Comparison of cropland emissions, carbon sequestration, and soil health outcomes in alfalfa (*Medicago sativa*) and corn (*Zea mays* L.) production fields in an integrated crop-livestock dairy system

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Abstract

Alfalfa and corn silage are important forage crops in dairy production systems, and often grown in rotation for both agronomic and environmental benefits. Alfalfa, a deep-rooted perennial legume, has been shown to have positive effects on soil health, but intensive field management practices can counteract these benefits. We evaluated the relationships among soil health metrics, crop, and stand age in alfalfa and corn fields on a dairy farm in Wisconsin, USA.

Three alfalfa and three corn fields were selected, with eight sampling locations per field assigned in a stratified random sampling design based on field topography and soil series. In situ soil respiration was measured monthly at each location from April through October, while soil physical, chemical, and biological measurements were sampled in the spring, spring/fall, and spring/summer/fall, respectively. Soil samples were collected in four depth increments to 60 cm depth, except for soil biological samples, which were collected to 10 cm.

An assessment of farm carbon balance at the study site was completed in 2019 and found 1- and 2-year old alfalfa fields were a net carbon sink, while alfalfa fields with stands >2 growing seasons were a net carbon source (Wiesner et al. 2022). Corn silage fields were a slight carbon sink, likely due to high biomass production during the growing season, only one harvest event, and field rotation with other forage crops.

Relationships between soil health metrics and crop type were not significant, except for soil microbial abundance and composition which varied with crop rotation history, crop type, and season. Alfalfa fields accumulated bacterial and fungal diversity with increasing stand age. Due to within-field topographic heterogeneity, landscape position was likely a larger driver of soil health outcomes than crop type in fields with a similar crop rotation and management history.

Introduction

Integrating perennials into the cropping system is an important practice for agricultural producers interested in improving farm environmental outcomes and promoting soil health. Among livestock producers, and dairy producers in particular, alfalfa is the most commonly selected perennial for inclusion in their crop rotations.

There is increasing concern among farm groups and the general public about extreme weather events and warming trends associated with climate change. In light of serious economic instability in the dairy sector, carbon-neutral farming and access to carbon markets may emerge as important farm income streams. Alfalfa, like other perennials, may serve as a farm carbon sink while improving soil health due to the continuous ground cover and extended growing season.

Farms are complex ecological systems with significant spatial and temporal variability. Dairy producers must manage this complexity effectively for both economic and environmental goals, and consider how management decisions applied to the field or herd might affect the entire farm system (Little et al. 2017). Although corn silage has become an important forage crop for dairy farms, continuous corn silage production is associated with significant loss of soil organic carbon and negative net ecosystem carbon balance (NECB) (Gamble et al. 2021). Adding alfalfa or other perennial forages to the rotation is an important practice for reducing soil organic carbon losses. However, intensive cutting schedules associated with alfalfa silage production may reduce the carbon accumulation capacity of alfalfa within the dairy forage rotation. Evaluating carbon balance and soil health outcomes associated with alfalfa and other crops in the dairy rotation is an area in urgent need of research to provide producers guidance about best management practices appropriate to their region.

Methods

Site description

The U.S. Dairy Forage Research Center (USDFRC) farm located in Prairie du Sac, WI, served as the study site. The farm herd composition includes approximately 400 dairy cows and 300 young stock, with most of the feed grown on the farm land base, and manure nutrients returned to the cropland. Alfalfa, corn (silage, grain), winter wheat, and soybeans are grown in rotation on 1,300 cropland acres, with another 900 acres of degraded natural lands (grassland, shrubland, forest) and pasture providing permanent perennial cover. The soils of the study site are well-drained silt loams, and the landscape has variable topography as is typical in southwestern Wisconsin.

Meteorological and carbon flux measurements

A 30-meter eddy covariance tower was installed at the farm in 2018. Instruments on the tower continuously measure meteorological variables as well as carbon dioxide, water, and energy fluxes at the field-atmosphere surface of crop fields within the tower footprint (600-meter radius on average). Due to COVID-19 postponement of the field and lab component as described in this proposal, the flux component of the research was conducted prior to the project start using data from the 2019 growing season. These data were used to establish differences in the energy and carbon fluxes of fields by crop type. A footprint partitioning approach was used to compare gross photosynthesis and ecosystem respiration of alfalfa and corn fields, and develop an estimated carbon balance by crop type and for the entire farm.

Field sampling

In 2021, three alfalfa (stand ages of 1, 2, and 3 growing seasons) and three corn fields with a similar crop rotation history were selected, and eight sampling locations per field were identified using a stratified random sampling design, with field topography and soil series used as the categories for stratification. In total, there were 48 locations designated for soil respiration and field sample collection (Figure 1). We increased the sampling intensity 3-fold from what was initially proposed in order to better capture within-field heterogeneity. The timeline for sample collection is detailed in Figure 2, and measurements included those related to soil carbon fractions and soil chemical, physical, and biological analyses.

Figure 1. Map of the sampling locations (N=48).

