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Methodology Report for SALUS Simulations

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Introduction

This report summarizes the methods used in an analysis of sustainable biofuel feedstock production performed by Michigan State University (MSU). For each biofuel feedstock (corn and soybeans) MSU estimated greenhouse gas (GHG) emissions for scenarios associated with the adoption of climate smart practices, including no-till, reduced tillage, winter cover crops, and nutrient management across 94 Major Land Resource Areas (MLRAs), spanning 40 states. Please note that only the results from the fall application scenarios (under corn fertilizer management) were included in the USDA FD-CIC tool. The results of the remaining scenarios were used for purposes of comparison with the DayCent simulations generated by Colorado State University. More information on those model runs can be found in the DayCent methodology report.

Model Description

The SALUS (System Approach to Land Use Sustainability) process-based crop model simulates at daily time step the interactions between soil, climate, genetics and management and their effects on crop growth and yield and on environmental outcomes (e.g. nitrate leaching, greenhouse gas emissions, soil carbon sequestration) (Basso et al., 2006, Basso and Ritchie, 2015). The model simulates different management practices, such as tillage, planting, irrigation, fertilization, harvest, and residues management. SALUS has been extensively used to evaluate soil carbon dynamics (Liu and Basso, 2020).

Model structure

The SALUS biophysical model is composed of three main structural components: i) a set of crop growth modules; ii) a soil organic matter and nutrient cycling module; iii) a soil water balance and temperature module [Basso and Ritchie, 2006, 2015]. Plant development is controlled by environmental variables (e.g., degree days, photoperiod) while carbon assimilation and dry matter production are a function of potential rates (controlled by light interception and parameters defining the variety-specific growth potential) which are then reduced according to water and/or N limitations. The soil organic matter (SOM) and nitrogen module simulates organic matter and N mineralization/immobilization from three SOM pools (active, slow and passive) which vary in their turnover rates and characteristic C/N ratios. A surface-active SOM pool associated with the surface residue pools was added to better represent conservation tillage systems. Soil C originates from fresh organic matter (FOM) sources that include non-harvested aboveground or incorporated belowground plant residues, belowground roots, and (any) organic amendments. The flow of carbon through the SOC model component is illustrated for a hypothetical soil in Figure 1. While these kinetics parameters are kept constant for each SOM pool, the different composition of the organic material entering the soil affects their decomposition and distribution into the three main SOM pools. Additional details of the model are reported by Basso and Ritchie, 2015 and Martinez-Feria and Basso, 2020.

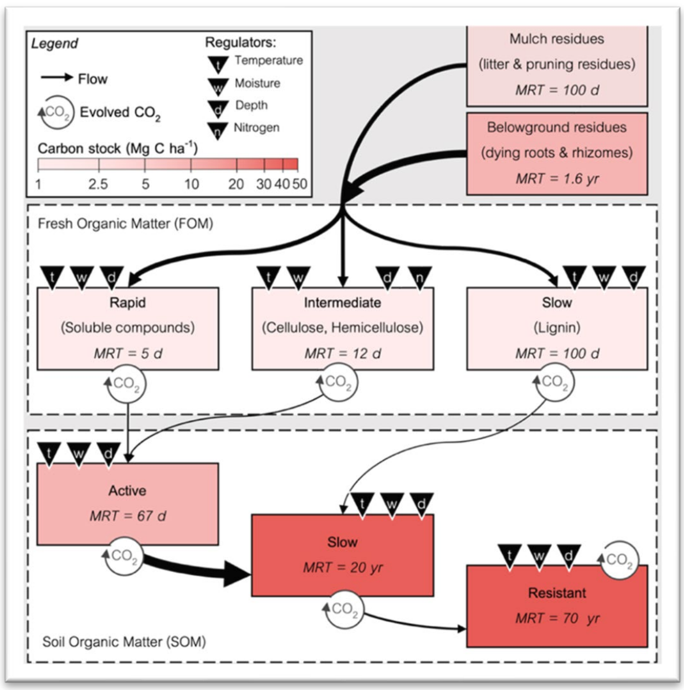

Figure 1 Schematic of the flow of C through the SALUS SOC simulation subroutine. Boxes indicate stocks, arrows depict flows. At each decomposition step, a portion of C evolves as CO_2-C. Inverse triangles show action of regulation factors on each pool. For illustration, shading in the box indicate relative size of the stock for a hypothetical soil with 100 Mg C ha^{-1} (figure from Martinez-Feria and Basso, 2020).

