



Project 104(C) Methodology for Assessing Changes in Soil Organic Carbon

University of Tennessee

Project Lead Investigator

Timothy Rials
Professor and Associate Dean
AgResearch, University of Tennessee
2506 Jacob Dr., Knoxville, TN 37996
865-946-1130
trials@utk.edu

University Participants

University of Tennessee (UT)

- P.I.: T. Edward Yu
- FAA Award Number: 13-C-AJFE-UTenn-025
- Period of Performance: December 3, 2024, through December 31, 2025
- Tasks:
 1. Enhance Soil Organic Carbon (SOC) Mapping Across the Continental United States (CONUS)
 2. Assess the direct and spatial spillover impact of agricultural management practices on agricultural productivity and sustainability
 3. Collaborate with other members in ASCENT Project 104 for SOC research (supporting role)

Project Funding Level

The Federal Aviation Administration (FAA) provided \$314,999 in funding; matching funding is provided by UT (\$317,753), including personnel salaries and benefits, software license, publication costs, soil sample data, and tuition remission.

Investigation Team

Timothy Rials (Project Director – PD), Task 3
T. Edward Yu (P.I.), Tasks 1-3
Joshua S. Fu (co-PI), Tasks 1 and 3
Le Chen (faculty), Task 2
Virginia Sykes (faculty), Task 1
Forbes Walker (faculty), Task 1
Robert Florence (faculty), Task 1
Hannah Williams (Research Associate), Task 2
Hannah Rubin (PhD student), Task 1
Xinxin Zhang (PhD student), Task 1

Project Overview

Utilizing sustainable aviation fuel (SAF) from agricultural and forestry feedstock has been considered the major means to meet the carbon reduction targets of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and the United States (U.S.) SAF Grand Challenge. It is crucial to have a well-designed life cycle analysis (LCA) for the SAF supply chain to align with the proposed carbon credit system to expedite SAF implementation. To make an adequate estimate of SOC in the SAF LCA, a systematic approach that *integrates spatial and temporal variations and continuity* is important. Most current soil carbon properties, flux, and storage databases are not spatially or temporally continuous. Thus, the goal of this study is to improve SOC estimates and investigate long-term trends in the U.S. using in-situ measurements from soil carbon networks and previous studies and incorporating satellite imagery and machine learning methods for more



complete spatial and temporal coverage. The impact of land use changes on SOC and agricultural sustainability is also the focus of this study.

Task 1 – Enhance Soil Organic Carbon (SOC) Mapping Across the Continental United States (CONUS)

University of Tennessee, Knoxville

Objectives

This task aims to develop improved estimates of SOC across the United States to support national soil health assessments and SAF LCAs. This year, our objectives are to refine SOC data inputs, rebuild the baseline modeling framework, and lay the foundation for transitioning from traditional machine learning methods to deep learning approaches.

Research Approach

Removing Duplicates/Outliers and Standardizing the Datasets from Various Sources

This year, we removed duplicate records and outliers, and standardized SOC observations across multiple datasets (Rapid Carbon Assessment [RaCA], National Cooperative Soil Survey [NCSS], International Soil Carbon Network [ISCN], World Soil Information Service [WOSIS], SOils DAta Harmonization [SoDaH], and Sanderman et al. (2018)). All soil profiles were harmonized to a consistent 0–30 cm depth and standardized for units, geographic coordinates, sampling year, and layer structure. The resulting harmonized dataset in Figure 1 provides a uniform, credible foundation for producing aggregated SOC estimates and supporting future model development.

