Greenhouse Gas Emissions Calculator for Grain and Biofuel Farming Systems

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ABSTRACT Opportunities for farmers to participate in greenhouse gas (GHG) credit markets require that growers, students, extension educators, offset aggregators, and other stakeholders understand the impact of agricultural practices on GHG emissions. The Farming Systems Greenhouse Gas Emissions Calculator, a web-based tool linked to the SOCRATES soil carbon process model, provides a simple introduction to the concepts and magnitudes of gas emissions associated with crop management. Users choose a county of interest on an introductory screen and are taken to the input/output window, where they choose crops, yields, tillage practices, or nitrogen fertilizer rates. Default values are provided based on convention and county averages. Outputs include major contributors of greenhouse gases in field crops: soil carbon change, nitrous oxide (N_2O) emission, fuel use, and fertilizer. We contrast conventional tillage and no-till in a corn–soybean–wheat (*Zea mays* L.–*Glycine max* (L.) Merr.–*Triticum aestivum* L.) rotation and compare continuous corn fertilized at 101 and 134 kg N ha^{-1} yr^{-1}. In corn years, N_2O was the dominant GHG, due to high fertilizer requirements for corn. No-till management reduced greenhouse gas emissions by 50% due to net soil carbon storage. Continuous corn fertilized at 101 kg N ha^{-1} yr^{-1} emitted 1.25 Mg CO_2 equivalents ha^{-1} yr^{-1} compared with 1.42 Mg CO_2 equivalents ha^{-1} yr^{-1} at 134 kg N ha^{-1} yr^{-1}, providing a 12% GHG savings. The calculator demonstrates how cropping systems and management choices affect greenhouse gas emissions in field crops.

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Agriculture is responsible for about 10% of total greenhouse gas emissions globally (IPCC, 2007). In non-irrigated field crops typical of the midwestern United States, agricultural practices affect the production of greenhouse gases mainly through fossil fuel use, nitrogen fertilizer application, and soil disturbance (Robertson et al., 2000; Johnson et al., 2007). Fossil fuel used in farm equipment contributes carbon dioxide (CO_2) to the atmosphere directly. Nitrogen fertilizer use contributes CO_2 during its manufacture, when natural gas is combined with atmospheric N_2 to yield ammonia and CO_2. Following application, nitrogen fertilizer also stimulates soil bacteria to emit nitrous oxide (N_2O), a greenhouse gas 300 times more potent than CO_2. Soil disturbance, in the form of tillage, stimulates microbes to oxidize soil organic matter to CO_2, although when soil disturbance is avoided, as in no-till, or when crop residue inputs exceed microbial decomposition rates, carbon (C) can be sequestered rather than oxidized.

At present, U.S. growers can receive carbon credits for practices and technologies that sequester carbon. Offset providers or offset aggregators sell credits on markets such as the Chicago Climate Exchange, earned through greenhouse gas reduction projects that include conservation tillage (Chicago Climate Exchange, 2009b), grassland establishment (Chicago Climate Exchange, 2009a), and in animal agriculture through methane capture and destruction (Chicago Climate Exchange, 2009c).

There are several soil carbon–based calculators that can be used as sophisticated decision-support tools for documenting soil carbon change, including the Voluntary Reporting of Greenhouse Gases-CarbOn Management Tool (COMET-VR; USDA, 2009), the Carbon OnLine Estimator (COLE; USDA Forest Service 2009), and the Carbon Offset Credit Payment Calculator (Illinois Conservation and Climate Initiative, 2009). Although sophisticated and detailed, these calculators lack the input simplicity and accessibility important for education and extension purposes. Students, producers, educators, offset aggregators, and other stakeholders require calculators that are easy to use and that place soil carbon credits in the context of other major sources of farmland greenhouse gas impacts, including N_2O production, fertilizer, and fuel use. For this reason we developed the Farming Systems Greenhouse Gas Emissions (FSGGE) calculator, based on the SOCRATES model for soil carbon change (Grace et al. 2006) and on Intergovernmental Panel on Climate Change (IPCC) greenhouse gas inventory methods for other greenhouse gas sources.

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Abbreviations: BD, bulk density; CEC, cation exchange capacity; COLE, Carbon OnLine Estimator; COMET-VR, Voluntary Reporting of Greenhouse Gases-CarbOn Management Tool; EF, emission factor; FSGGE, Farmland Systems Greenhouse Gas Calculator; GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; NASS, National Agricultural Statistics Service; NWS, National Weather Service; NRCS, Natural Resources Conservation Service; SOCRATES, Soil Organic Carbon Reserves And Transformations in EcoSystems; USDA, United States Department of Agriculture.