Model inputs

Input data required by SALUS consist of weather, soil properties, management and genetic characteristics of the crop/tree. In terms weather variables the minimum requirements are daily solar radiation, daily maximum and minimum temperature and daily precipitation. On-site measurement of soil properties is recommended where possible. Minimum soil properties are required such as texture, bulk density, and organic matter content. Soil water limits such as lower limit, field capacity and saturated hydraulic conductivity are preferable when measured in the field, even if the model is capable to estimate automatically. In terms of management the minimum information required are the type, dates, and mode of fertilizer application, tillage or irrigation event along with planting and harvest dates. Additional information required are plant density at planting and percentage of residue left on the ground after harvest.

Data Inputs

Locations

Final simulations results were provided for 94 Major Land Resource Areas (MLRAs), spanning 40 states. Thousands of locations within the MLRAs were simulated and then the results were spatially aggregated to the MLRA-level, producing a final output of average values and statistics for each of the 94 MLRAs. To accurately represent cropland within each MLRA, the simulations were conducted at a high-resolution of 4km based on the grid of the input weather data source. Locations where corn or soybean were grown in any year between 2008 and 2022 according to USDA National Agricultural Statistics Service Cropland Data Layer (NASS CDL) were extracted at the 30m spatial resolution and the total cropland area per 4km grid cell was calculated. Within the Midwest, the grid cells with small cropland amounts were excluded, with the remaining grid cells accounting for 90% of cropland in the Midwest. To limit computation time, a total of 40,000 grid cells were selected using a weighted random selection process accounting for cropland area, soil texture, and latitude (Basso et al., in review). For the MLRAs outside of the Midwest, grid cells were included if more than 10% of the cell contained cropland (i.e., at least 400 ha of cropland within the cell). A total number of 105,767 grid cells were simulated to represent the 94 MLRAs across the Midwest and Eastern United States (Figure 2). The results from the grid cells were then aggregated to the MLRA-level.

