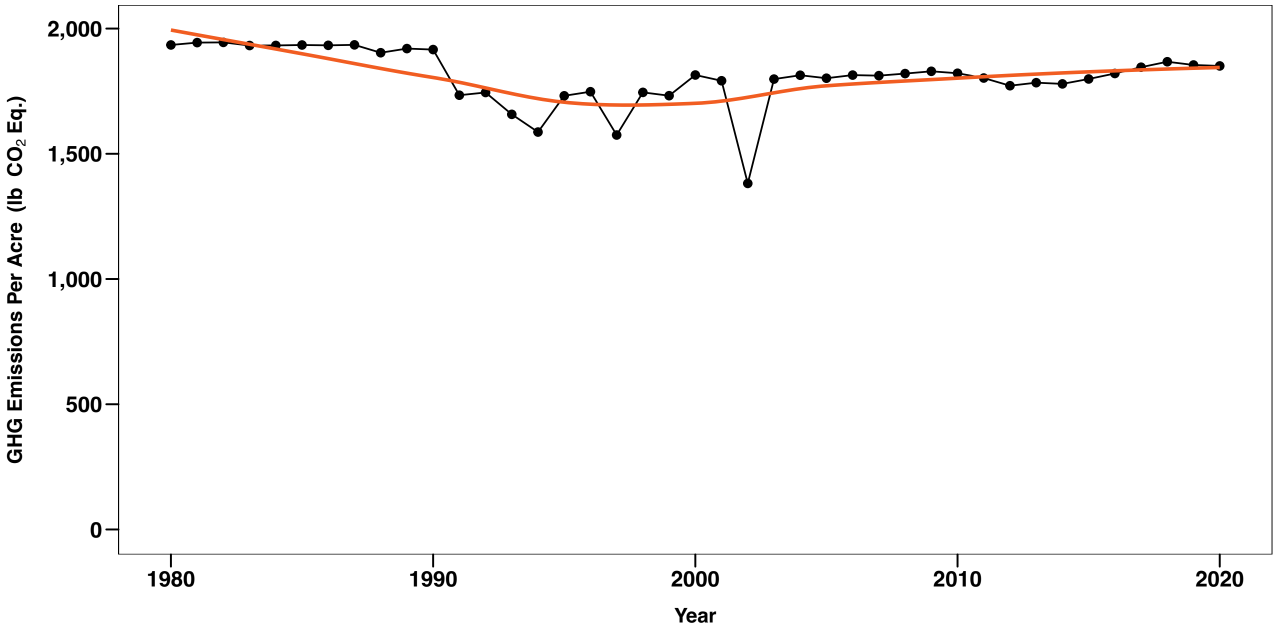
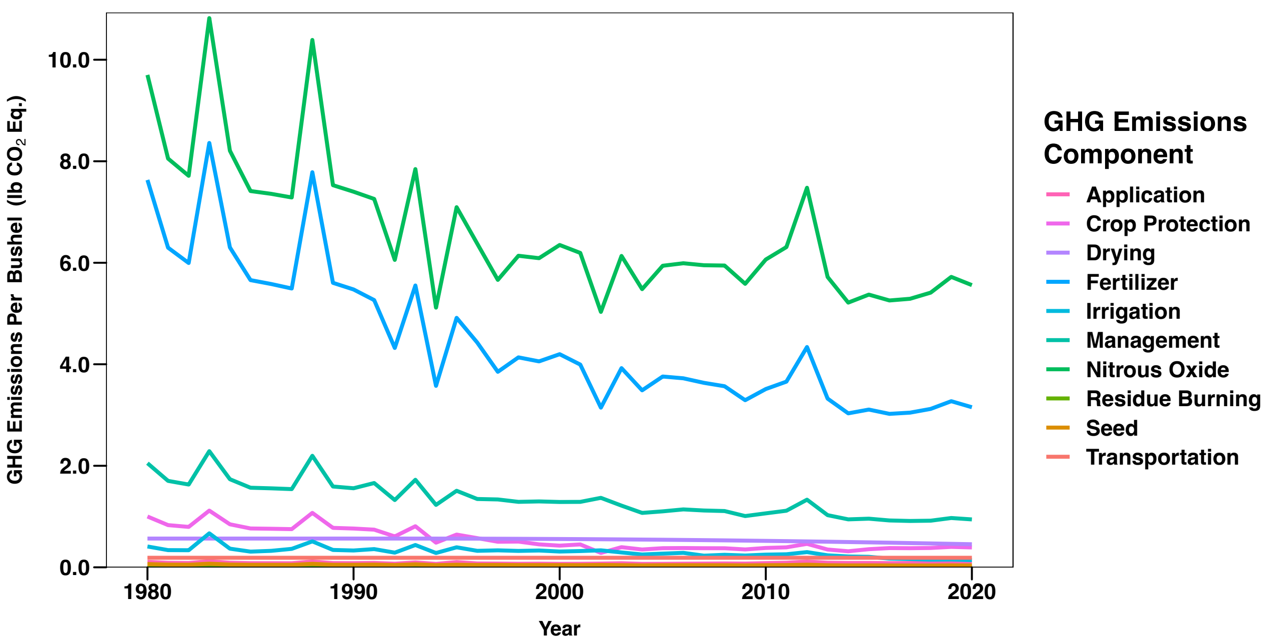


Figure B.8. GHG emission efficiency (lb. CO_2 Eq. / bushel) for corn grain during 1980-2020 colored by component



CORN (SILAGE)

Figure B.9. Energy use (million BTU / acre) for corn silage during 1980-2020

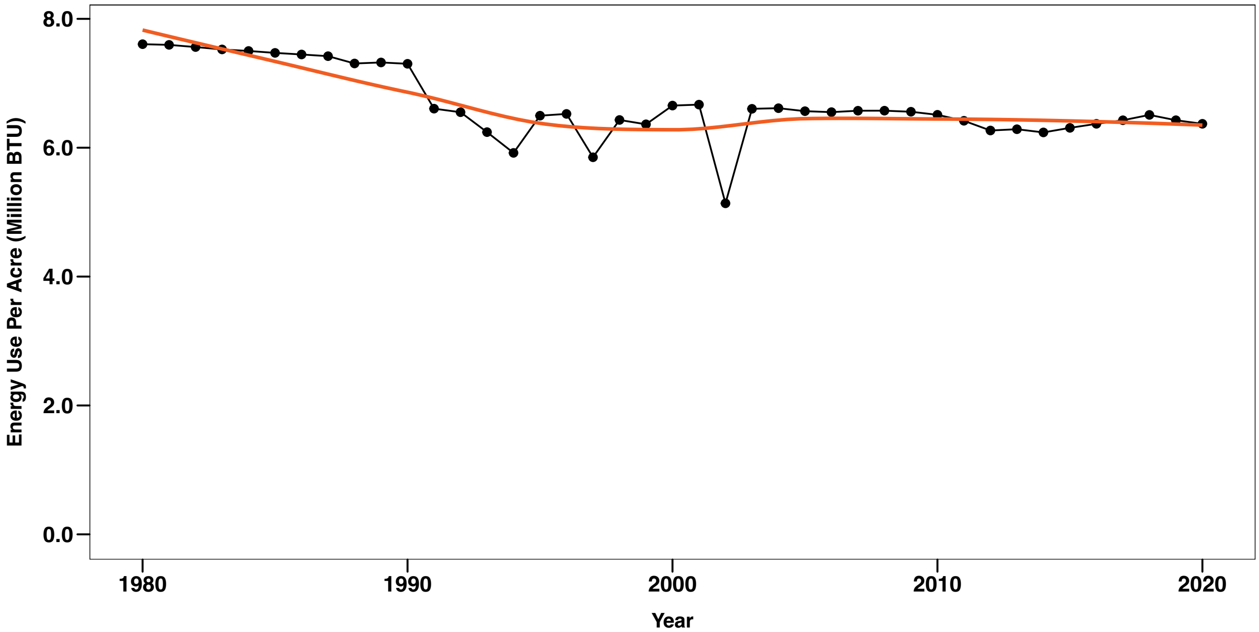


Figure B.10. Energy use efficiency (BTU / ton) for corn silage during 1980-2020 colored by component

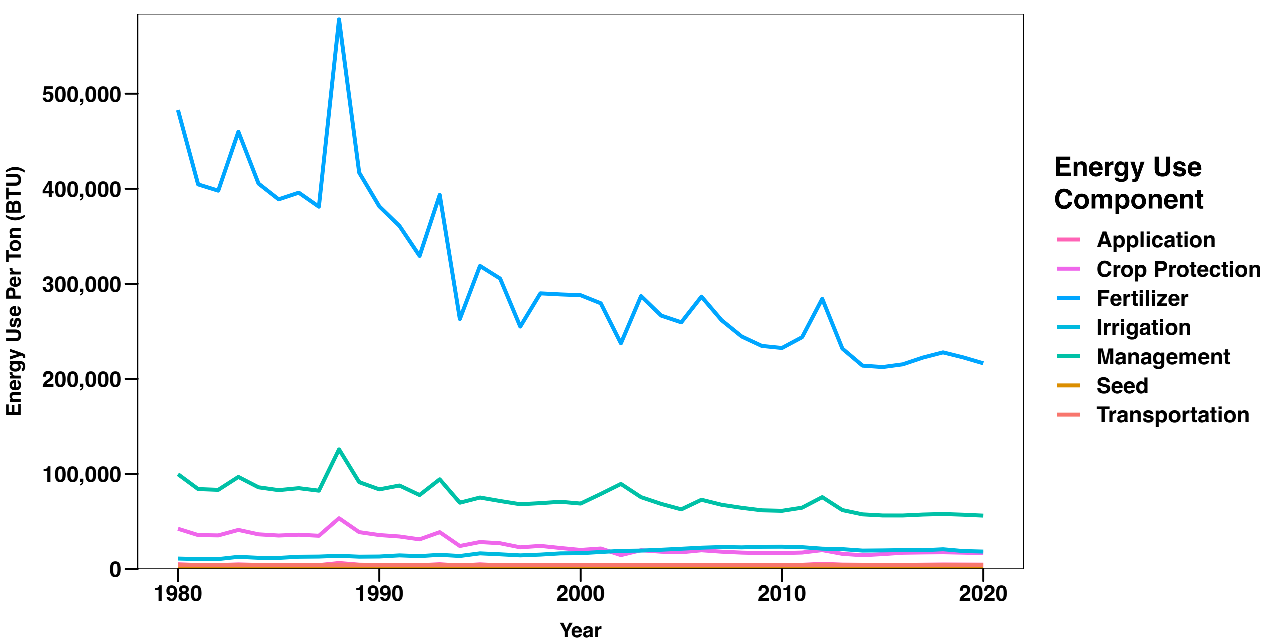


Figure B.11. Greenhouse gas emissions (lb. CO_2 Eq. / acre) for corn silage during 1980-2020