The FSGGE calculator is designed to provide users a general understanding of how different management practices might be adjusted to minimize the greenhouse gas impact of field crops and to maximize opportunities to participate in emerging greenhouse gas markets. We include major grain crops (corn, soybean, wheat), a perennial cellulosic biofuel crop (switchgrass, *Panicum virgatum* L.), alfalfa (*Medicago sativa* L.), and corn silage. Default weather, soil, and crop parameters are determined on the basis of location in the United States, and input parameters can be adjusted to make results appropriate for temperate region soils worldwide.

Our objective in this article is to describe the FSGGE calculator and demonstrate its teaching utility under different management scenarios.

Methods

Farming Systems Greenhouse Gas Calculator

The user enters the FSGGE calculator via an introductory map screen (Fig. 1; http://lter.kbs.msu.edu/ghgcalculator/; verified 7 June 2010) that allows a U.S. county to be selected for a baseline scenario. Clicking on the county of interest takes the user to the input/output window (Fig. 2). In this window, options are provided for different crops, yields, tillage practices, and rates of nitrogen fertilizer application. Crop choices include corn, soybean, winter wheat, switchgrass, corn silage, and alfalfa. Tillage practices are conventional, reduced tillage, and no-till. Crop yields are based on county-level averages (rather than simulated) in order to simplify model input requirements and provide realistic scenarios. Default values for crop nitrogen fertilizer rates are also provided based on mean rates for the North Central Region (USDA-ERS 2008), except for switchgrass, which is based on Schmer et al. (2008). For each scenario, years may be added to the rotation, each with a different crop, yield, tillage, and nitrogen rate. Multiple scenarios may be run for comparisons of management strategies. Inputs and outputs can be expressed as imperial or metric units at the user's discretion.

Climate and soils data for the county chosen are presented near the bottom of the input/output window. Values include annual average precipitation, maximum and minimum air temperature, and dominant surface soil characteristics (0- to 10-cm depth): percentage clay, bulk density (BD), and initial soil carbon. Weather data are average values for the 1972–1990 period (NOAA, 2009), and soils data are from USDA-NRCS as described in Grace et al. (2007). Climate and soil parameters may be changed to examine the effects of climate or soil changes on greenhouse gas emissions, or if the user has data for a specific location.

Greenhouse gas costs are provided for the four major sources in field crop systems: soil carbon, N_2O flux, fuel use, and fertilizer use. All units are in CO_2–equivalents ha^{-1} yr^{-1}, and calculated as described below. Soil carbon represents the difference between C returned to the soil via residues and roots from crops vs. soil C oxidized to CO_2 over the course of the year. Negative values indicate soil carbon sequestration and positive values indicate soil carbon loss. Nitrous oxide represents the amount of N_2O emitted by soil bacteria. Fuel represents the amount of CO_2 produced by farm equipment during field operations. Fertilizer is the amount of CO_2 produced during manufacture of the nitrogen fertilizer applied. For each year in the rotation, numerical results are placed to the right of the input table and are summarized in graphical form above the input table, one figure per scenario (Fig. 3). Different scenarios are placed side-by-side in the same window, with graphical results presented as adjacent bar graphs at the top of the screen. Each is labeled with the difference between the annual average total for that scenario and the base scenario to the left, with positive numbers colored red because they represent greater GHG fluxes to the atmosphere as a result of the management changes in that scenario relative to the base scenario. In contrast, negative numbers are green to represent lower GHG fluxes resulting from the management changes in the proposed scenario relative to the base scenario.

Flux Calculations

To calculate soil carbon change under different crop–soil–climate–management combinations we use the SOCRATES (Soil Organic Carbon Reserves And Transformations in EcoSystems) soil carbon model (Grace et al., 2006). SOCRATES is a process-based model that uses relatively simple inputs (mean annual precipitation, temperature, CEC, BD, and clay content) to calculate organic C accumulation in ecosystems (Grace et al., 2006). Soil carbon change is the difference between mineralization of soil organic matter to CO_2 for the year and the amount of carbon returned in crop residues. The model takes into account carbon that leaves the field at harvest and differential decomposition of recalcitrant and labile fractions of both plant and soil organic matter (Grace et al., 2006).

