# 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:

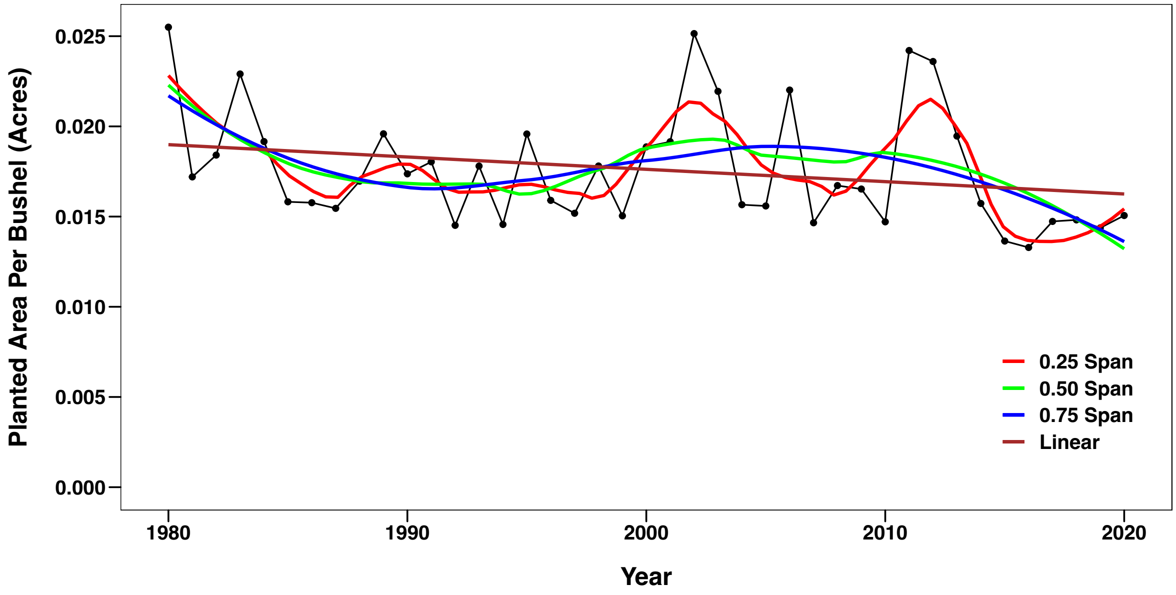
- For synthetic fertilizers (nitrogen, phosphate and potash) and crop protectants (herbicide, insecticide, fungicide, all others), the data items *Applications*, *Measured in Number*, *Average and Applications*, *Measured in Pounds*.
- The data items *Acres Harvested*; *Acres Planted*; *Production*, *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:

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

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 $CO_2$e, 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 CH4emissions. 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.

## APPENDIX A REFERENCES

Ali, M.B. 2002. Characteristics and Production Costs of U.S. Wheat Farms.

Ali, M., N. Brooks, and R. McElroy. 2000. Characteristics of U.S. Wheat Farming.

Audsley, E., K. Stacey, D.J. Parsons, and A.G. Williams. 2009. Estimation of the greenhouse gas emissions from agricultural pesticide manufacture and use.

Becker, J., and S. Ratnayake. 2010. Acres Planted per Day and Seeding Rates of Crops Grown in the United States.

Brown, S., and T. Sandlin. 2019. How to Think About Cotton: Plant Growth Regulators.

Cai, H., A. Burnham, M. Wang, W. Hang, and A. Vyas. 2015. The GREET Model Expansion for Well-to-Wheels Analysis of Heavy-Duty Vehicles.

Conservation Technology Information Center. 2008. Conservation Technology Information Center's (CTIC) National Crop Residue Management Survey.

Field to Market. 2009. Environmental Resource Indicators for Measuring Outcomes of On-Farm Agricultural Production in the United States.

Field to Market. 2012. Environmental and Socioeconomic Indicators for Measuring Outcomes of On-Farm Agricultural Production in the United States.

Field to Market. 2016a. Environmental and Socioeconomic Indicators for Measuring Outcomes of On-Farm Agricultural Production in the United States.

Field to Market. 2016b. Environmental and Socioeconomic Indicators for Measuring Outcomes of On-Farm Agricultural Production in the United States. Field to Market: The Alliance for Sustainable Agriculture.

Fournier, A., P. Ellsworth, R. Norton, and W. Dixon. 2012. Mepiquat Chloride and Mepiquat Pentaborate Use in Arizona.

Intergovernmental Panel on Climate Change. 2019. $N_2O$ Emissions From Managed Soils, and $CO_2$ Emissions From Lime and Urea Application.

International Energy Agency. 2019a. Energy Efficiency 2019.

International Energy Agency. 2019b. Tracking the decoupling of electricity demand and associated $CO_2$ emissions.

International Energy Agency. 2019c. Global Energy and $CO_2$ Status Report 2019.

International Fertilizer Association. 2018. Ammonia Plant Energy Efficiency and $CO_2$ Emissions Benchmarking.

National IPM Database. 2021. Pest Management Strategic Plan. https://ipmdata.ipmcenters.org/source_list.cfm?sourcetypeid=4 (accessed 30 April 2021).

Office of Energy Efficiency. 2000. Fuel Efficiency Benchmarking in Canada's Trucking Industry.

Ott, L., and M. Longnecker. 2001. An Introduction to Statistical Methods and Data Analysis. Fifth Edit. Duxbury Press, Pacific Grove, CA.

R Core Team. 2021. A language and environment for statistical computing.

Roth, G.W., and A.J. Heinrichs. 2001. Corn Silage Production and Management.

Sanford, S. 2005. Reducing Grain Drying Costs.

Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, et al. 2007. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA.

U.S. Department of Agriculture. 2019. 2017 Census of Agriculture. Appendix B, Section 9.

U.S. Department of Agriculture. 2020. Summary Report: 2017 National Resources Inventory.

U.S. Department of Agriculture. 2021. USDA National Agricultural Statistics Service - Quick Stats. https://data.nal.usda.gov/dataset/nass-quick-stats (accessed 21 May 2021).

U.S. Department of Agriculture Economic Research Service. 2021. ARMS Farm Financial and Crop Production Practices. https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices.aspx.

U.S. EPA. 2014. Index of pesticide types and families.

U.S. EPA. 2021a. Emissions and Generation Resource Integrated Database (eGRID).

U.S. EPA. 2021b. Inventory of U.S. Greenhouse Gas Emissions and Sinks.

Wang, M., A. Elgowainy, U. Lee, A. Bafana, P.T. Benavides, et al. 2020. Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model ® (2020 Excel). Computer Software.

West, T.O., and G. Marland. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91(1–3): 217–232. doi: 10.1016/S0167-8809(01)00233-X.

Wright, L., B. Boundy, P.C. Badger, B. Perlack, and S. Davis. 2009. Biomass Energy Data Book. Second. Oak Ridge National Laboratory.