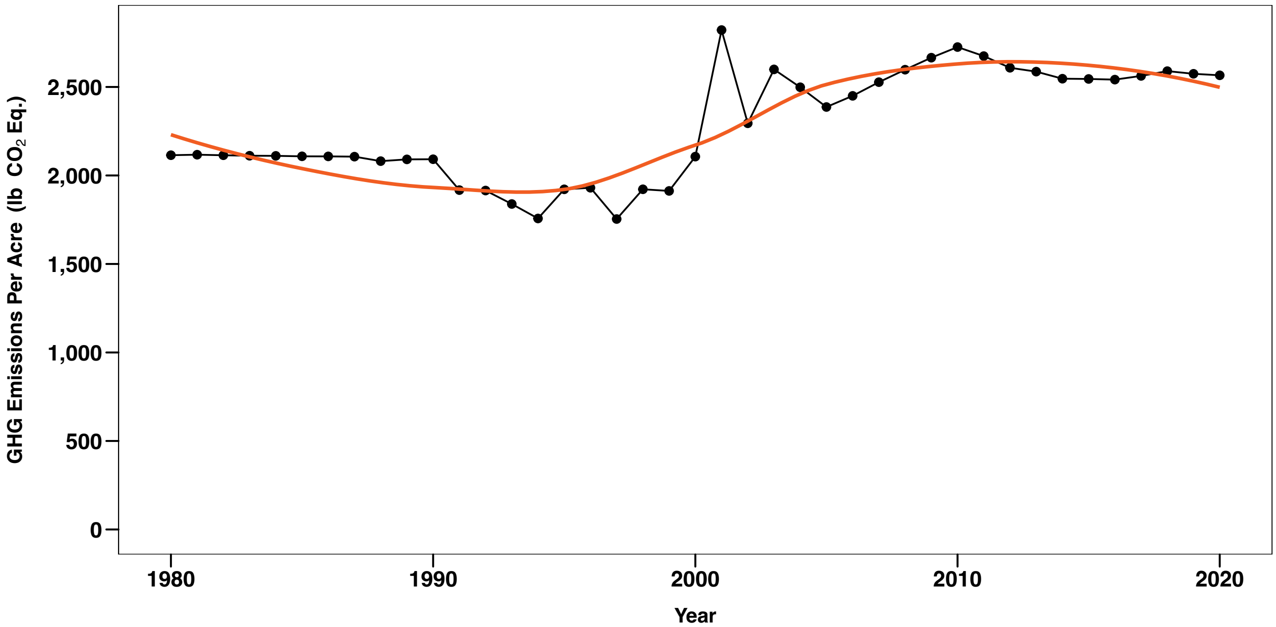
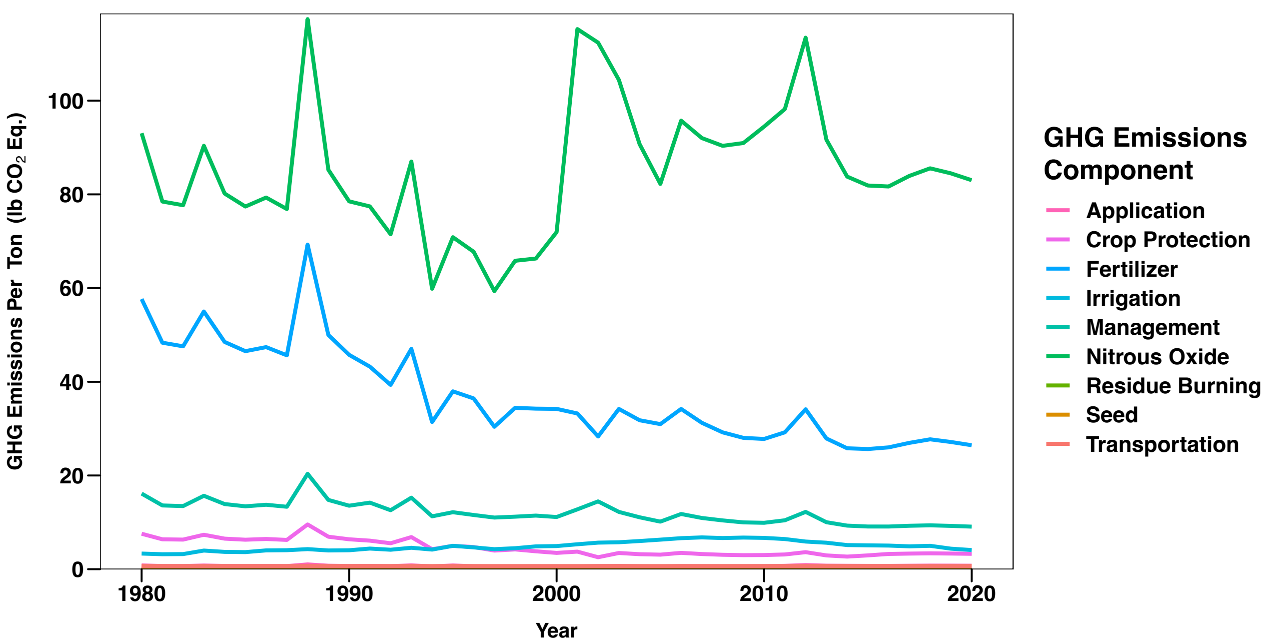


Figure B.12. GHG emission efficiency (lb. CO_2 Eq. / ton) for corn silage during 1980-2020 colored by component



COTTON

Figure B.13. Energy use (million BTU / acre) for cotton during 1980-2020

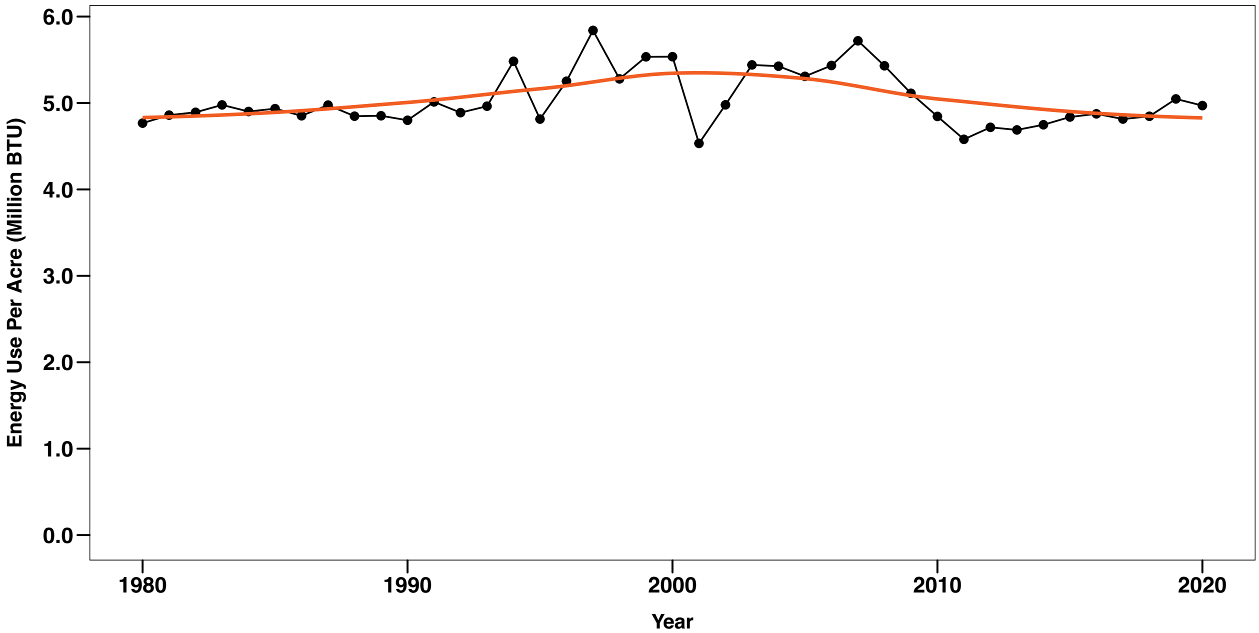


Figure B.14. Energy use efficiency (BTU / lb. of lint) for cotton during 1980-2020 colored by component

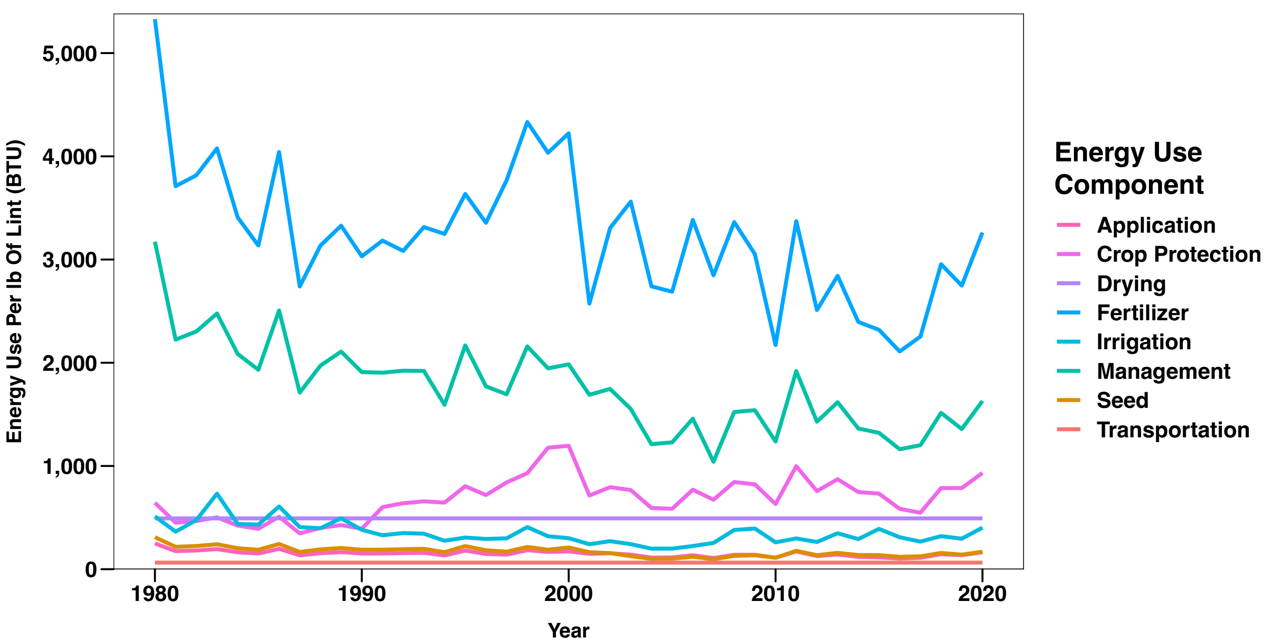


Figure B.15. Greenhouse gas emissions (lb. CO_2 Eq. / acre) for cotton during 1980-2020

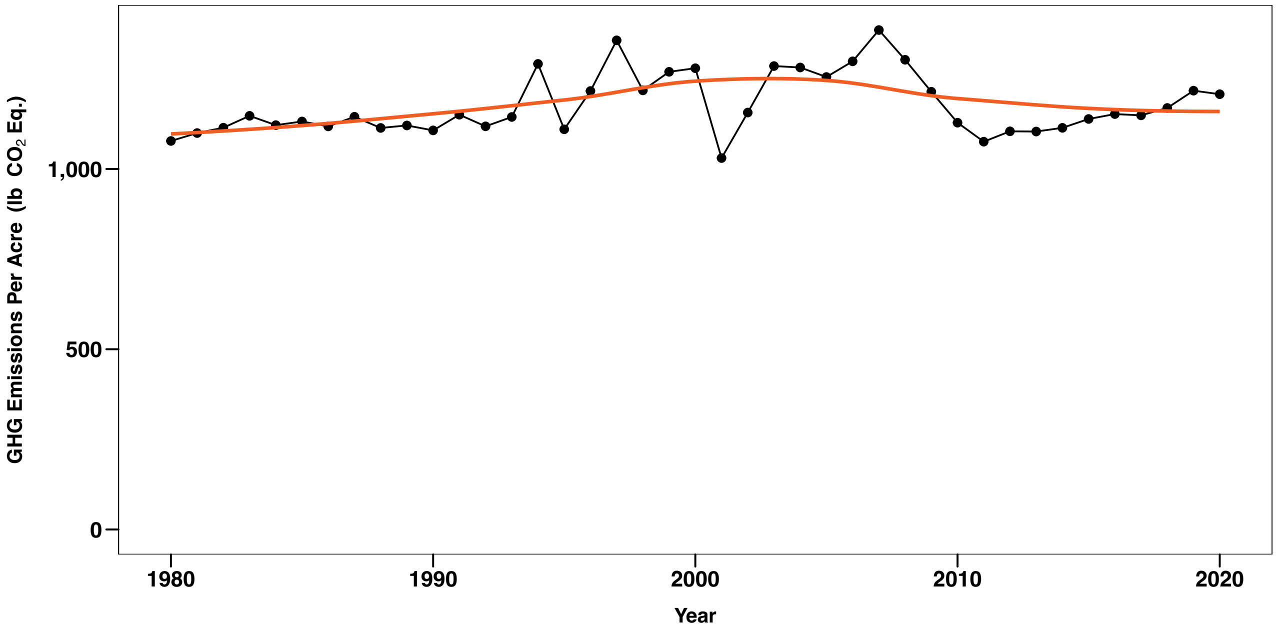
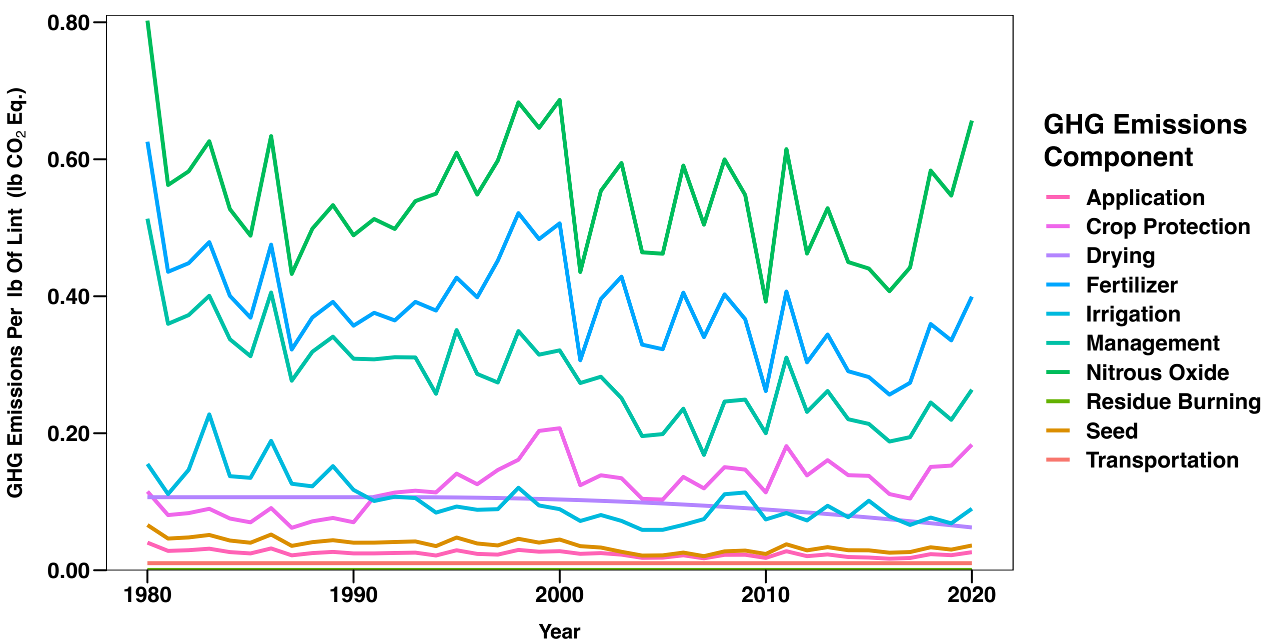


