U.S. DEPARTMENT OF AGRICULTURE

CSU Management Practice Analysis for Agriculture Crops Used as Biofuel Feedstocks

Stephen M. Ogle, Ames F. Fowler and Alisa Keyser

Natural Resource Ecology Laboratory, Colorado State University (CSU)

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Introduction

This report provides a summary of the methods that were used in an analysis of feedstock production for sustainable biofuels that was conducted by Colorado State University (CSU). For each biofuel feedstock—corn, soybean and sorghum—CSU estimated greenhouse gas (GHG) emissions for a baseline scenario developed from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks (US GHG Inventory)*, and scenarios associated with adoption of climate smart practices. The analysis includes adoption of single climate smart practices as well as stacking multiple practices for a total of 23 scenarios for each feedstock.

Baseline

The baseline scenario used in this analysis utilizes the model, methods and data inputs used in the US GHG Inventory. The DayCent model is used to simulate baselines for soil organic carbon stock (SOC) changes and soil nitrous oxide (N_2O) emissions for U.S. agricultural lands with corn, soybean and sorghum production using the U.S. Department of Agriculture's 2017 National Resources Inventory (NRI) (USDA-NRCS 2020). The model is initialized in three steps. In the first step, the model is run to a steady state condition (e.g., equilibrium) under native vegetation, historical climate data and the soil characteristics for the NRI survey locations. In the second step, the model simulates the expansion of agriculture following European settlement to the beginning of the NRI survey in 1979. This step captures the loss of soil C and N following conversion of native vegetation to cropland and includes varying time periods of land conversion depending on historical settlement patterns starting in the 1700s. In the third step, the model simulates the cropping histories in the NRI survey from 1979 to 2017, which have been extended through 2020 using the USDA-NASS Crop Data Layer (CDL) (USDA-NASS 2021).

CSU simulated every NRI survey location with at least one of the biofuel crops (corn, soybean, and sorghum) in the most recent five years of available crop history (2016-2020).

The baseline projection replicated this five-year rotation for 30 years. CSU excluded NRI survey locations with recent grass-to-cropland conversions in the previous 20 years (2000 or later) because land use change has much larger effects on trends in SOC stocks and, to a lesser extent, soil N_2O emissions, compared to changes in management practices. By excluding these points CSU was able to ensure that GHG emissions were driven by management effects rather than the effects of land use change. In addition, lands enrolled in the Conservation Reserve Program were excluded from the analysis since they are not actively used for crop production.

The baseline scenario uses the same cropland management data that are used in the US GHG Inventory. These management data capture the current management practices in US farmland, which includes a combination of conventional and conservation practices. Management data are drawn from several sources in addition to the NRI data. The USDA-NRCS Conservation Effects and Assessment Project (CEAP) provided spatial data on mineral fertilization, manure amendments, cover crop usage, as well as planting and harvest dates (USDA-NRCS 2022; USDA-NRCS 2018; USDA-NRCS 2012)[1]. Fertilizer data were also used from Agricultural Resource Management Surveys (ARMS) at the state scale (USDA-ERS 2020). Tillage and cover crop data were also informed by the OpTIS Data Product[2], which is derived from remote sensing imagery (Hagen et al. 2020). Cover crop data are also utilized from the USDA Census of Agriculture at the state scale (USDA-NASS 2012, 2017). See the US GHG Inventory report (US-EPA 2024) for more information about the historical management data that were used to create the baseline.

CSU made several assumptions in the baseline that are listed below.

- Cover crops were not planted before or after hay or pasture crops except when present on the first year of the baseline sequence where they were carried through the 30-year projection, and the fifth year could have been hay or pasture.
- Tillage was classified at the NRI point scale as a management system based on the US GHG Inventory data that is statistically imputed based on OpTIS and CEAP survey data using machine learning methods (US-EPA 2024). All crops in a rotation received the same tillage practice (i.e., no-till system had no-till in each year). Consequently, there is no intermittent tillage in the baseline. The exception was hay and pasture in rotation with annual crops, in which hay and pasture were not tilled in years following establishment.
- Fertilizer rates were based on CEAP and ARMS data as statistically imputed for 2016-2020 in the US GHG Inventory (US-EPA 2024). The CEAP data were collected

[1] CEAP surveys are conducted at a subsample of NRI locations and collect detailed information on farm management practices.