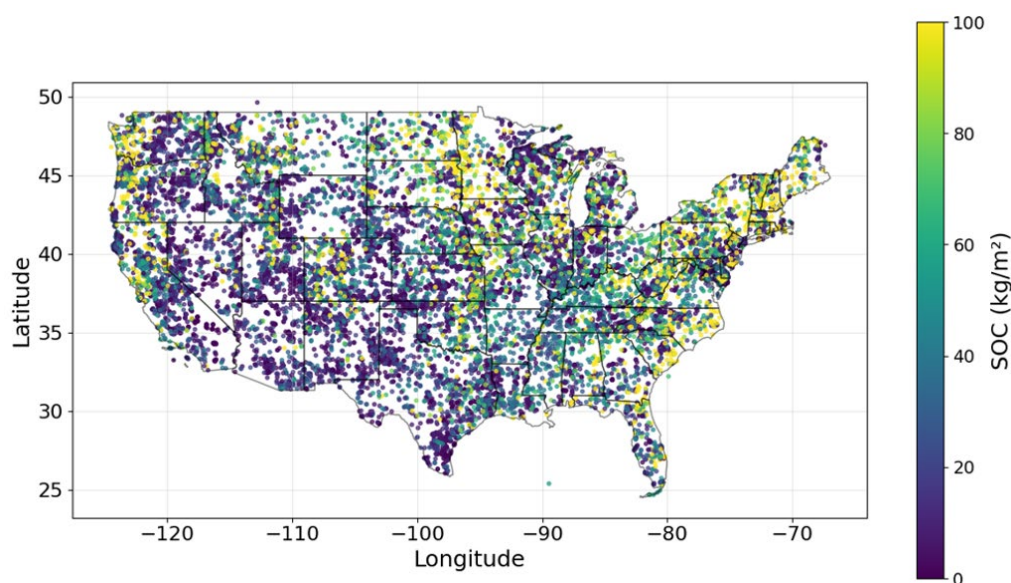


Figure 1. Spatial distribution of combined soil organic carbon (SOC) observations across all datasets (CONUS).

Environmental Covariates and Predictor Design

We compiled an expanded suite of environmental covariates, including vegetation indices (Normalized Difference Vegetation Index [NDVI], Enhanced Vegetation Index [EVI], Normalized Burn Ratio [NBR], Normalized Difference Moisture Index [NDMI], near-infrared [NIR], Short-wave infrared (SWIR)1/2 and red reflectance), topography indices (elevation, slope, aspect, Topographic Wetness Index [TWI], Topographic Position Index [TPI], and geology), climate variables (temperature and precipitation), soil properties (pH, texture, drainage class, soil moisture), and land use indicators. All predictors were spatially aligned with SOC observations using their geographic coordinates and sampling years. Together, these covariates form a robust foundation for improving existing machine learning models and enabling the development of forthcoming

deep learning approaches. Figure 2 summarizes vegetation, topographic, climate, soil, and land-use covariates, along with the SOC observations used as the target variable.