Figure B.16. GHG emission efficiency (lb. CO_2 Eq. / lb of lint) for cotton during 1980-2020 colored by component



PEANUTS

Figure B.17. Energy use (million BTU / acre) for peanuts during 1980-2020

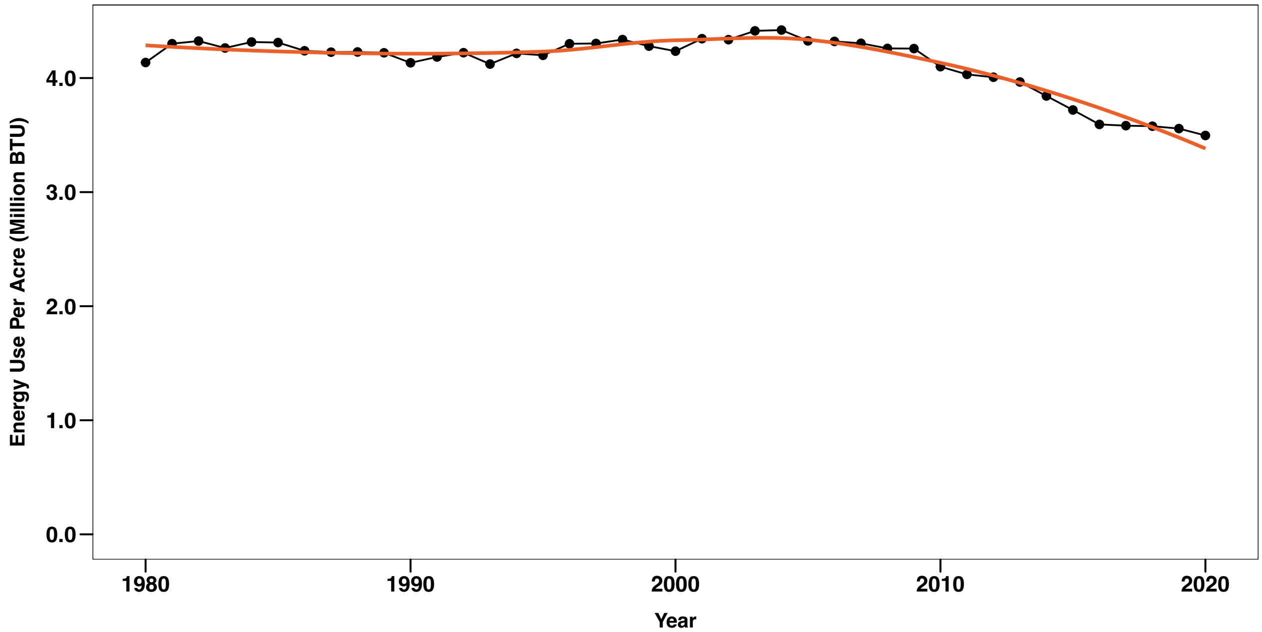


Figure B.18. Energy use efficiency (BTU / lb.) for peanuts during 1980-2020 colored by component

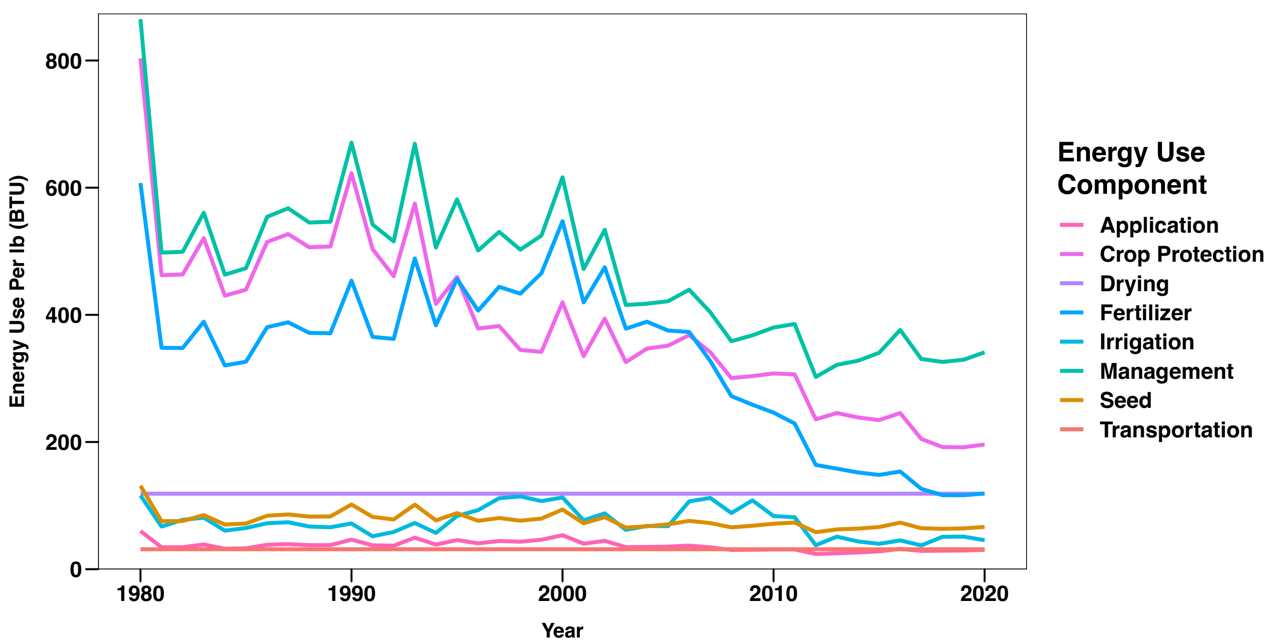


Figure B.19. Greenhouse gas emissions (lb. CO_2 Eq. / acre) for peanuts during 1980-2020

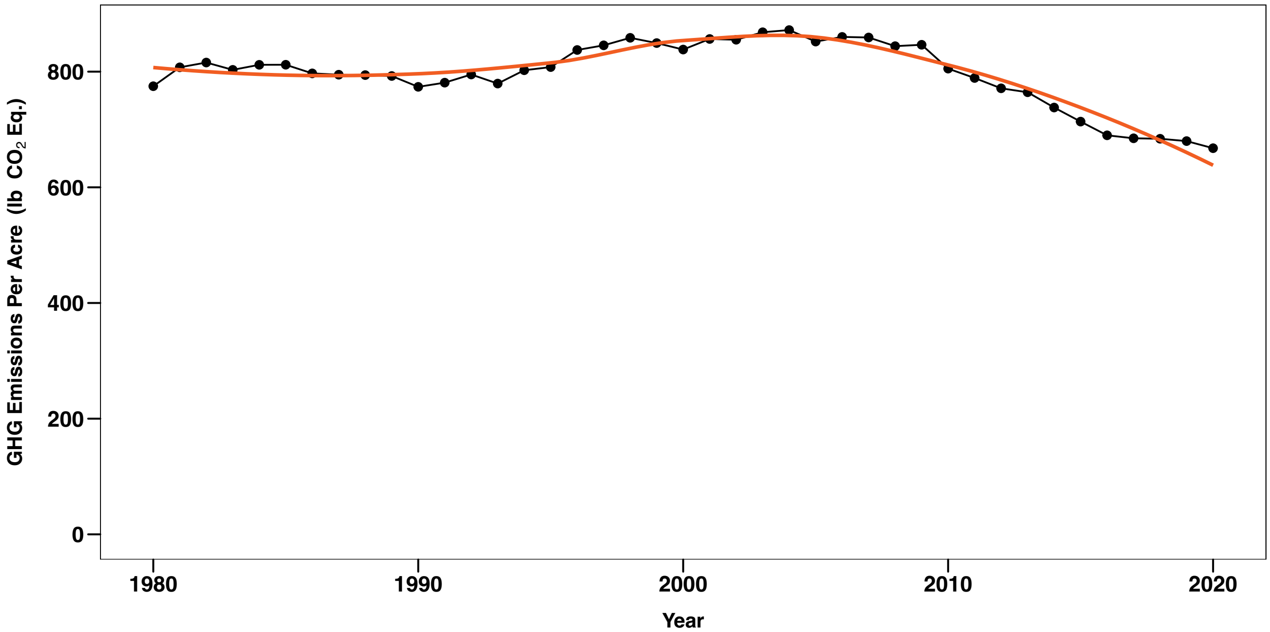
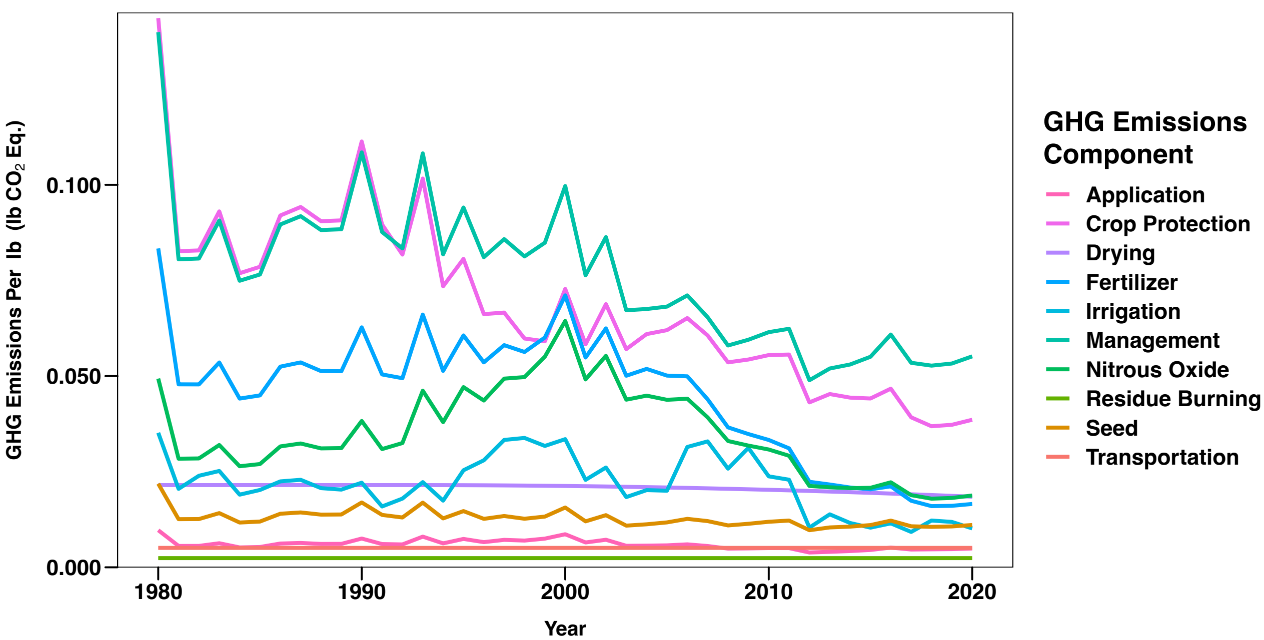


Figure B.20. GHG emission efficiency (lb. CO_2 Eq. / lb.) for peanuts during 1980-2020 colored by component