[2] OpTIS data on tillage practices provided by Regrow Agriculture, Inc.

through surveys conducted on a sub-sample of the NRI point locations and were used to infer rates on individual fields. The ARMS data provided state-level fertilizer rates over two decades that were used to infer trends over time. Fertilizer sales data were used to constrain the total application of mineral fertilizer at the state scale (US-EPA 2024, Brakebill and Gronberg 2017, AAPFCO 2013 – 2022). All fertilizer was assumed to be 80%/20% ammonium/nitrate. There were insufficient data to inform the timing when the last US GHG Inventory was compiled (US-EPA 2024). All fertilizer was applied at the time of planting except for corn and grass hay which received split applications. Corn received 25% at planting and 75% 40 days after planting, while grass hay received 50% at planting and 50% in June.

Using the US GHG Inventory baseline for the forward projection captures the current mixture of conventional and conservation practices. This approach limits over-estimation of SOC gains in the management scenarios, which could occur if we assumed that all lands were under conventional management practices.

The three biofuel feedstocks (corn, soybeans, sorghum) were categorized into ten rotation types based on the five-year crop rotation sequences from the NRI survey (2016-2020) in order to differentiate generalized rotation effects on SOC and N_2O emissions (Table 1). The influence of changing practices in each rotation was simulated at the NRI survey points and then aggregated to Major Land Resource Areas (MLRA) for assessing sustainability metrics associated with the SAF tax credit program. Rotation types include:

- Continuous corn (CC) with corn in the last five years of the NRI history;
- Continuous soybeans (SS) with soybeans in the last five years of the NRI history;
- Corn and soybeans (CS) with any combination of corn and soybeans in the last five years of the NRI history;
- Corn and hay/pasture (CHP) with at least one year of corn and two years of hay or pasture (grass, alfalfa, etc.) in the last five years of the NRI history;
- Soybeans and hay/pasture (SHP) with at least one year of soybeans and two years of hay or pasture (grass hay, alfalfa, etc.) in the last five years of the NRI history;
- Corn, soybeans and hay/pasture (CSHP) with at least one year of soybeans, one year of corn, and two years of hay or pasture (grass hay, alfalfa, etc.) in the last five years of the NRI history;
- Corn and other crops in rotation (CO) with a year or more of corn in the last five years of the NRI history;
- Soybeans and other crops in rotation (SO) with a year or more of soybeans in the last five years of the NRI history;
- Continuous Sorghum (SGSG) with sorghum in the last five years of the NRI history;

- Sorghum and other crops in rotation (SGO) with sorghum in at least one of the last five years of the NRI history.

Table 1. Crop rotations in the analysis where crop abbreviations are corn (C), soybeans (S), sorghum (SG), hay/pasture (HP), and other crops (O).

Rotation	Abbreviation
Corn-soybeans	CS
Continuous corn	CC
Continuous soybeans	SS
Corn and hay/pasture	CHP
Soybeans and hay/pasture	CHP
Corn-soybeans and hay/pasture	CSHP
Corn and other crops	CO
Soybeans and other crops	SO
Continuous Sorghum	SG
Sorghum and other crops	SGO

Some rotations are non-exclusive, so the same NRI survey point may be evaluated for multiple crop rotation types. For example, points with both soybeans and sorghum in rotation are defined as both Soybean Other and Sorghum Other, and that NRI survey point would be used for assessing scenario effects for both rotation types[3].

Weather data: CSU replicated the most recent eight years of weather data from PRISM (PRISM Climate Group 2022); this accounts for the timing of leap years and provides an offset with the crop rotation length to reduce crop year interactions that could produce artifacts in the projection. PRISM provide daily weather data on a 4km grid with daily minimum and maximum temperatures, in addition to daily precipitation, which are used in the DayCent model simulations. The time span was limited to 8 years to represent recent climatic conditions since the climate has been changing (IPCC 2023). CSU did not simulate future climate effects, which is still challenging to forecast for climate modelers with high uncertainty based on variation in projections from global circulation models. A future improvement is to incorporate climate change projections in the framework to better address the interaction among crop choices, management and future weather patterns.