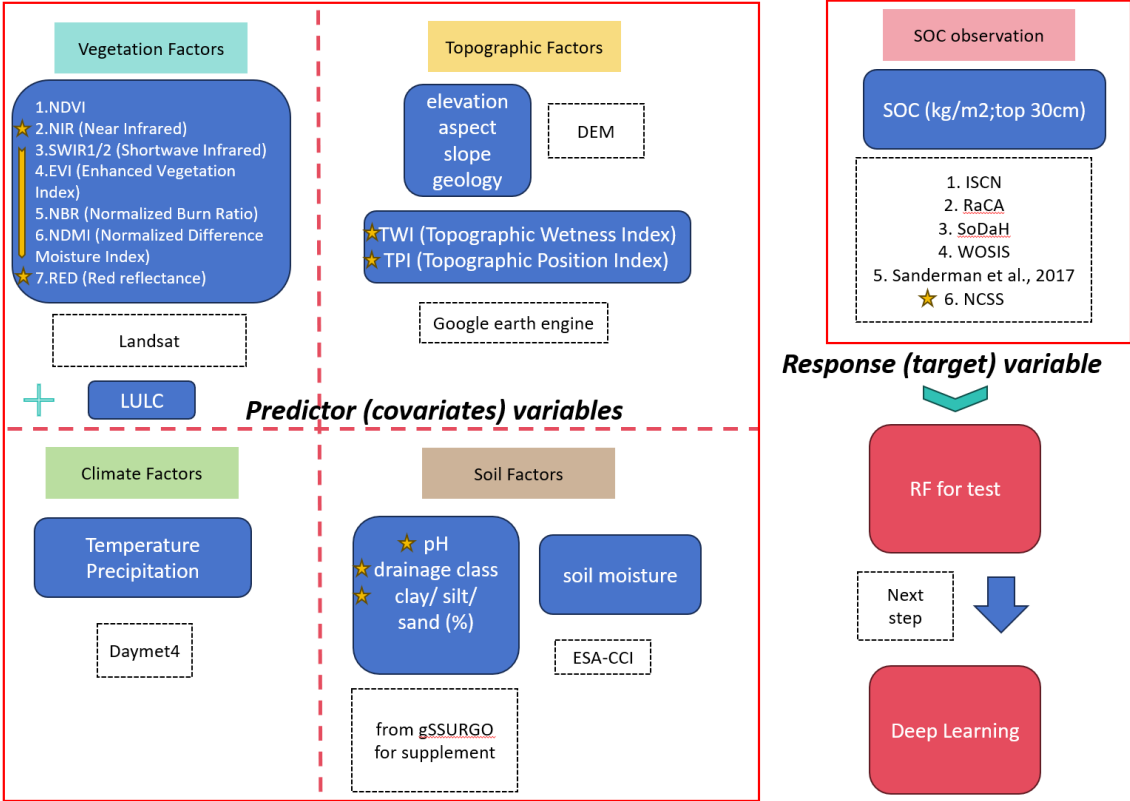


Figure 2. Overview of SOC predictor variables (blue boxes) and their corresponding data sources (dashed boxes) in model.

Machine-Learning Baseline and Model Improvement

We rebuilt the Random Forest (RF) baseline model using the cleaned SOC dataset and the expanded predictor set of predictor variables. A five-fold spatial cross-validation framework was implemented to evaluate model performance and assess its ability to generalize across different regions and environmental gradients.

To address the limitations of traditional machine-learning methods in handling large, high-dimensional SOC datasets, we also began laying the groundwork for transitioning to deep-learning approaches.

Reference

Sanderman, J. et al. (2018) A global map of mangrove forest soil carbon at 30 m spatial resolution. Environ. Res. Lett. 13, 55002.

Milestones

- Completed the compilation and standardization of SOC datasets from multiple sources.
- Mapped and evaluated the national spatial distribution of SOC observations.
- Established an updated SOC modeling framework incorporating an expanded set of predictor variables.
- Generated a preliminary 30-m SOC prediction for the year 2020.
- Prepared data structures and modeling routes for future deep-learning development.



Major Accomplishments

All SOC datasets were reprocessed by removing duplicates and standardizing units, sampling depths, and geographic coordinates. This effort substantially increased the number of usable, harmonized SOC observations and ensured consistent representation of 0–30 cm SOC stocks across all sources. The improved data foundation directly supports more robust modeling for both current machine-learning applications and future deep-learning development.

The updated SOC dataset led to a substantial improvement in model performance compared with earlier versions. Applying the RF model to the harmonized dataset increased the validation R^2 (coefficient of determination) from 0.59 (previous baseline) to 0.74, highlighting the benefits of both data cleaning and the expanded predictor set. Using this enhanced modeling framework, we generated a refined 2020 SOC stock estimate of approximately 70.45 Pg C, higher than the previous baseline estimate of 60.4 Pg C reported in the earlier SOC mapping study. This increase reflects the strengthened data foundation and improved modeling capability, rather than any temporal change in SOC. The 2020 map in Figure 3 serves as a test-year product that demonstrates the enhanced predictive capacity of the updated workflow.