POTATOES

Figure B.21. Energy use (million BTU / acre) for potatoes during 1980-2020

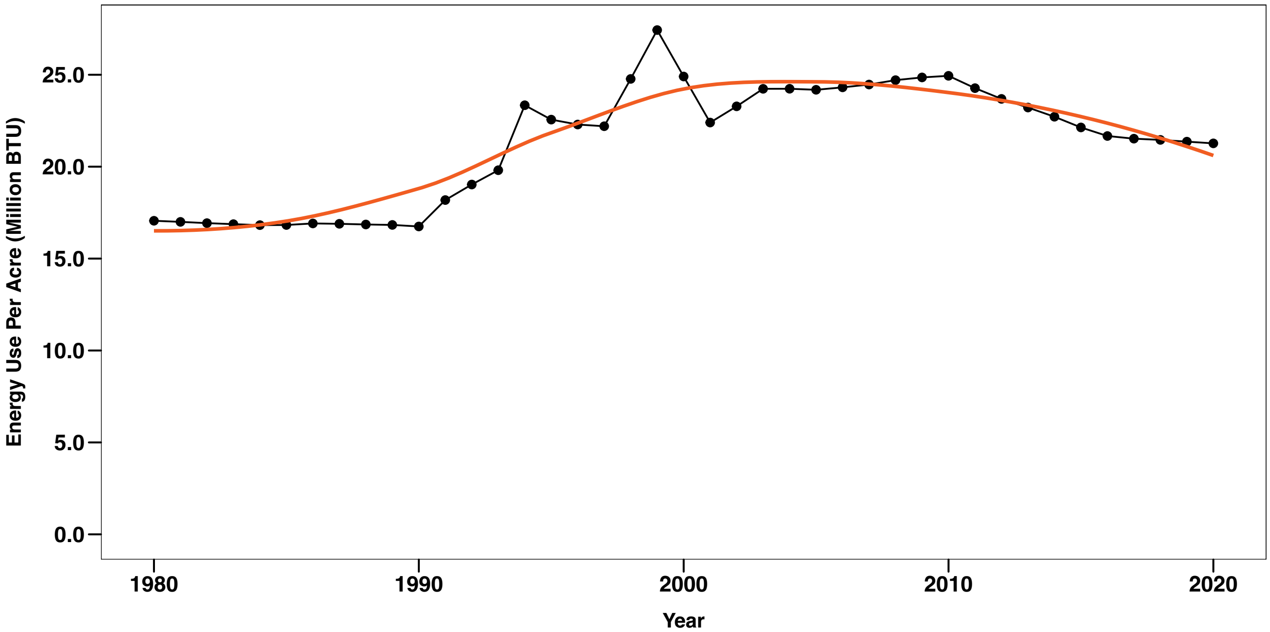


Figure B.22. Energy use efficiency (BTU / cwt) for potatoes during 1980-2020 colored by component

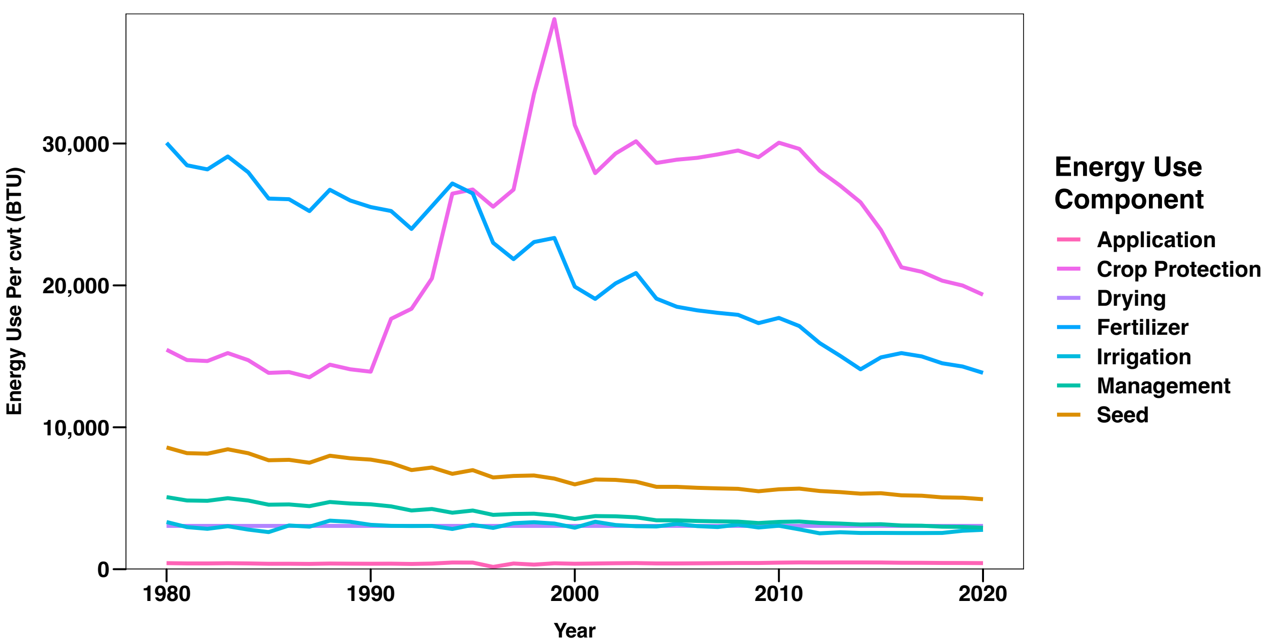


Figure B.23. Greenhouse gas emissions (lb. CO_2 Eq. / acre) for potatoes during 1980-2020

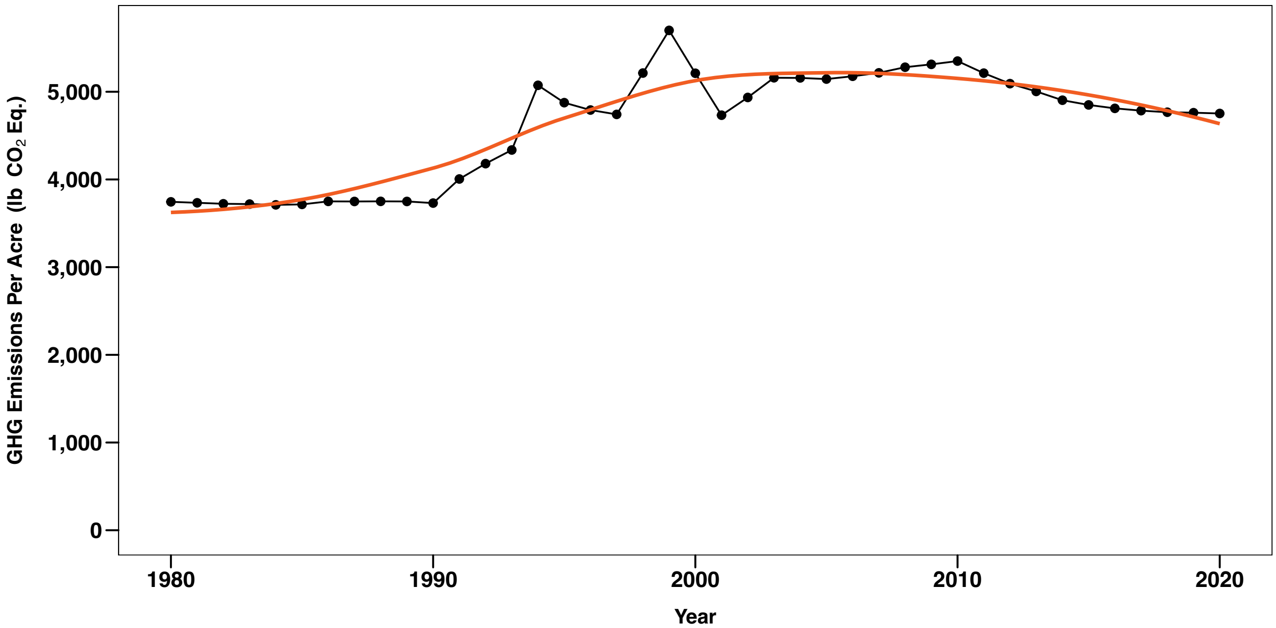
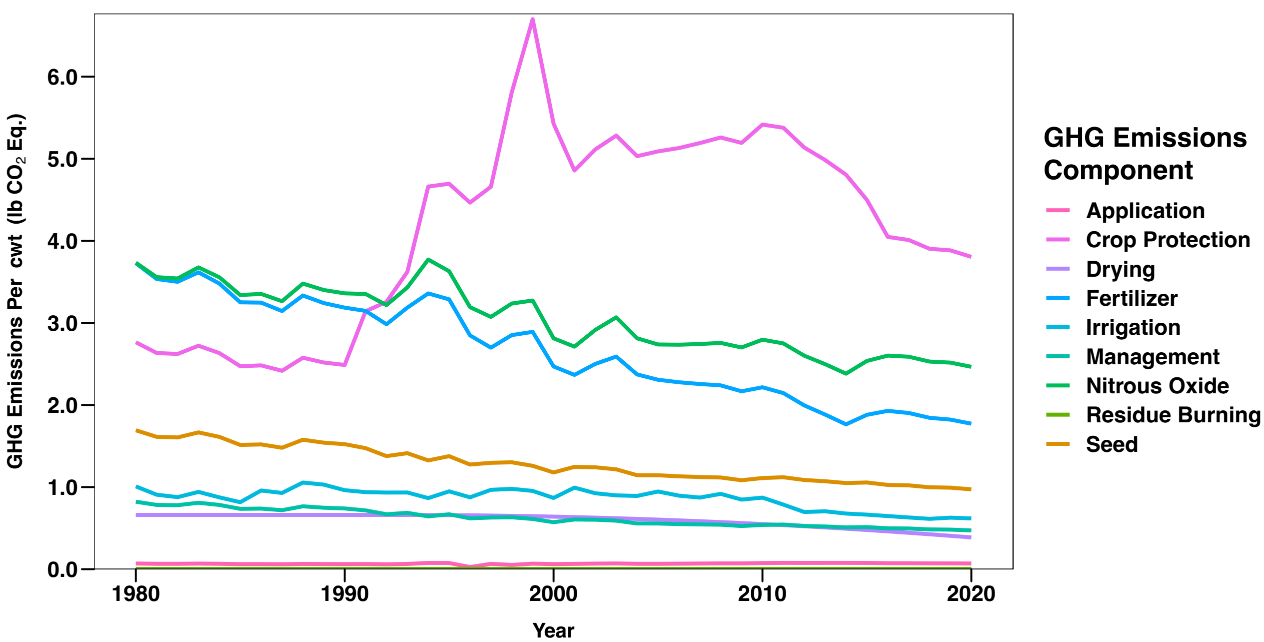


Figure B.24. GHG emission efficiency (lb. CO_2 Eq. / cwt) for potatoes during 1980-2020 colored by component



RICE

Figure B.25. Energy use (million BTU / acre) for rice during 1980-2020

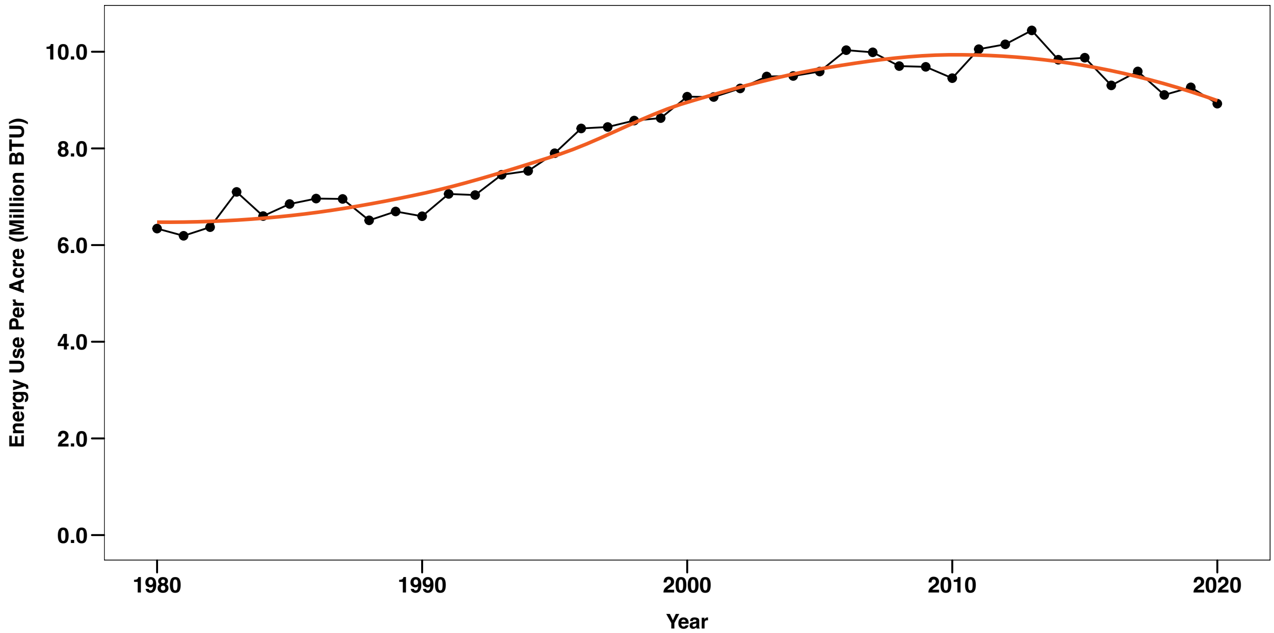


Figure B.26. Energy use efficiency (BTU / cwt) for rice during 1980-2020 colored by component