We calculate N_2O flux from soil using IPCC Tier 1 guidelines (IPCC, 2006). Where nitrogen fertilizer is applied, 1.25% of fertilizer nitrogen is presumed to be emitted as N_2O–N. This represents both the direct (1%) and indirect or off-site (0.25%) emission rate. To convert to CO_2–equivalents, the N_2O emitted is multiplied by the 100-year time horizon greenhouse warming potential for N_2O (IPCC, 2006). The overall formula is calculated as follows using Eq. [1]:

$$\mathrm{N_2O\ (kg\ CO_2e\ ha^{-1}\ yr^{-1})} = \mathrm{EF} \times (\mathrm{N_{fert}} + \mathrm{N_{res}}) \times (44\ \mathrm{kg\ N_2O} \div 28\ \mathrm{kg\ N}) \times (298\ \mathrm{kg\ CO_2e} \div 1\ \mathrm{kg\ N_2O}) \quad [1]$$

where EF = N_2O emission factor (1.25% or 0.0125); N_{fert} = nitrogen fertilizer in kg N ha^{-1} yr^{-1}; and N_{res} = nitrogen in above- and belowground residues in kg N ha^{-1} yr^{-1}. For unfertilized legumes, N_2O is calculated as follows using Eq. [2]:

$$\mathrm{N_2O\ (kg\ CO_2e\ ha^{-1}\ yr^{-1})} = \mathrm{EF} \times \mathrm{N_{res}} \times (44\ \mathrm{kg\ N_2O} \div 28\ \mathrm{kg\ N}) \times (298\ \mathrm{kg\ CO_2e} \div 1\ \mathrm{kg\ N_2O}) \quad [2]$$

where EF = N_2O emission factor (1.25% or 0.0125) and N_{res} = nitrogen above- and belowground residues in kg N ha^{-1} yr^{-1}.

Fuel use is calculated based on 47, 33, and 26 liters of diesel fuel per hectare for conventional, reduced tillage, and no-till, respectively, based on the number of tractor passes for each level of tillage. Fertilizer manufacture and transport contributes 1.436 moles of CO_2–C per mole of fertilizer nitrogen applied or 4.51 kg CO_2 kg N^{-1} (Robertson et al., 2000). All results are expressed in Mg CO_2–equivalents per acre or hectare, depending on whether the user has chosen metric or imperial units.

Fig. 1. Map screen with clickable map of the United States. The user clicks on a county to launch an analysis, which then displays the input/output window.

Fig. 2. Input/output window. The user enters crop, yield, tillage, and nitrogen fertilizer data that are then used by the calculator to compute net soil carbon flux, N_2O produced by soil microbes from fertilizer and crop residue nitrogen, CO_2 produced by the combustion of diesel in field equipment, and CO_2 produced during nitrogen fertilizer manufacture. Note: "MT" is used in the figure to mean "metric tons"; in text "Mg" was used due to the journal's SI unit requirement. 1 Mg = 1 MT.

Table 1. Calculator output for Scenario 1, corn–soy–wheat rotation with conventional tillage.

Inputs					Outputs				
					CO_2–equivalents				
Year	Crop	Yield	Tillage	N fertilizer	Soil	N_2O	Fuel	Fertilizer	Total
		Mg ha^{-1}		kg ha^{-1}	Mg ha^{-1} yr^{-1}				
1	corn	9.42	conventional	101	0.08	0.99	0.13	0.05	1.24
2	soy	4.03	conventional	0	0.37	0.38	0.13	0	0.88
3	wheat	3	conventional	56	0.5	0.55	0.13	0.03	1.19
Annual average					0.31	0.64	0.13	0.02	1.11

Table 2. Calculator output for Scenario 2, corn–soy–wheat rotation fertilized with no-till management.

Inputs					Outputs				
					CO_2–equivalents				
Year	Crop	Yield	Tillage	N fertilizer	Soil	N_2O	Fuel	Fertilizer	Total
		Mg ha^{-1}		kg ha^{-1}	Mg ha^{-1} yr^{-1}				
1	corn	9.42	no-till	101	−0.77	0.99	0.07	0.05	0.34
2	soy	4.03	no-till	0	−0.22	0.38	0.07	0	0.23
3	wheat	3	no-till	56	0.04	0.55	0.07	0.03	0.68
Annual average					−0.32	0.64	0.07	0.02	0.42