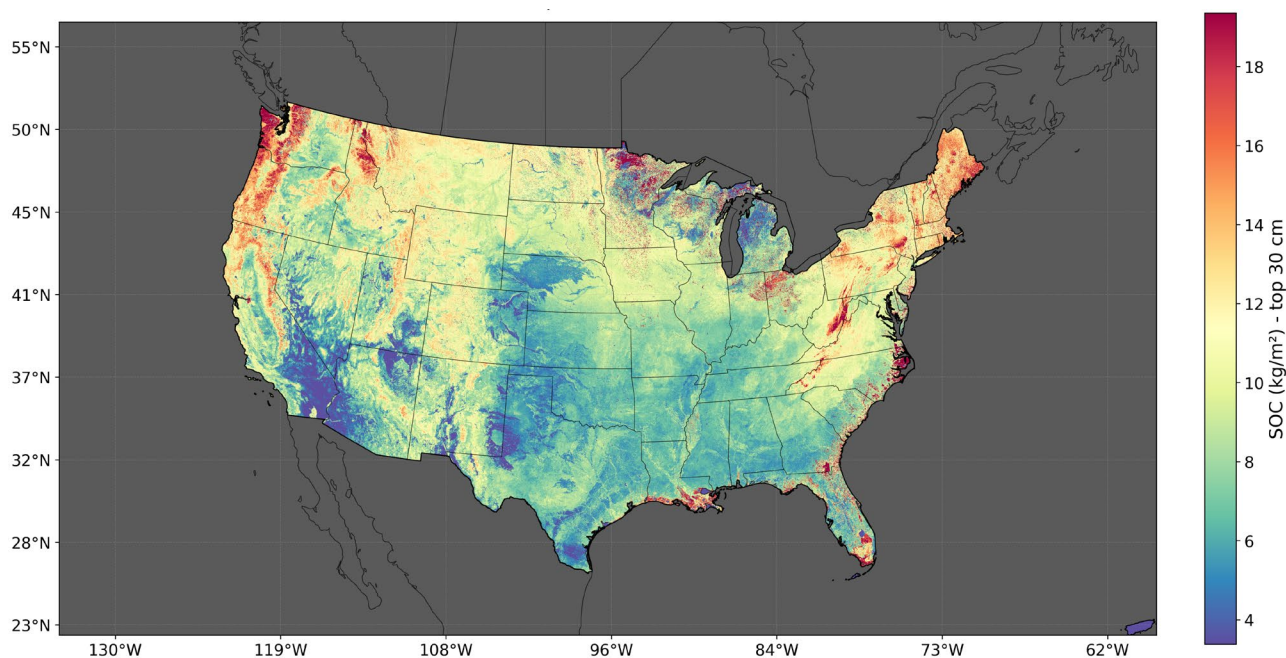


Figure 3. Estimated SOC stock for the year 2020 in the top 30 cm of soil (kg/m^2).

Publications

Rubin, H. J., Fu, J. S., & Yu, T. E. (2025). Mapping historical soil carbon in the United States with machine learning. *Manuscript under review.*

Outreach Efforts

None.

Awards

None.

Student Involvement

Hannah Rubin, a previous Ph.D. student, conducted the earlier phases of SOC analysis and graduated in May 2025. She is no longer involved in the project.



Xinxin Zhang, a Ph.D. student, took over Hannah Rubin's work and led the SOC-related work this year, including reorganizing SOC datasets, expanding predictor variables, running the updated RF model, and preparing data inputs for future deep learning applications.

Plans for Next Period

In the next reporting period, we will focus on advancing the SOC modeling framework beyond the current RF implementation. To support this transition, we will refine the predictor set by evaluating variable importance and reducing noise from less informative covariates. We will also incorporate additional satellite-derived indices and phenological variables to further enhance spatial and temporal coverage.

Building on the improved data foundation established this year, we will initiate the development of deep learning models to better capture the nonlinear, high-dimensional relationships that influence SOC formation. These models will be evaluated alongside traditional machine-learning approaches within a unified spatial cross-validation framework. Our goal is to produce more robust and reliable SOC prediction products that can support future soil-health assessments and SAF life-cycle analyses.

Task 2 - Assess the Direct and Spatial Spillover Impact of Farm Practices on Agricultural Productivity and Sustainability

University of Tennessee

Objective

Soil erosion has increasingly become a major concern in agricultural sustainability and environmental conservation. It is recognized as one of the most serious environmental challenges affecting global agriculture, as it adversely affects on-site crop productivity by reducing the availability of water, nutrients, and organic matter. Given the potential impact of soil erosion on agricultural productivity, there is extensive literature investigating the effects of soil erosion levels on crop yields. Studies have suggested that some farm practices, such as cover crops or no-tillage, could mitigate the soil erosion issue. However, little research has examined its spillover effects on surrounding agricultural fields. Soil erosion is inherently a spatial process, wherein displaced soil, nutrients, and sediments move beyond the eroded site, affecting adjacent farmlands. The objective of this study is to fill this gap by addressing the impact of soil erosion on crop yield using spatial statistical analysis, with an emphasis on both direct and spillover effects.