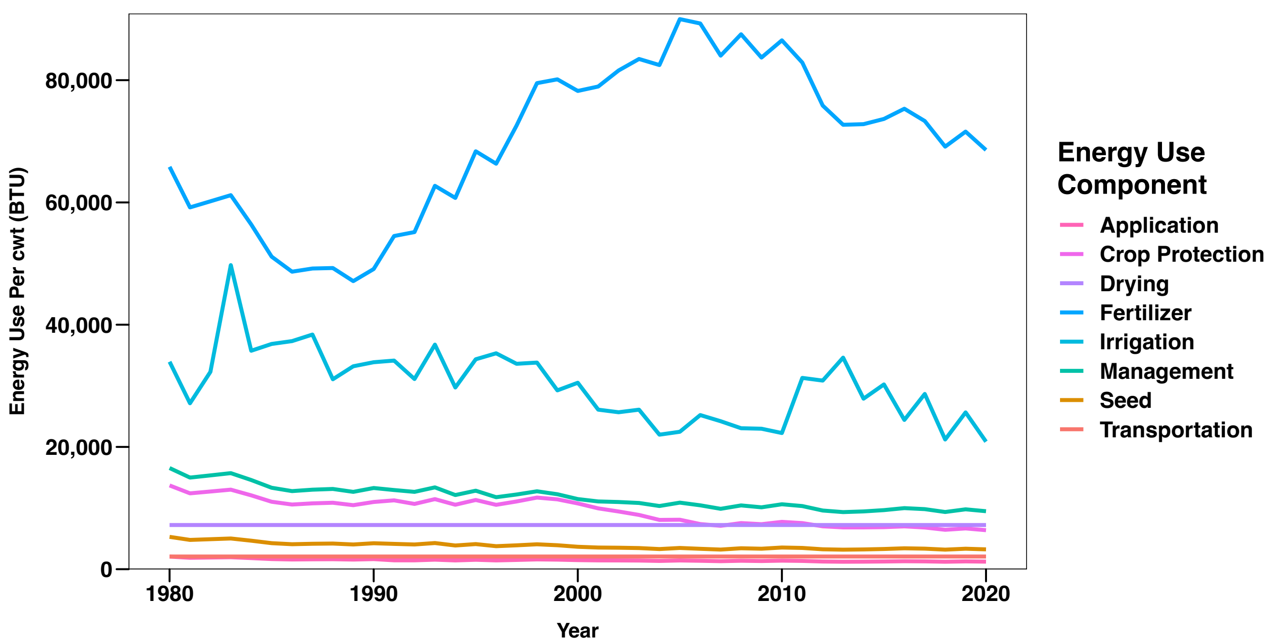


Figure B.27. Greenhouse gas emissions (lb. CO_2 Eq. / acre) for rice during 1980-2020

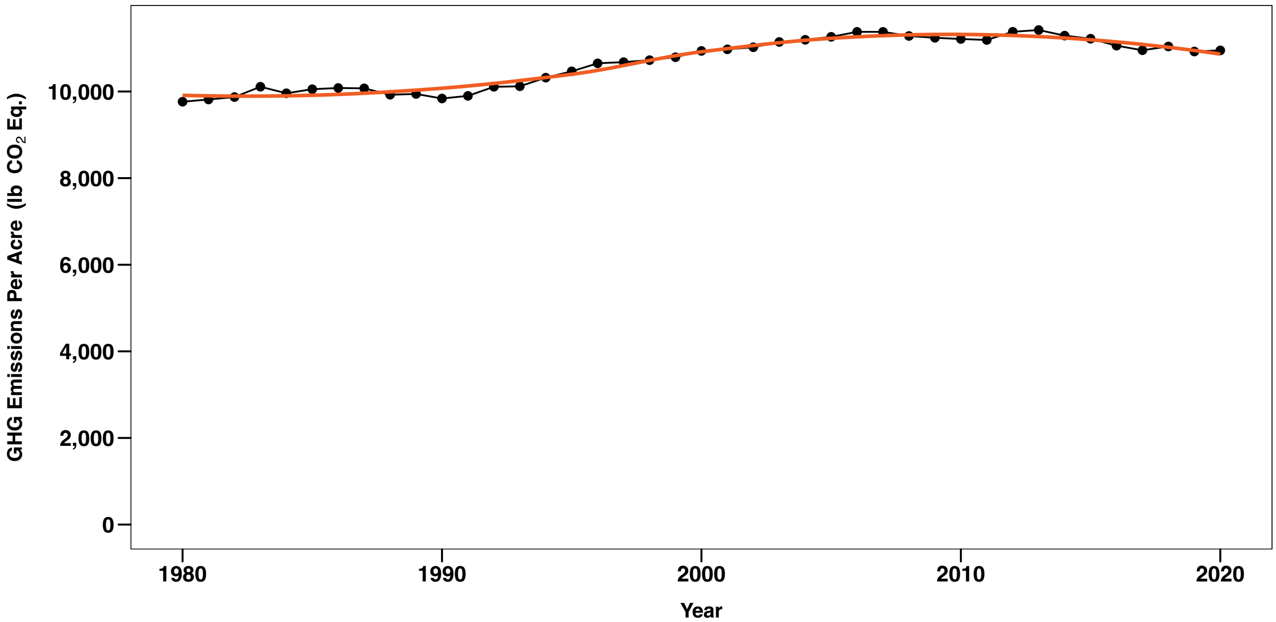
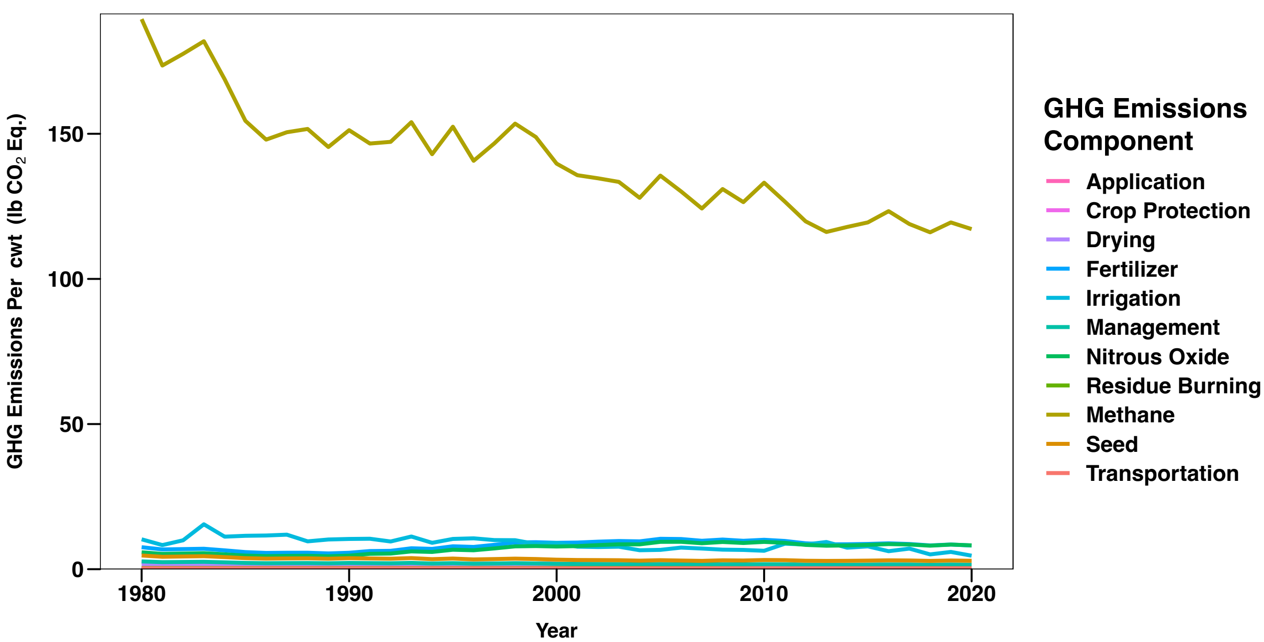


Figure B.28. GHG emission efficiency (lb. CO_2 Eq. / cwt) for rice during 1980-2020 colored by component



SORGHUM

Figure B.29. Energy use (million BTU / acre) for sorghum during 1980-2020

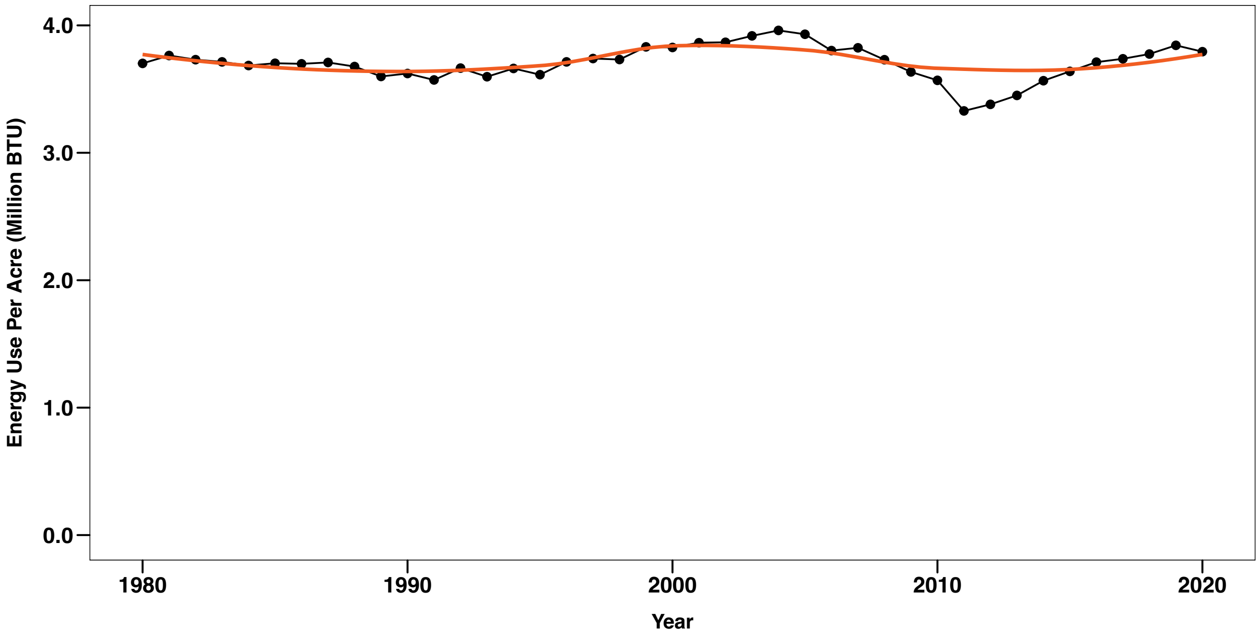


Figure B.30. Energy use efficiency (BTU / bushel) for sorghum during 1980-2020 colored by component

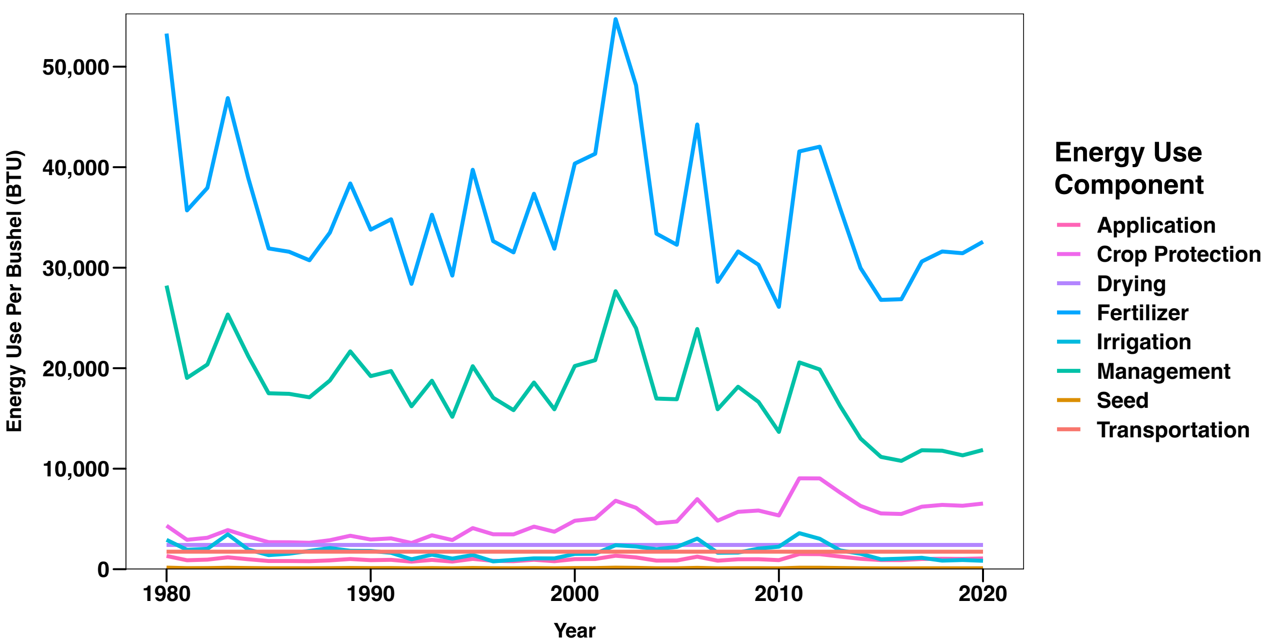


Figure B.31. Greenhouse gas emissions (lb. CO_2 Eq. / acre) for sorghum during 1980-2020