[3] This application is not double-counting effects, but rather assessing average impacts for individual crops that may be used for SAF. Total changes are not assessed in this analysis, such as the total amount of SOC stock change or total N_2O emission reductions, in which double-counting would be problematic.

Soils data*:* CSU used the soils data from the US GHG Inventory. Soil profiles and associated edaphic characteristics are from the NRCS gSSURGO database (Soil Survey Staff 2020). These data include bulk density, pH, and soil texture, which are needed as input for the DayCent model simulations.

Single Practice Scenarios

Practice scenarios were simulated with the DayCent model to evaluate the impact of practice change with including cover crop adoption, tillage, and nutrient management. All scenarios have the same crop sequences, management events and timing, as well as weather and soils data as the baseline, except for specific management interventions detailed below. The climate smart practices that were evaluated include practices associated with cover crops, tillage type, and nutrient management (Table 2).

Table 2. Single practice scenarios in the analysis.

Practice Type	Count	Scenario	Abbreviation
Cover Crop	1	Winter rye cover crop	ccR
Tillage[4]	2	Reduced tillage	RT
	3	No-tillage with intermittent reduced tillage	NTRT
	4	No-tillage with intermittent intensive tillage	NTIT
Nutrient management	5	Nitrification inhibitors	NI
	6	Reduced fertilizer rates by 10% and split applications	RF10split

Descriptions of the assumptions used to model each of climate smart practice scenarios are provided in detail below.

Cover crop scenario (ccR):

- Cover crops were simulated as winter rye
- Cover crops were simulated every year except in years that have small winter grains (e.g., winter wheat) or perennial hay or pasture.
- Cover crop termination was simulated as a chemical/herbicide termination without biomass removal and soil disturbance. Tillage termination was evaluated in a

[4] Full tillage is defined as multiple tillage operations every year, including significant soil inversion (e.g., plowing, deep disking) and low surface residue coverage. No-till is defined as not disturbing the soil except through the use of fertilizer and seed drills and where no-till is applied to all crops in the rotation. The remainder of the cultivated area is classified as reduced tillage, including mulch tillage, strip tillage and ridge tillage (CTIC 2004).

previous study and resulted in decreases or no change in SOC stocks (Ogle et al., 2023) and thus was not included in this analysis.
- Planting and harvest dates were based on US GHG Inventory data for cover crops (US-EPA 2024).
- Cover crops did not receive any fertilizer (US-EPA 2024).

Tillage scenarios*:*

CSU simulated scenarios with conversion to continuous reduced tillage (RT), no-till with intermittent reduced tillage (NTRT) and no-till with intermittent intensive tillage[5] (NTIT) as noted below.

- Reduced tillage (RT): All NRI survey points with intensive tillage (IT) in the baseline were converted to RT.
- Intermittent no-till with reduced till (NTRT): All NRI points in the baseline were converted to NT with one year of RT in the fifth year. If the fifth year occurred on a hay/pasture crop, the reduced tillage event was moved to the next non-perennial crop in the rotation.
- Intermittent no-till with intensive till (NTIT): All NRI points in the baseline were converted to NT with one year of intensive tillage in the fifth year. If the fifth year occurred on a hay/pasture crop, the intensive tillage event was moved to the next non-perennial (i.e., annual) crop in the rotation because tillage was assumed to not occur after the first year of planting hay or pasture until an annual crop is planted again.

Nutrient management scenarios:

CSU simulated nutrient management scenarios by applying enhanced efficiency fertilizers and split application timing paired with decreased fertilizer application rates, as described below. Note that for NRI points where only manure was applied, there were no changes in nutrient management applied. For NRI survey locations where both manure and synthetic fertilizer are applied, only the synthetic fertilizer applications were adjusted (either through application of nitrification inhibitors or changes in rate and timing in the case of split application).