Research Approach

In this period, we conducted two studies to examine the related issue: first, we estimated the spatial spillover effect of soil erosion on crop productivity; and second, we explored the potential spillover effect of farm practices on SOC.

Study 1: The Impact of Soil Erosion on Corn Yields

We utilized unique county-level data for annual soil loss caused by erosion (in tons/acre) from the NRI program of the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) and county-level data on corn yield from the USDA National Agricultural Statistics Service (NASS) for the census years 1992, 1997, 2002, 2007, 2012, and 2017. The resulting panel dataset used in the study covers 559 counties over eight states in the U.S. Corn Belt. We then applied a spatial regression approach to this panel dataset to assess the broader influence of soil erosion on crop yield beyond the area where it occurred, accounting for how erosion-induced changes in soil quality affect neighboring areas.

Study 2: The Impact of Cover Crops and No-Till Systems on Soil Organic Carbon

We used SOC data from 1990 to 2022 within the CONUS from Task 1. The fine-resolution SOC estimates (30 m) for the top 30 cm of soil are aggregated to the county level to match the farming management data. Satellite-based county-level adoption data for cover crops and no-till are then collected from the Operational Tillage Information System (OpTIS) database and compiled with the SOC data. The resulting dataset covers sixteen states (Colorado, Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, Oklahoma, South Dakota, Tennessee, and Wisconsin) from 2005 to 2020.

Milestones

- Completed the spatial regression analysis of the impact of soil erosion on corn yield in the Midwest for study 1.



- Disseminated the findings of the soil erosion analysis at the 2025 Southern Agricultural Economics Association annual meeting and developed a manuscript, which is accepted for publication in *Agrosystems, Geosciences & Environment*.
- Made a preliminary analysis of the impact of farm practices on SOC in study 2.
- Presented the preliminary analysis of study 2 at the 2025 Agricultural and Applied Economics Association annual meeting.

Major Accomplishments

Study 1: The Impact of Soil Erosion on Corn Yields

Table 1 summarizes the estimated coefficients of the explanatory variables and their direct, indirect (i.e., spatial spillover), and total effects. The results indicate that water erosion has a statistically significant and negative effect on corn yield, both within a county and in neighboring counties. The direct effects of water erosion on corn yield generally suggest that counties with higher levels of water erosion tend to have statistically lower corn yield, and this productivity effect is not explained by climate. Specifically, we find that each additional ton of soil loss per acre due to water erosion in a county can lead to a statistically significant decrease of 0.48 bushels (BU) per acre in its corn yield.

In addition to the direct effect, there is also a spillover effect of water erosion on corn yield in adjacent counties: each additional ton per acre of soil loss due to water erosion can lead to a statistically significant decrease of 1.22 BU/ac in corn yield. Thus, considering the direct and spillover effects of water erosion on corn yield, the total effect of water erosion indicates that each additional ton per acre of water erosion would result in a 1.70 BU/ac decrease in corn yield, suggesting a substantial overall regional impact of water erosion on corn yield in the U.S. Midwest. These findings imply that water erosion is not only a localized phenomenon but also has spatial externalities that affect surrounding agricultural productivity. Our study provides new empirical evidence that soil erosion is inherently a spatial phenomenon, whereby displaced soil, nutrients, and sediments are transported beyond the site of origin, impacting agricultural productivity in neighboring areas.

Table 1. Estimated coefficient and effect of explanatory variables on corn yield.