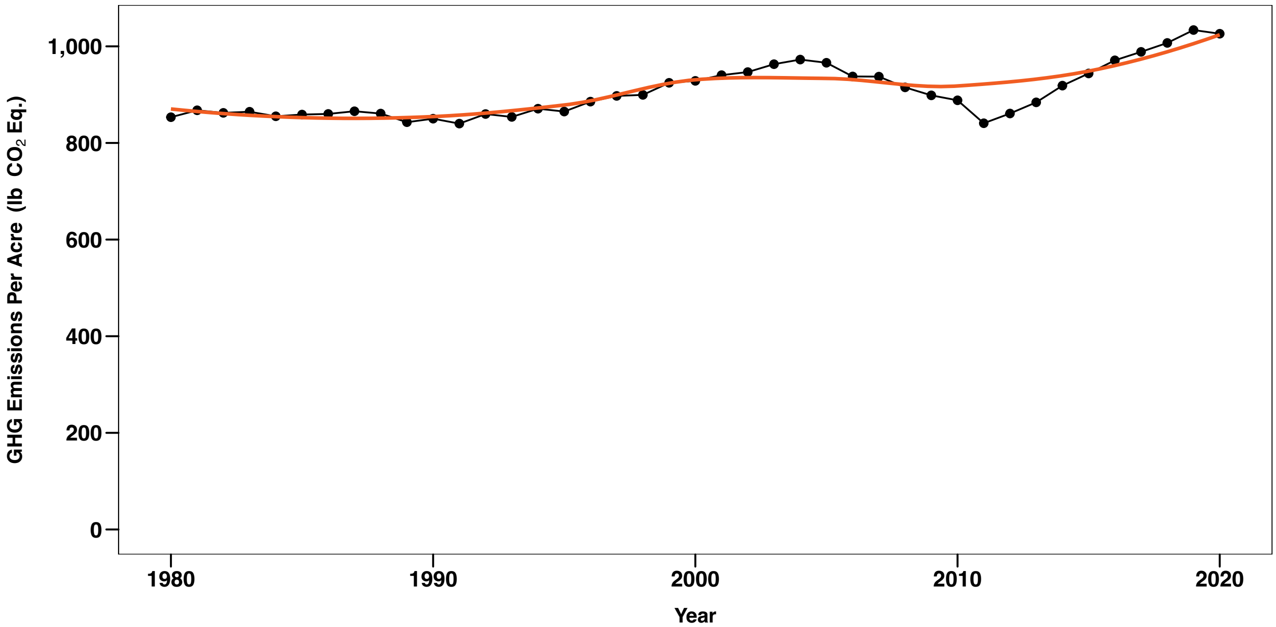
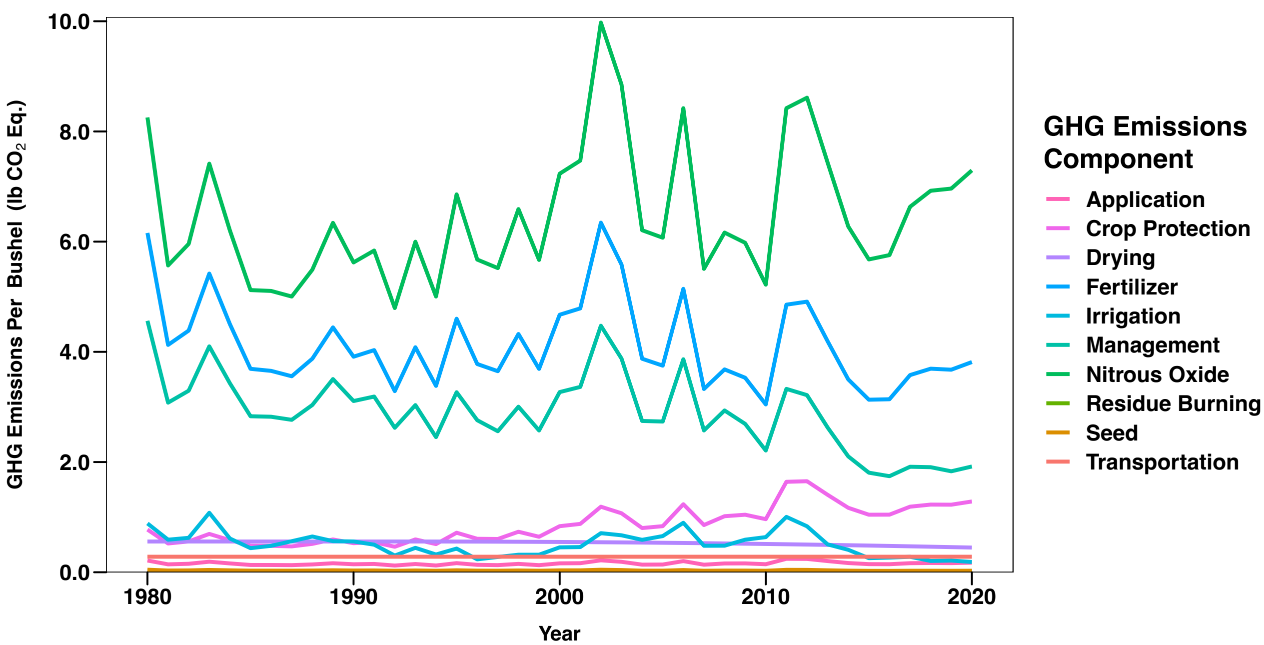


Figure B.32. GHG emission efficiency (lb. CO_2 Eq. / bushel) for sorghum during 1980-2020 colored by component



SOYBEANS

Figure B.33. Energy use (million BTU / acre) for soybeans during 1980-2020

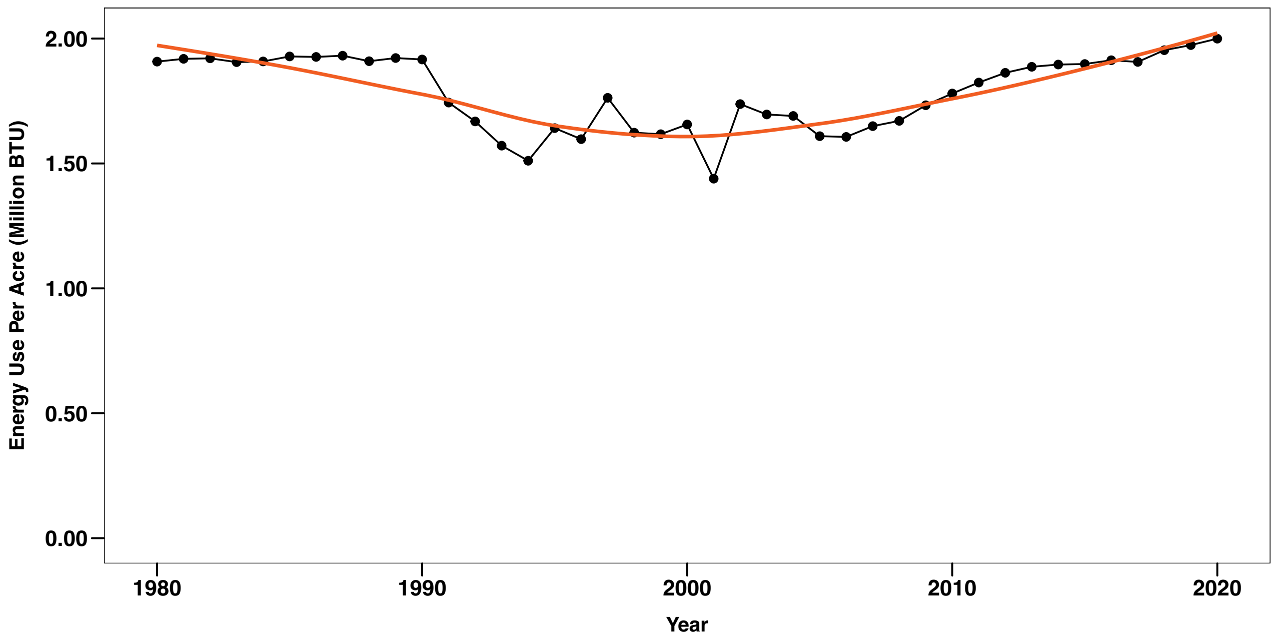


Figure B.34. Energy use efficiency (BTU / bushel) for soybeans during 1980-2020 colored by component

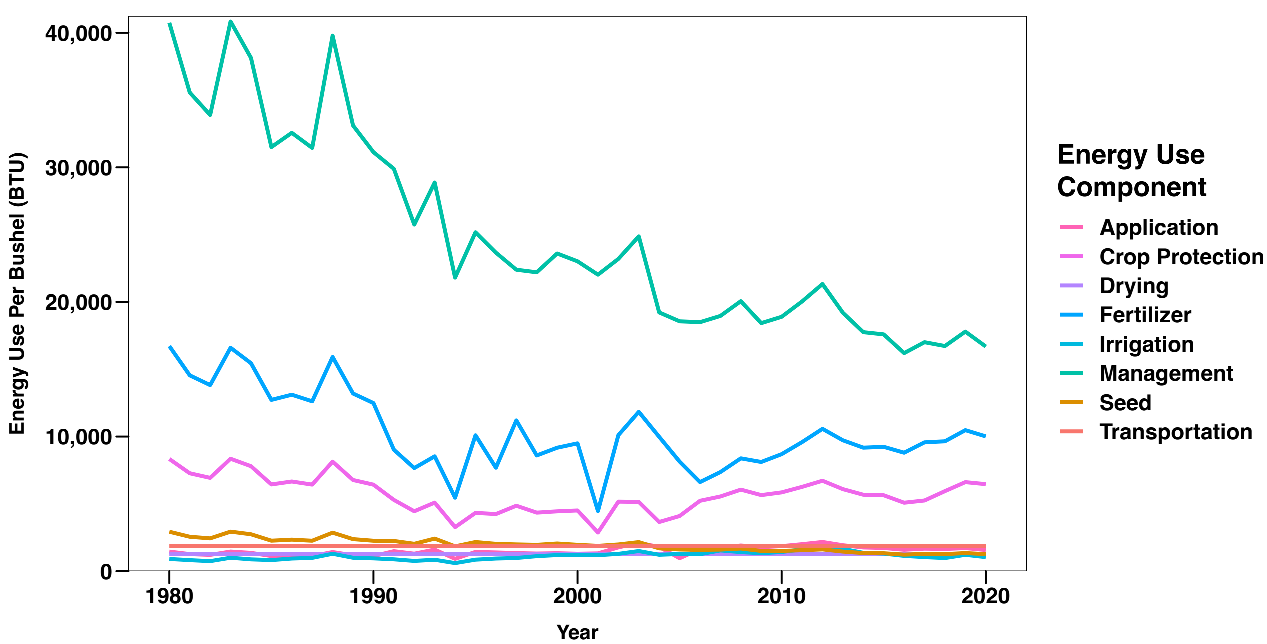


Figure B.35. Greenhouse gas emissions (lb. CO_2 Eq. / acre) for soybeans during 1980-2020