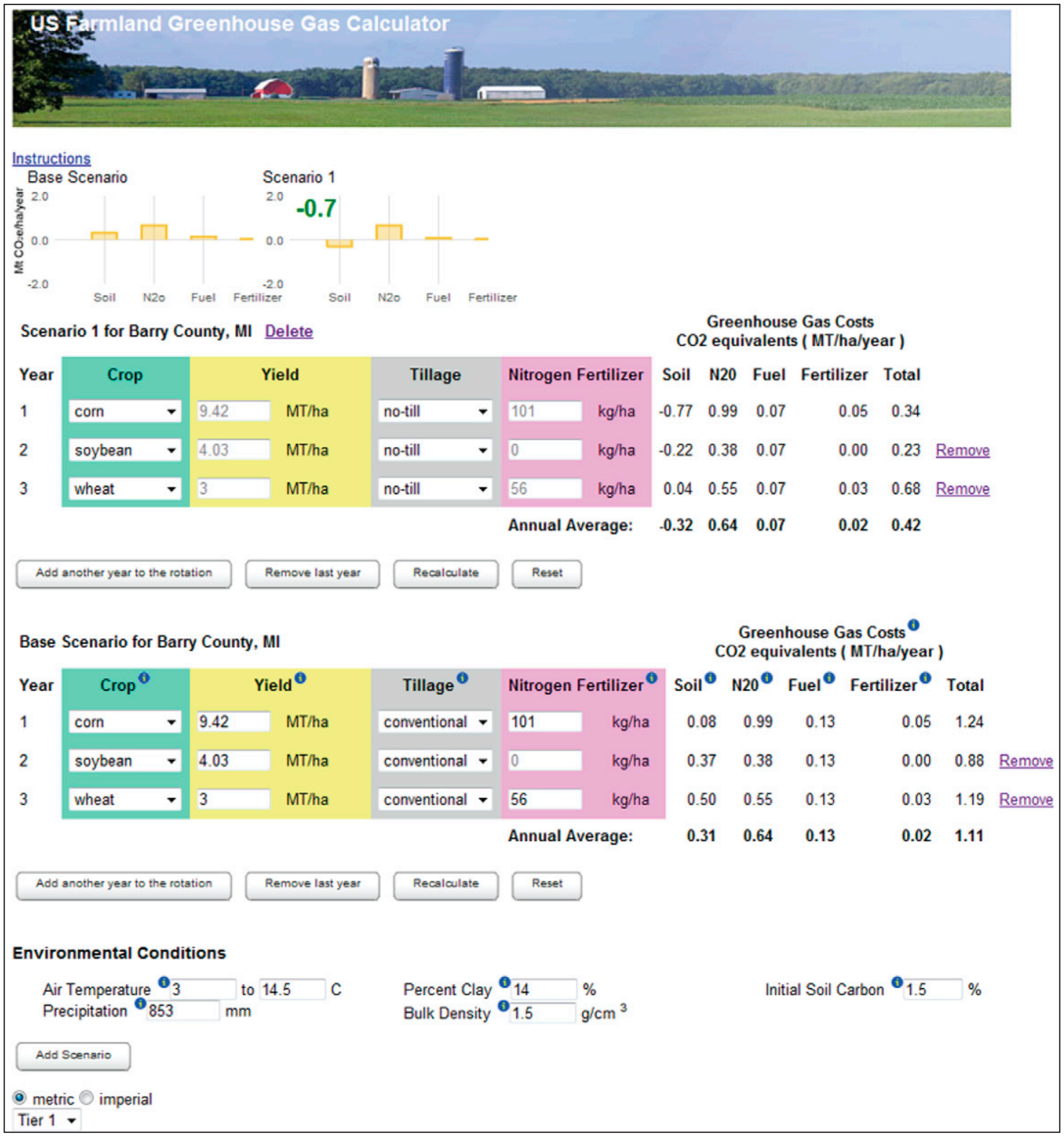

Fig. 3. Input/output window with results comparing corn–soy–wheat rotations with conventional and no-till soil management. Note: "MT" is used in the figure to mean "metric tons"; in text "Mg" was used due to the journal's SI unit requirement. 1 Mg = 1 MT.

Table 3. Calculator output for Scenario 3, continuous corn fertilized at 101 kg N ha⁻¹.

Inputs					Outputs				
					CO_2–equivalents				
Year	Crop	Yield	Tillage	N fertilizer	Soil	N_2O	Fuel	Fertilizer	Total
		Mg ha⁻¹		kg ha⁻¹	Mg ha⁻¹ yr⁻¹				
1	corn	9.42	conventional	101	0.08	0.99	0.13	0.05	1.24
2	corn	9.42	conventional	101	0.09	0.99	0.13	0.05	1.26
3	corn	9.42	conventional	101	0.09	0.99	0.13	0.05	1.25
Annual average					0.09	0.99	0.13	0.05	1.25

Table 4. Calculator output for Scenario 4, continuous corn fertilized at 134 kg N ha⁻¹.