- Nitrification inhibitor (NI): All fertilizer was applied with a nitrification inhibitor. NI fertilizer was assumed to be 80% ammonium and 20% nitrate.

[5] Farmers are incorporating occasional tillage in no-till systems to address problems with weed resistance (Lu et al. 2022), and possible other issues such as compaction of the soil. The specific tillage implements can vary so both a less intensive reduced tillage implement and more intensive full tillage implement were simulated to capture the variation.

- Split application with 10% reduced fertilizer (RF10 split): All fertilizer rates were reduced by 10%, and their application was split with 25% applied at the time of planting and 75% applied 5 weeks later for corn. Note that the split fertilizer application was not changed for hay. A 10% reduction in fertilizer rate was simulated because there is little to no yield loss with this level of fertilizer reduction.

Stacked practices scenario definition and assumptions

CSU evaluated the full set of stacked practices by simulating the adoption of two and three practices by combining cover crops, tillage, and nutrient management types. Examples of two stacked practices include the adoption of cover crops (ccR) and no-till with reduced till (NTRT) for the NTRT_ccR scenario, and nitrification inhibitors (NI) and cover crops (ccR) for the NI_ccR scenario. Three stacked practices include scenarios such as combining cover crops, no-till with reduced till, and nitrification inhibitor fertilizer applications, as NTRT_NI_ccR. The complete list of stacked practices with two and three combinations are listed below. There are no additional assumptions or modifications from the single practice definitions.

Two Practices

1. NI_ccR
2. RT_ccR
3. RT_NI
4. NTRT_ccR
5. NTRT_NI
6. NTIT_ccR
7. NTIT_NI
8. RF10split_ccR
9. RF10split_RT
10. RF10split_NTRT
11. RF10split_NTIT

Three Practices

12. RT_NI_ccR
13. NTRT_NI_ccR
14. NTIT_NI_ccR
15. RF10split_ccR_RT
16. RF10split_ccR_NTIT
17. RF10split_ccR_NTRT

Aggregation and Outputs

For each rotation type and scenario, simulated values and supporting scenario data are aggregated to the MLRA level using NRI survey area weights. The results were aggregated to the MLRA to maintain regional variability and statistical relevance while also adhering to data disclosure restrictions. Outputs are aggregated by rotation (across all years) or by rotation and crop type (across years with the crop of interest) for each scenario. The reported outputs include:

1) Across all rotations by MLRA:

- Percentage of the area each crop rotation relative to the total simulated area in each MLRA

2) Within each rotation by MLRA and scenario:

- Average annual area proportion of the crop and any "Other" crop/silage
- Average annual area proportion (0:1) with a cover crop by year
- Average annual area proportion with a cover crop in any year
- Average number of years with a cover crop
- Average annual delta SOC
- Average annual area proportion of full tillage (IT)
- Average annual area proportion of reduced tillage (RT)
- Average annual area proportion of no-tillage (NT)
- Average annual area proportion receiving manure[6]
- Average annual area proportion receiving manure in any year
- Average number of years receiving manure

3) Within each rotation and crop by MLRA and scenario:

- Average annual direct N_2O flux in kg/ha
- Average annual indirect N_2O flux in kg/ha
- Average annual C in grain (yield) in gC/m^2
- Average annual aboveground biomass in gC/m^2

[6] Manure amendments do occur in the baseline as represented in the Inventory of US Greenhouse Gas Emissions and Sinks (EPA 2024), but amendments were not changed between the baseline and practice scenarios. Therefore, NRI survey points that had been amended in the baseline were also amended in the scenarios during the same years in the rotation sequences.