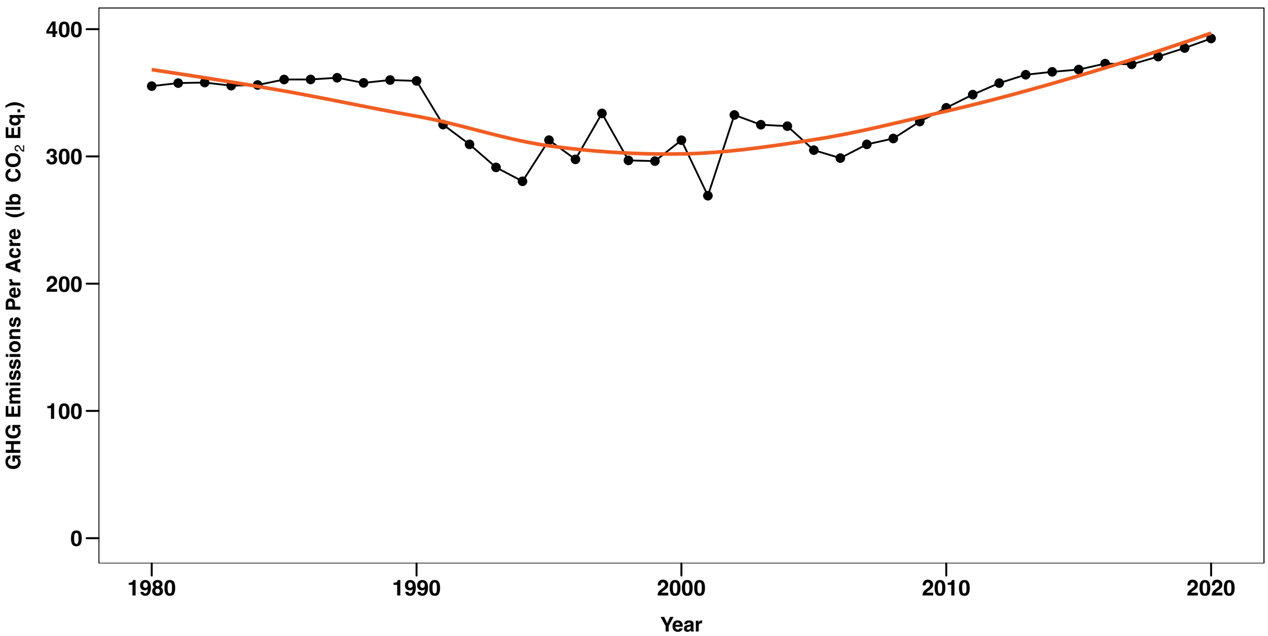
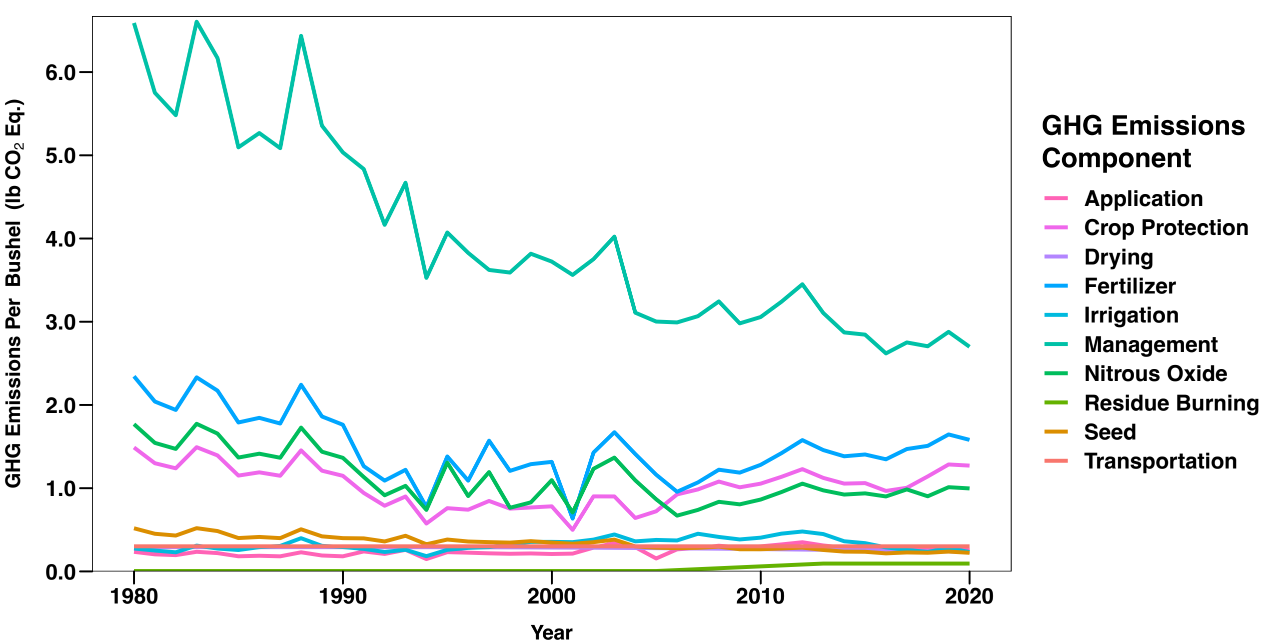


Figure B.36. GHG emission efficiency (lb. CO_2 Eq. / bushel) for soybeans during 1980-2020 colored by component



SUGAR BEETS

Figure B.37. Energy use (million BTU / acre) for sugar beets during 1980-2020

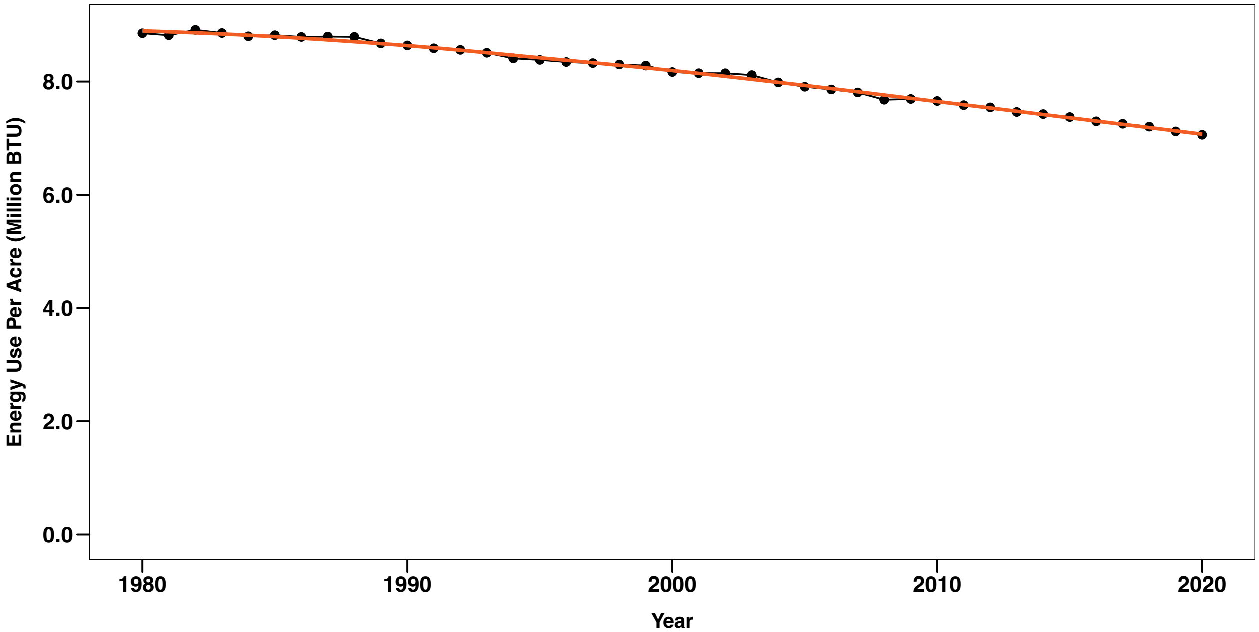


Figure B.38. Energy use efficiency (BTU / ton of sugar) for sugar beets during 1980-2020 colored by component

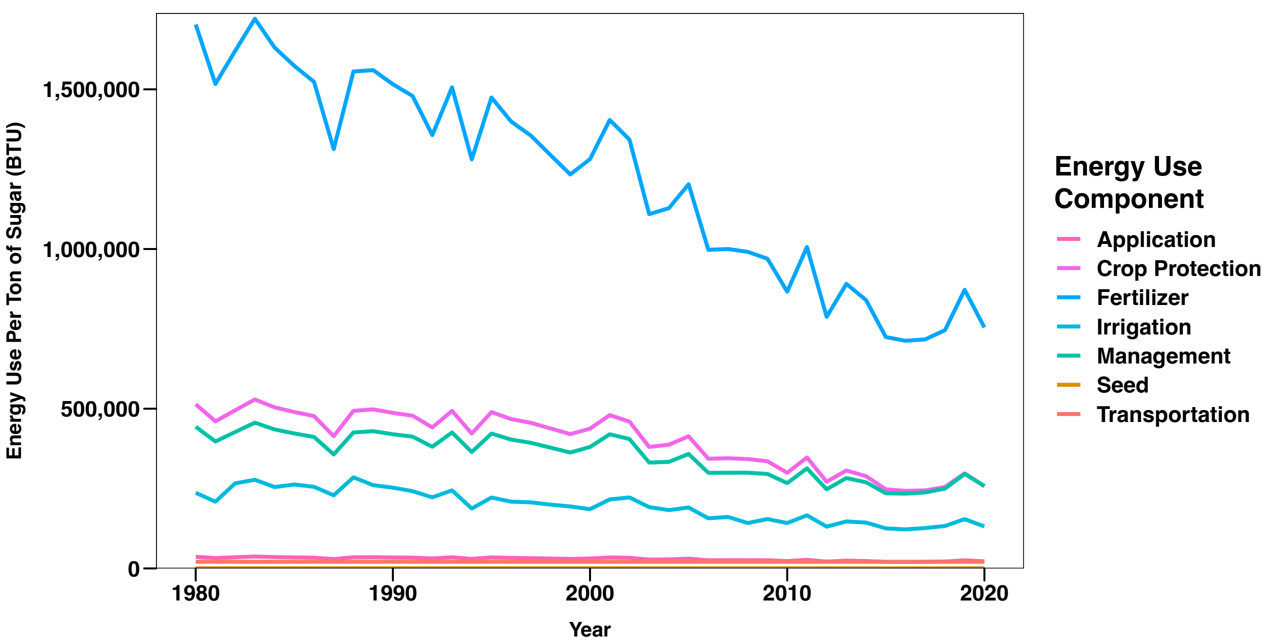


Figure B.39. Greenhouse gas emissions (lb. CO_2 Eq. / acre) for sugar beets during 1980-2020

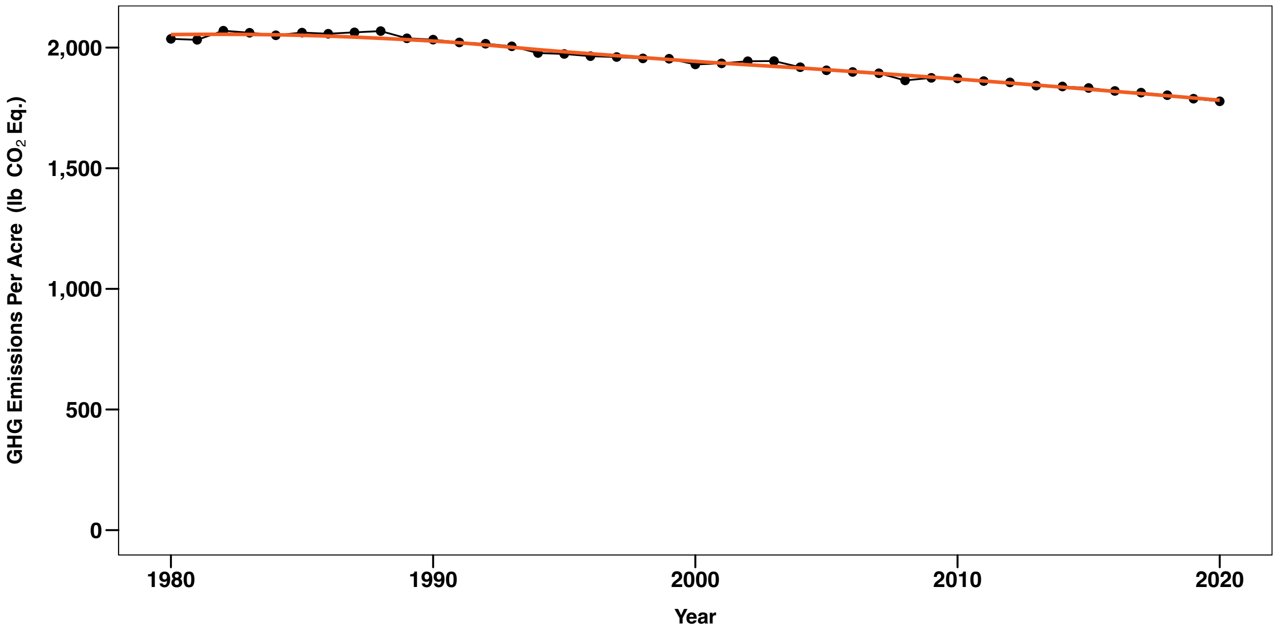
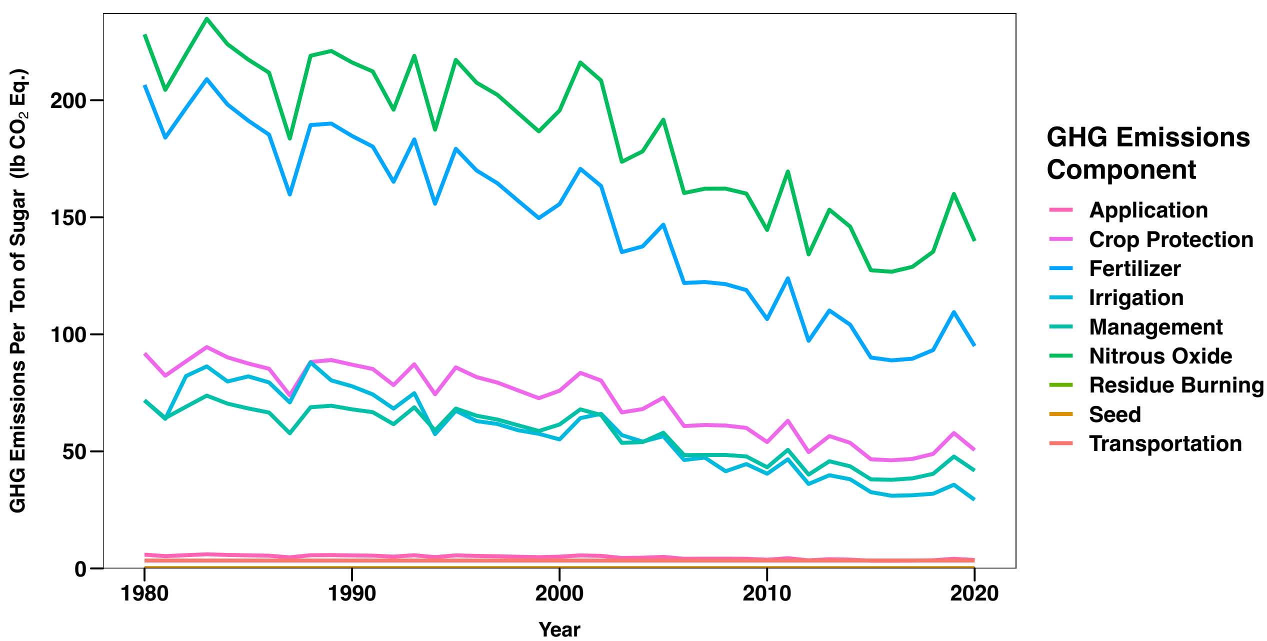