Inputs					Outputs				
					CO_2–equivalents				
Year	Crop	Yield	Tillage	N fertilizer	Soil	N_2O	Fuel	Fertilizer	Total
		Mg ha^{-1}		kg ha^{-1}	Mg ha^{-1} yr^{-1}				
1	corn	9.42	conventional	134	0.08	1.15	0.13	0.06	1.41
2	corn	9.42	conventional	134	0.09	1.15	0.13	0.06	1.43
3	corn	9.42	conventional	134	0.09	1.15	0.13	0.06	1.42
Annual average					0.09	1.15	0.13	0.06	1.42

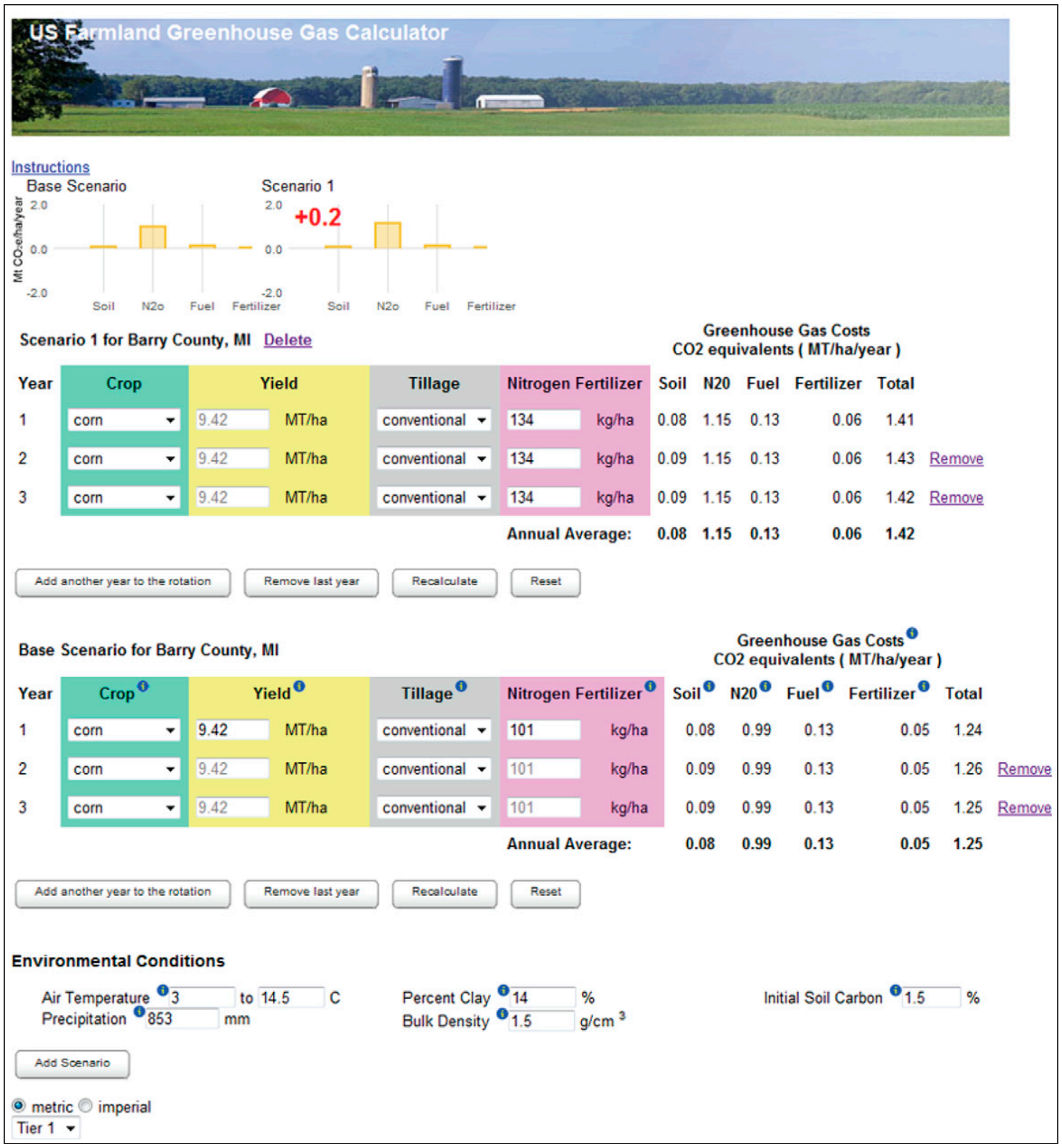

Fig. 4. Input/output window with results comparing continuous corn fertilized at 101 and 134 kg N ha⁻¹. Note: "MT" is used in the figure to mean "metric tons"; in text "Mg" was used due to the journal's SI unit requirement. 1 Mg = 1 MT.