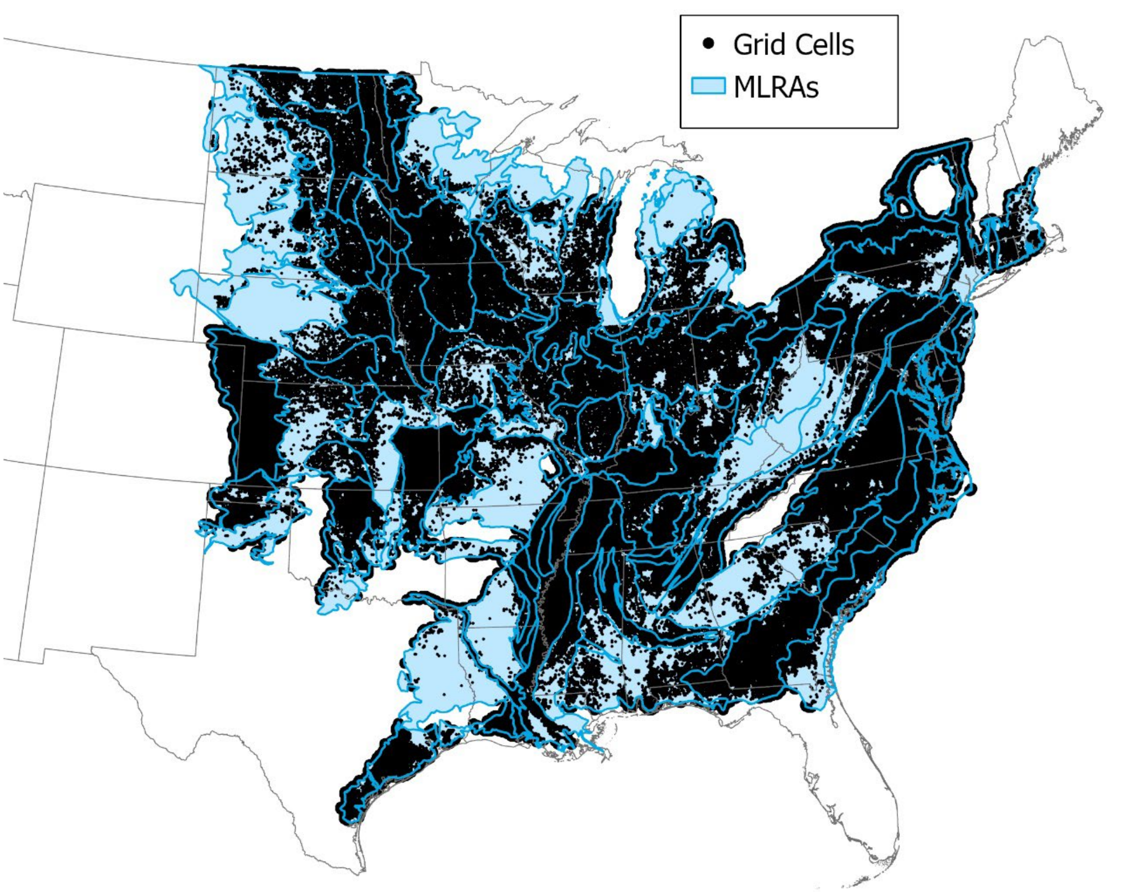

Figure 2. Grid cells where the crop model was simulated (black points) in order to represent the MLRAs (blue polygons). The high-resolution results from the grid-cells were aggregated to the MLRA-level for the final report.

Soil

Required soil input data for the simulations were downloaded from the USDA Natural Resources Conservation Service Gridded Soil Survey Geographic (gSSURGO) database at the 30m spatial resolution. The dominant soil within each grid cell was selected to represent each cell. Since gSSURGO provided multiple soil components per soil map unit, the soil component that best represented (highest percentage) of the soil map unit was selected. The soil data included bulk density, sand/silt/clay content, stone content, organic matter, calcium carbonate, and pH for each soil layer in the soil profile. From these data, the following variables were calculated: soil hospitality factor (Jones et al., 1991), organic carbon, total nitrogen, drained upper limit and lower limit (Ritchie et al., 1999), and saturated hydraulic conductivity (Suleiman et al., 2001). Where the soil data was lacking or unreasonable in soil content or the soil profile was shallower than 30 cm, the soil was excluded from the analysis.

Weather

Daily variables of maximum and minimum temperature, precipitation accumulation, and downward surface shortwave radiation were downloaded from gridMET for 1991-2020 at a spatial resolution of 4km (Abatzoglou, 2013).

Management

Planting and Harvesting Dates

Planting and harvesting dates varied for each grid cell based on USDA National Agricultural Statistics Service (NASS) state-level weekly progress reports. The progress reports were downloaded for corn and soybean for 1979 to 2022 if the year was available. Soybean planting data were available in 1980 and harvest data for corn and soybean were available starting in 1981. The progress percentage from the weekly reports were linearly interpolated to estimate dates when 50% of the state completed planting or harvesting. The dates were then predicted across the 4km grid cells using a generalized additive model based on latitude and longitude. The average planting and harvesting dates were calculated across all available years for each grid cell. These representative planting and harvesting dates were used for all corn and soybean simulations.

For scenarios with a cover crop, the cover crop was planted 7 days after the main crop's harvest and was terminated 7 days prior to the main crop's planting. The cover crop residue was left in the field.

Fertilizer Application Rates

Corn

Corn fertilizer nitrogen (N) application rates varied by state, using the values from USDA Agricultural Resource Management Survey (ARMS) dataset and university extension recommendations as reported in Basso et al., 2019. For the other states, the state-level N rates were extracted from USDA NASS survey data from 2021. Table 2 lists the corn fertilizer rates by state used in the simulations. For all other states where data was not provided, an average NASS value of 162 kg N ha^{-1} was used.

Table 1. Corn fertilizer rates by state.