- Average annual belowground biomass in gC/m^2
- Average annual total biomass in gC/m^2
- The proportion of the total nitrogen available applied as fertilizer
- The proportion of the crop's total biomass to the rotation's total biomass
- Average annual total nitrogen sources in $g\ N/m^2$
- Average annual total N fertilizer in gN/m^2
- Average annual litter N in gN/m^2
- Average annual total N in manure for NRI survey points receiving manure in gN/m^2
- Average annual total C in manure for NRI survey points receiving manure in gC/m^2
- Average annual total N in manure across all NRI survey points in gN/m^2
- Average annual total C in manure across all NRI survey points in gC/m^2

Modeling framework

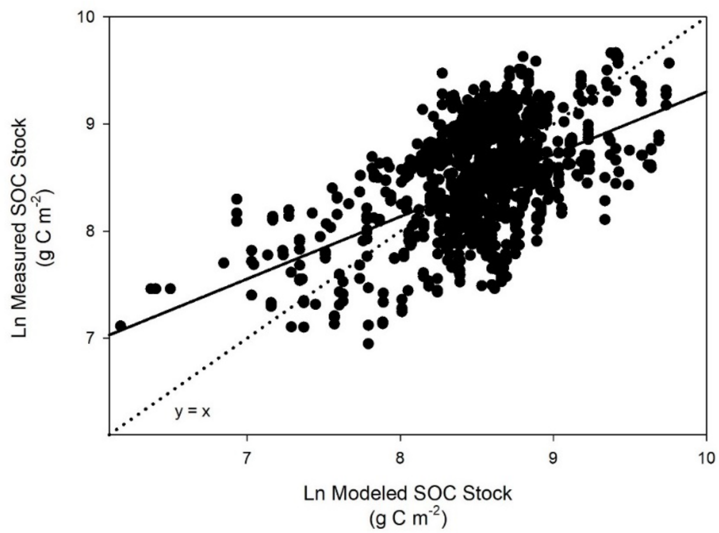
The DayCent ecosystem model (Parton et al. 1998, 2001; Del Grosso et al. 2001, 2011, 2022) has been used in this analysis. DayCent simulates biogeochemical carbon and nitrogen cycles between the atmosphere, vegetation, and soil, using a broad suite of environmental drivers. These drivers include soil characteristics, weather patterns, crop and forage characteristics, and management practices. The DayCent model utilizes the soil carbon modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994), but has been refined to simulate dynamics at a daily time-step. Carbon and nitrogen dynamics are linked in plant-soil systems through biogeochemical processes of microbial decomposition and plant production. Nutrient supply is a function of external nutrient additions as well as litter and soil organic matter (SOM) decomposition rates. Increasing decomposition can lead to a reduction in soil organic carbon stocks due to microbial decomposition, and greater N_2O emissions by enhancing mineral nitrogen availability in soils. DayCent has been tested and applied in many studies, but the most recent calibration associated with this version utilized Bayesian methods for soil C and N_2O emissions (US-EPA 2024; Gurung et al. 2020, 2021).