For demonstration purposes we present the results of four different scenarios below: (1) three years of corn–soybean–wheat rotation with conventional tillage, (2) three years of corn–soybean–wheat rotation with no-till, (3) three years of continuous corn fertilized at 101 kg N ha^{-1} with conventional tillage, and (4) three years of continuous corn fertilized at 134 kg N ha^{-1} yr^{-1} with conventional tillage. For all four scenarios we set yields for corn, soybean, and wheat to 9.42, 4.03, and 3 Mg ha^{-1}, respectively. For Scenario 1 and 2, N fertilizer rates were 101, 0, and 56 kg N ha^{-1} yr^{-1} for corn, soybean, and wheat, respectively. For Scenario 3, the nitrogen fertilizer rate for corn remained at 101 kg N ha^{-1} yr^{-1} and for Scenario 4 the N fertilizer rate was increased to 134 kg N ha^{-1} yr^{-1}. All scenarios were run with environmental data from Barry County, MI.

Results and Discussion

Both corn–soybean–wheat rotations had lower greenhouse gas costs than either of the continuous corn scenarios. Corn grown in Year 1 had the greatest GHG cost of the three crops because it had the highest N fertilizer rate applied, which resulted in higher soil N_2O emissions and CO_2 contributions from fertilizer manufacture (Table 1 and 2; Fig. 3). Growing soybean in Year 2 provided GHG savings because lack of fertilizer inputs resulted in no CO_2 contributions from fertilizer manufacture, and there was a smaller N_2O flux coming from soils (Table 1 and 2; Fig. 3). Wheat as the crop in Year 3 provided additional GHG savings for the rotation with lower rates of nitrogen application, resulting in lower soil N_2O emissions and lower contributions from fertilizer manufacture (Table 1 and 2; Fig. 3). The average annual emission for the corn–soybean–wheat rotation was 1.11 Mg CO_2 equivalents ha^{-1} yr^{-1} for conventional tillage and 0.42 Mg CO_2 equivalents ha^{-1} yr^{-1} for the no-till system. No-till provided greater than 50% savings in greenhouse gas emissions due to carbon offset savings from carbon sequestration.

Continuous corn fertilized at 101 and 134 kg N ha^{-1} yr^{-1} was also examined because these two N rates represent the range of N rates where the economic return on N applications is maximized (Sawyer et al., 2006). Fertilizing continuous corn at a rate of 101 kg N ha^{-1} yr^{-1} resulted in an annual average GHG emission of 1.25 Mg CO_2 equivalents ha^{-1} yr^{-1} (Table 3; Fig. 4). There were no differences between years for the soil, N_2O, fuel, or fertilizer manufacture outputs because crop, yield, nitrogen fertilization rate, and tillage all remained the same (Table 3; Fig. 4). Continuous corn fertilized at 134 kg N ha^{-1} yr^{-1} had the greatest GHG cost of all the scenarios presented, at 1.42 Mg CO_2 equivalents ha^{-1} yr^{-1} (Table 4; Fig. 4). As was the case for continuous corn fertilized at 101 kg N ha^{-1} yr^{-1}, none of the outputs changed between years. The increase in nitrogen fertilizer rate resulted in increases in the N_2O flux coming from the soil and a slight increase in CO_2 released during fertilizer manufacture when compared with the results for continuous corn fertilized at 101 kg N ha^{-1} yr^{-1} (Table 3 and 4; Fig. 4).

Results from the FSGGE calculator suggest several ways to reduce greenhouse gases from U.S. farmland. Of the scenarios presented¸ the more complex crop rotations produced the lowest greenhouse gas emissions. Comparing continuous corn grown at 134 and 101 kg N ha^{-1}, we saw a GHG savings of 12% simply by using less nitrogen (Table 3 and 4; Fig. 4). For three of the scenarios chosen, greenhouse gas cost savings were predominantly due to reductions in the amount of nitrogen fertilizer applied during the 3-year periods that we considered. No-till provides additional GHG savings for all management scenarios because of carbon offsets provided by soil carbon storage.

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