State	Corn Fertilizer Rates (kg N ha^{-1})	Source
Colorado	109	USDA NASS
Georgia	229	USDA NASS
Illinois	204	Basso et al., 2019
Indiana	209	Basso et al., 2019
Iowa	180	Basso et al., 2019
Kansas	173	USDA NASS
Kentucky	160	USDA NASS
Michigan	170	Basso et al., 2019
Minnesota	183	Basso et al., 2019
Missouri	224	Basso et al., 2019
Nebraska	179	USDA NASS
New York	132	USDA NASS

North Carolina	178	USDA NASS
North Dakota	163	Basso et al., 2019
Ohio	194	Basso et al., 2019
Pennsylvania	84	USDA NASS
South Dakota	158	Basso et al., 2019
Texas	140	USDA NASS
Wisconsin	155	Basso et al., 2019

For the management scenarios with fall applications of N fertilizer, the fertilizer rates were altered to keep the corn yields consistent between the scenarios with fall and spring application timings. To determine the fertilizer rate required to match yields, the management scenario with fall N fertilizer application with conventional tillage was simulated 14 times with 5% incremental increases in fertilizer amounts, ranging from 0 to 70%. The fertilizer rate that provided the closest match in yield to the spring application scenario yield per grid cell was selected. However, in many locations, even with an increase of 70% in the fertilizer rates, the corn yields remained lower than the yields in the scenario with spring application timing due to N leaching prior to the growing season.

Soybean

Soybean N fertilizer amounts vary by MLRA as provided in collaboration with NRCS and Colorado State University (CSU). For the three MLRAs without specified soybean fertilizer rates (beyond the extent of CSU's simulations), an average N rate of 9.5 kg N ha^{-1} was used. The soybean fertilizer rates remain constant across all management scenarios.

Cover Crop

For scenarios with a cover crop, the cover crop was considered unfertilized.

Other

Typical seeding management for corn and soybean were used. For scenarios with cover crop, winter rye was planted. Table 2 describes the plant density, row spacing, and sowing depth for each crop.

Table 2. Plant density, row spacing, and sowing depth for corn, soybean, and cover crop.

Crop	Plant density (seeds m^{-2})	Row spacing (cm)	Sowing depth (cm)
Corn	8	76	5
Soybean	40	50	2.5
Winter rye (cover crop)	200	15	3

Scenario Description and Parameters

The SALUS crop model was used to simulate the high-resolution locations with representative soil and weather inputs for a period of 30 years, 1991 to 2020.[1] The following management parameters were used in combination to create multiple scenarios encompassing various crop rotations including the addition of a cover crop, tillage management, and corn fertilizer management (Table 3).

Table 3. List of parameters for crop rotation, tillage management, and corn fertilizer management which can be combined to create numerous management scenarios.

Crop Rotation	**Tillage Management**	**Corn Fertilizer Management**
Continuous corn	Conventional tillage	Spring N application
Continuous soybean	Reduced tillage	Fall N application
Corn-soybean rotation	No-till	Fall-Spring split N applications
Addition of cover crop	Intermittent tillage with conventional tillage	Fall N application with enhanced efficiency fertilizer
	Intermittent tillage with reduced tillage	Spring N application with enhanced efficiency fertilizer
		Spring split N applications

As noted above, only the results from the fall application scenarios (under corn fertilizer management) were included in the USDA FD-CIC tool. The results of the remaining scenarios were used for purposes of comparison with the DayCent simulations generated by Colorado State University. Information on those scenarios can be found in the DayCent methodology report.

Crop Rotation and Cover Crop

Three main crop rotations were simulated: continuous corn, continuous soybean, and corn-soybean rotation. The continuous crop rotations indicate a monoculture cropping system for the entire 30-year period, and the corn-soybean rotation is defined as corn followed by soybean in alternating years.

The inclusion of a cover crop, simulated as winter rye, was incorporated within each of the three main crop rotations in scenarios where a cover crop was specified. The cover crop was planted in between the main crops and allowed to overwinter.

Tillage Management

Five tillage management scenarios were simulated to cover a wide range of practices. Conventional tillage is very invasive and typically involves multiple tillage passes. The

[11] A 10-year spin-up period was conducted beforehand to stabilize nitrogen levels and soil water content, ensuring accurate representation of managed agricultural soils. Data from the spin-up period is excluded from the final analysis. The longer spin-up for SOC (>100 years) was executed as part of the SALUS procedure to determine SOC pools and decompositions factors.

conventional tillage scenario was defined with two tillage passes, a chisel plow to 20 cm depth in the spring 7 days prior to planting and a field cultivator to 10cm depth 1 day prior to planting. If the scenario included a cover crop, a field cultivator to 10cm depth was implemented 1 day prior to planting the cover crop in the fall. All other tillage scenarios did not have a tillage event associated with the cover crop.