	Corn Yield			
	Coefficient	Direct Effect	Indirect Effect	Total Effect
Water Erosion	-0.3880* (0.2097)	-0.4815* (0.2537)	-1.2175* (0.6503)	-1.6990* (0.9208)
GDD	0.0023 (0.0051)	0.0031 (0.0066)	0.0079 (0.0166)	0.0110 (0.0232)
HDD	-0.2766*** (0.0212)	-0.3459*** (0.0240)	-0.8726*** (0.0610)	-1.2185*** (0.0799)
Precipitation	0.0365*** (0.0125)	0.0471*** (0.0149)	0.1191*** (0.0385)	0.1663*** (0.0533)
Precipitation squared	-0.0000*** (0.0000)	-0.0000*** (0.0000)	-0.0001*** (0.0000)	-0.0001*** (0.0000)
ρ	0.7720*** (0.0606)			
λ	0.8964*** (0.0424)			
County FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Observations	3354	3354	3354	3354

Note: *p<0.1, **p<0.05, *** p<0.01

FE: fixed effects; GDD: growing degree days; HDD: harmful degree days



Study 2: The Impact of Cover Crops and No-Till Systems on Soil Organic Carbon

Table 2 presents preliminary results on the effects of cover crops and no-till adoption on SOC using linear panel fixed effects (FE) estimation. Our parameter estimates suggest that counties with higher acres under no-till tend to have significantly higher SOC levels. Specifically, our results show that a 1% increase in acres under no-till adoption in a county can increase its SOC level by 0.0005%, indicating that no-tillage adoption has a positive effect on SOC by potentially promoting higher SOC accumulation over time. In contrast, the coefficient on the acreage of corn planted with cover crops is positive, but statistically insignificant. This suggests that cover crops may not have a measurable effect on SOC accumulation.

Table 2. Estimated coefficient of the explanatory variables on SOC. CC_ac: percent of cover crops per acre; FE: fixed effects; GDD: growing degree days; HDD: harmful degree days; NT_ac: percent of no-tillage per acre.

	0.00ln (Soil Organic Carbon)
ln (CC_ac)	0.0001 (0.0002)
ln (NT_ac)	0.0005* (0.0003)
GDD	-0.0076 (0.0056)
HDD	-0.0026 (0.0197)
Precipitation	0.0001*** (0.0000)
Precipitation squared	-0.0000***
County FE	Yes
Year FE	Yes
Adjusted R ²	0.050
Observations	11744

Standard error in parenthesis

* p<0.10, **p<0.05, ***p<0.010

Publications

Chen, L., T.E. Yu, and H. Williams. (2025). The Impact of Soil Erosion on Corn Yields: A Spatial Regression Analysis. *Agrosystems, Geosciences & Environment*, Accepted.

Outreach Efforts

Presentations

Chen, L., Yu, T.E., Rubin, H., Fu, J.S., & Rejesus, R. (2025, July 27-29). *The Impact of Adopting Cover Crops and No-Till Systems on U.S. Soil Organic Carbon* [Conference presentation]. 2025 Agricultural and Applied Economics Association (AAEA) Annual Meeting, Denver, Colorado. <https://doi.org/10.22004/ag.econ.361059>

Chen, L., Yu, T.E., & Williams, H. (2025, February 1-4). *Impact of Water and Wind Erosion on Corn and Soybean Yields: A Spatial Regression Analysis* [Conference presentation]. Southern Agricultural Economics Association (SAEA) 2025 Annual Meeting, Irving, Texas.

Awards

None.

Student Involvement

None.



Plans for Next Period

- Use satellite image data to further examine the impact of farm practices on SOC, as county-level data are too coarse to represent individual farm operations.
- Plan to incorporate spatial heterogeneity in both studies 1 and 2 to enhance the understanding of the variations in the impacts.

Task 3 - Collaborate with other Members in ASCENT Project 104 for SOC Research (supporting role)

University of Tennessee

Objective

Provide support to other members of the ASCENT Project 104 as requested.

Research Approach

Provide necessary input through research efforts in SOC estimates. The approach will differ as questions surface from other teams.

Milestone

Shared SOC estimates at the ASCENT fall and spring meetings.

Major Accomplishments

See Task 1 above.

Publications

None.

Outreach Efforts

None.

Awards

None.

Student Involvement

None.

Plans for Next Period (Year)

Enhance the SOC estimates and comparison.