Figure B.40. GHG emission efficiency (lb. CO_2 Eq. / ton of sugar) for sugar beets during 1980-2020 colored by component



WHEAT

Figure B.41. Energy use (million BTU / acre) for wheat during 1980-2020

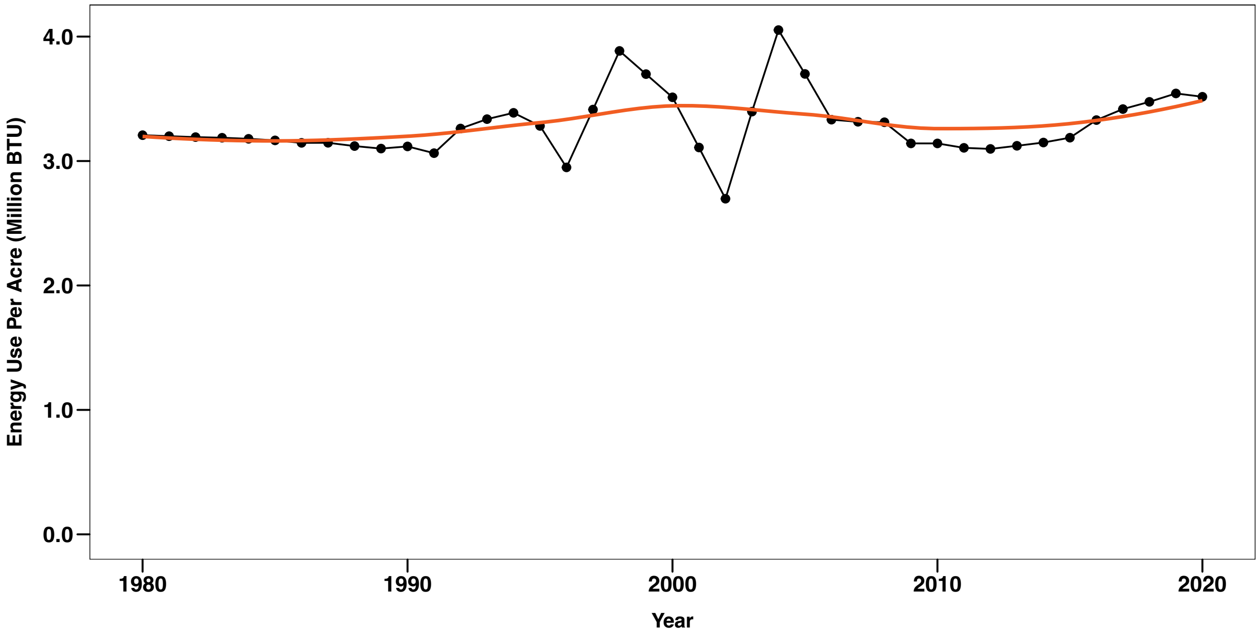


Figure B.42. Energy use efficiency (BTU / bushel) for wheat during 1980-2020 colored by component

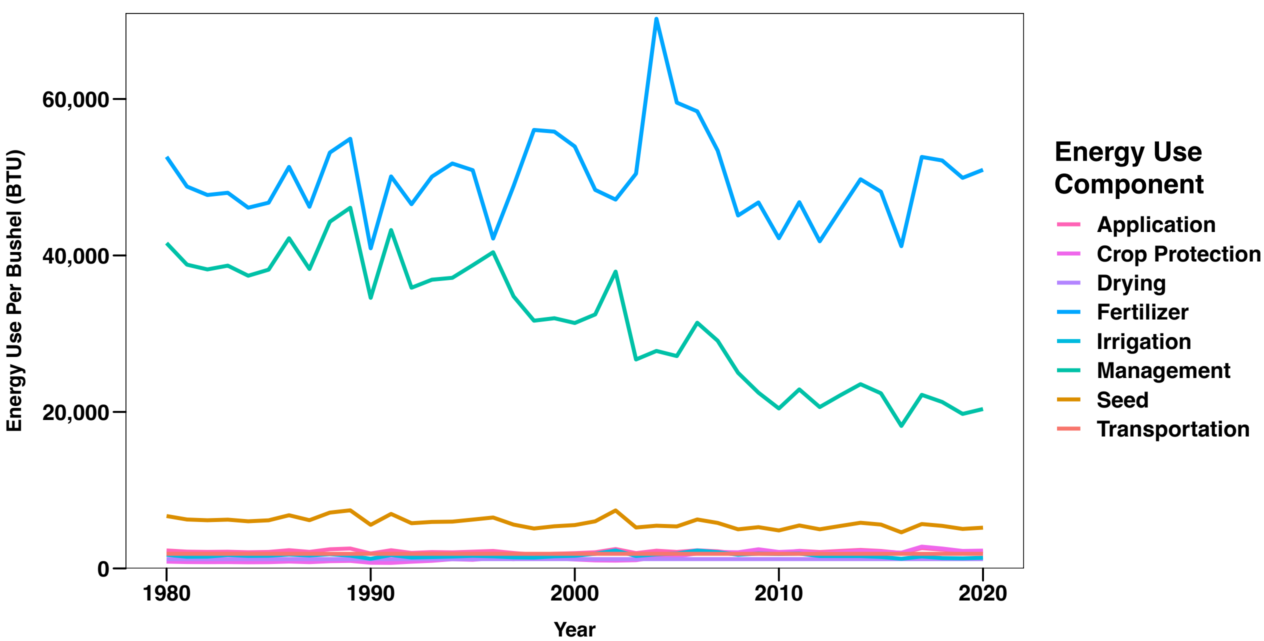


Figure B.43. Greenhouse gas emissions (lb. CO_2 Eq. / acre) for wheat during 1980-2020

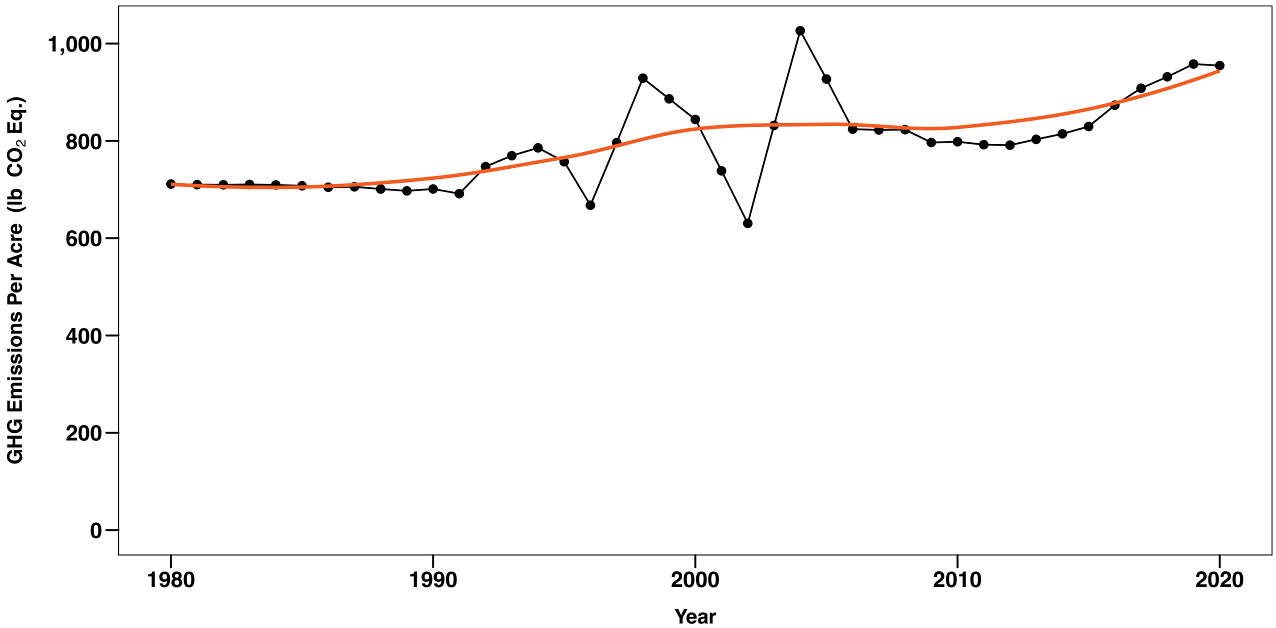
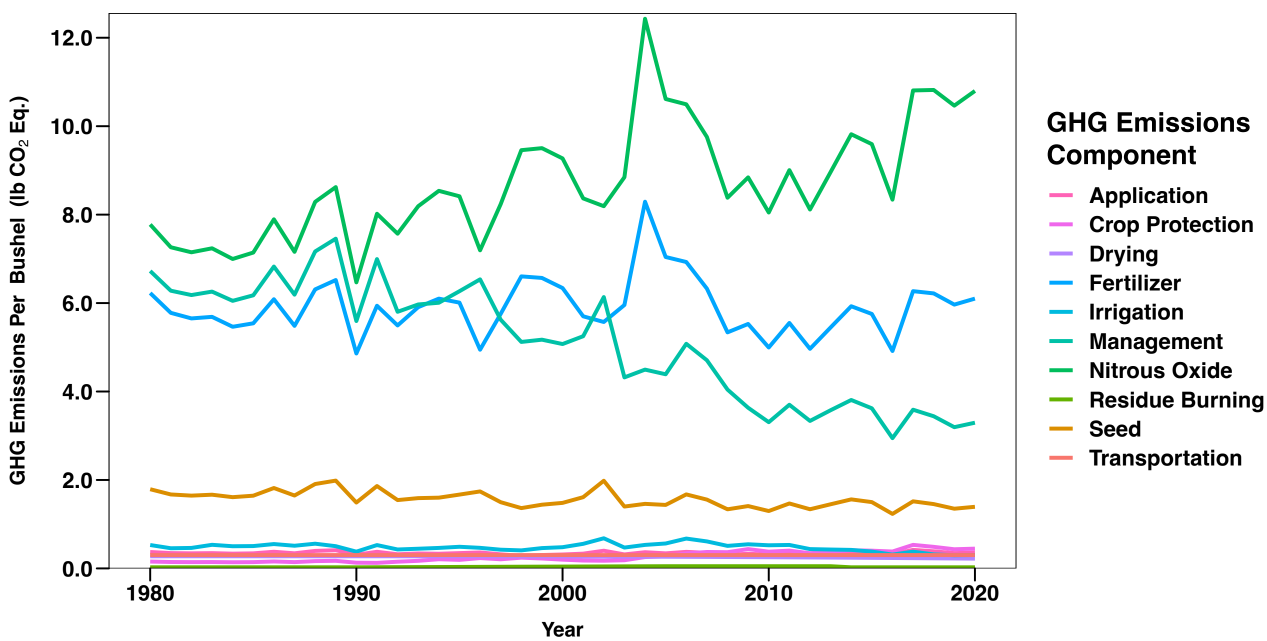


Figure B.44. GHG emission efficiency (lb. CO_2 Eq. / bushel) for wheat during 1980-2020 colored by component



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