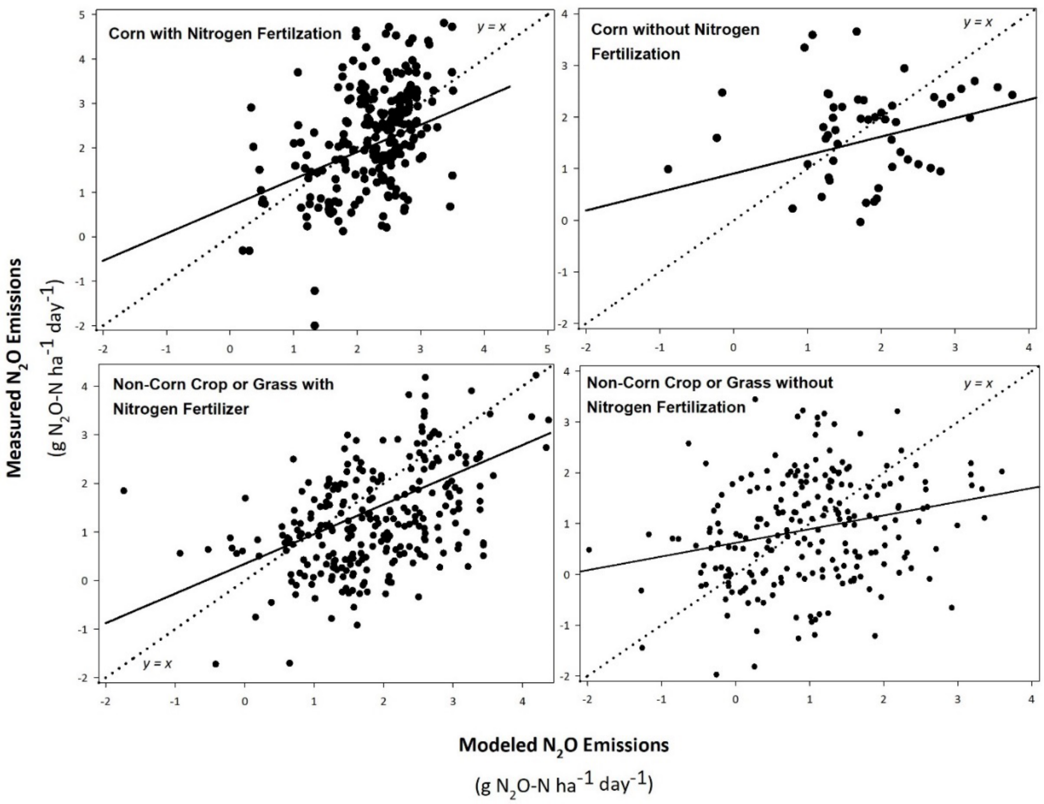
DayCent is used to approximate initial values of C and N in the plant and soil system for the biofuels analysis using the US GHG Inventory framework and NRI survey data. First, the DayCent model is used to establish the initial conditions and carbon stocks for 1979, which is the first year of the NRI survey. Second, DayCent is used to simulate land-use and management histories recorded in the 2017 NRI histories (USDA-NRCS 2020) extended through 2020 using USDA-NASS Crop Data Layer (CDL) (USDA-NASS 2021). Using these histories to establish initial conditions ensures that forward projection for the sustainable biofuels analysis is consistent with the US GHG Inventory for agricultural lands (US-EPA 2024). The forward simulations for the 30-year projection are described in sections above using the last 5 years of the NRI histories, which are replicated 6 times in this analysis.

Evaluating uncertainty is an integral part of the analysis and key uncertainties include uncertainty in the management activity data inputs (input uncertainty) and uncertainty in the model formulation and parameterization (model structural uncertainty) (Ogle et al. 2010; Del Grosso et al. 2010, Ogle et al. 2023). Input uncertainty is based on the six imputations underlying the management data product that combines data from the CEAP survey, ARMS, OpTIS data product, Census of Agriculture and CTIC survey data. CSU randomly selected imputations for each iteration in a Monte Carlo analysis to propagate this error.

Model structural uncertainty is the estimation error associated with model formulation and parameterization. This component is the largest source of uncertainty in this model-based analysis, accounting for more than 80 percent of the overall uncertainty in the final estimates (Ogle et al. 2010; Del Grosso et al. 2010). An empirically based procedure is applied to develop a structural uncertainty estimator from the relationship between modeled results and field measurements from agricultural experiments using linear-mixed effect modeling techniques (Ogle et al. 2007). The modeled emissions are treated as a fixed effect in the statistical models along with other covariates that are significant based on the model fit in R, such as crop type, tillage practice and fertilization rates. The resulting relationships are used to make an adjustment to modeled values to address biases due to significant mismatches between the modeled and measured values (Figure 1). Random effects are included to capture the dependence in time series and data collected from the same site, which are needed to estimate appropriate standard deviations for parameter coefficients. The resulting mixed effect model is applied in the DayCent model framework using a Monte Carlo framework with 10,000 draws for parameter values in a joint probability distribution from the linear mixed-effect model. In this step, DayCent output is adjusted for bias and a level of precision is quantified according to the statistical model relationships. See US-EPA (2024) for more information about the DayCent modeling framework.

Figure 1. Relationship between DayCent model predictions and empirical observations of soil C stocks from 1406 observations from 69 long-term experiment sites and 145 NRI soil monitoring network sites (Spencer et al. 2011), and empirical observations of N_2O emissions from 76 experimental sites with 857 observations. Appendix A includes publication references for the experiments. These figures are from US-EPA (2024).





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Appendix A: References for DayCent Model Calibration and Evaluation

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