Reduced tillage, also known as minimum tillage, is less invasive than conventional tillage, typically involving only one tillage event and a smaller area of disturbance. The reduced tillage scenario was defined as a single tillage event using a tandem disk to 10cm depth in the spring 1 day prior to planting.

A no-till scenario was also simulated, where the soil remained undisturbed, and the crops were directly seeded into the previous crop's residue.

Additional tillage scenarios of intermittent tillage were simulated, where the tillage management changed by year. Intermittent tillage with conventional tillage was defined as no-till followed by conventional tillage in alternating years. Similarly, intermittent tillage with reduced tillage was defined as no-till followed by reduced tillage in alternating years. For the corn-soybean crop rotation with intermittent tillage, the corn years received the no-till management.

Corn Fertilizer Management

Six fertilizer scenarios were simulated, focused on alternating the timing and type of N fertilizer for corn. The spring N application was defined as a single application of the total fertilizer amount in the spring at planting using the fertilizer type of ammonium nitrate.

The fall N application was defined as a single application of fertilizer in the fall 10 days after soybean harvest. The fertilizer type was anhydrous ammonia, and the total fertilizer amount was increased compared to the spring N scenario to keep corn yields as consistent as possible between the two scenarios, as previously described.

The fall-spring split N applications scenario was defined as 2 applications with 1 application in the fall 10 days after soybean harvest with anhydrous ammonia and 1 application in the spring at planting with ammonium nitrate. The total amount of N was split with 51.5% applied in the fall and 48.5% applied in the spring, based on the average of the national N application rates from 2016 and 2022 provided by USDA NASS. The total N amount was the same as the fall N scenario.

The fall N application with enhanced efficiency fertilizer (EEF) utilized the same timing and N amount as the fall N scenario, but with the EEF fertilizer type. Similarly, the spring N application with EEF kept the same timing and N amount as the spring N scenario, but with the EEF fertilizer type.

The spring split N applications scenario was defined as 2 applications in the spring, with 25% of the total amount applied at planting and 75% applied as side-dress 40 days after planting. The total N amount was reduced by 10% compared to the spring N scenario.

Model Outputs

The SALUS crop model provides many output variables related to the crop and the environment including aboveground biomass, belowground biomass, grain yield, and N_2O emissions. The 4km-level simulation results were aggregated to the MLRA-level. The 30-year averages and trends for each 4km grid were calculated and then aggregated to the MLRA level using a weighted average accounting for cropland area within each grid cell. This method ensures robust representation of spatial variability within each MLRA, with all results reported at the MLRA-level.

N_2O Emissions

The 30-year averages of direct N_2O emissions were calculated from SALUS output. Indirect N_2O emissions were calculated as 1.5% of direct N_2O emissions.

N Output

N components, including N sources, N fertilizers, and N in residues, are key factors in N_2O emissions. The total N sources was defined as the sum of N from fertilizer, roots and stover, and asymbiotic fixation from bacteria. For soybeans, the symbiotic N is also included. N mineralization is not included in this output variable. The N in crop residue was defined as the N from roots and biomass, excluding the N from grain. The average N fertilizer amounts were provided as well.

Carbon

The 30-year averages were calculated for the amount of carbon in grain, aboveground biomass, and belowground biomass. The amount of carbon was calculated as 44% of the dry matter. The grain and aboveground biomass were provided for the day of harvest. The belowground biomass was provided as the maximum root weight which typically occurs during grain fill, and this value is often used in literature when measuring roots in field studies (Ordonez et al 2020).

Change in SOC

Soil organic carbon was provided for 0-30cm layer of the soil profile. The change in SOC was calculated for each grid cell as the difference between the starting year and final year, divided by number of years. The change in SOC was then aggregated to the MLRA level.

$$\Delta\, SOC = \frac{SOC_{year30} - SOC_{year1}}{30}$$

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