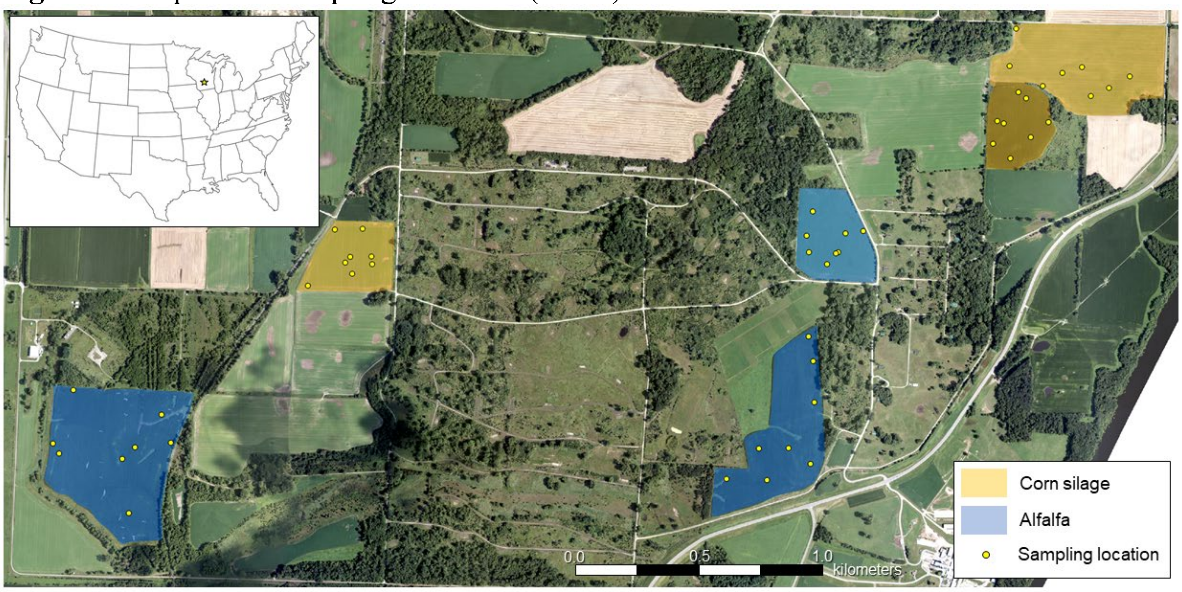
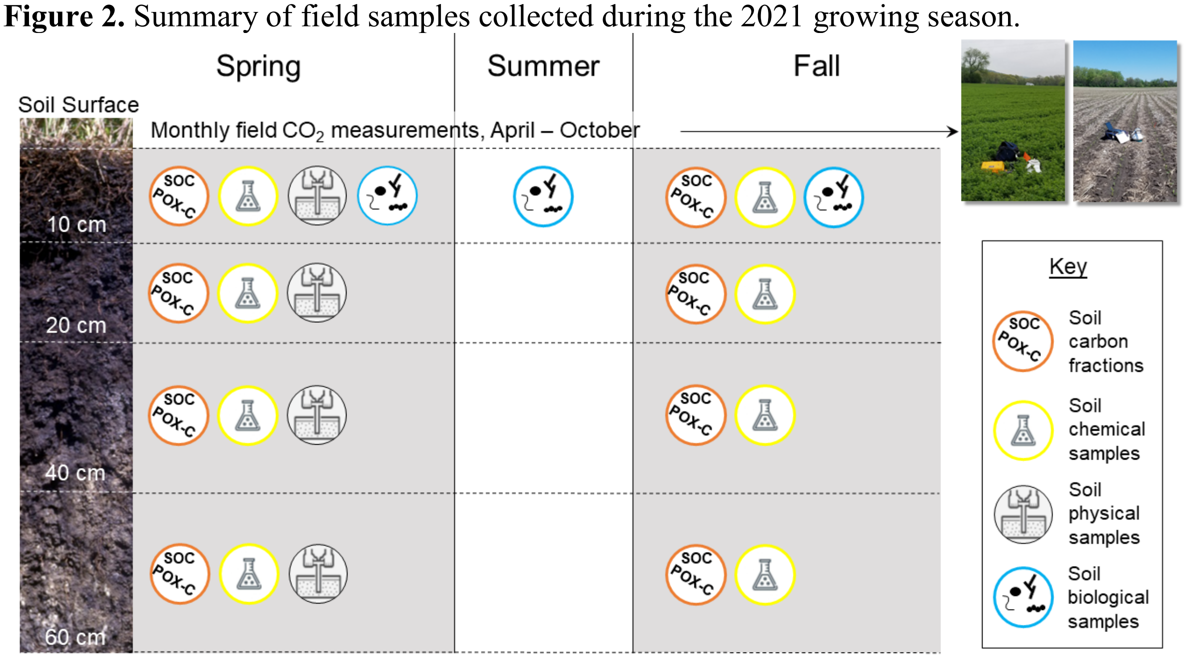


Figure 2. Summary of field samples collected during the 2021 growing season.



Field respiration and NDVI measurements
A 10-inch diameter PVC collar was installed in spring 2021 at each sampling location. In situ field respiration measurements were collected monthly at each collar using an automated soil CO_2 flux system (LICOR-8100 infrared gas analyzer, LICOR Inc., Lincoln, NE), along with soil temperature and soil volumetric water content (Fieldscout TDR 300, Spectrum Technologies, Inc., Painfield, IL) measurements.

A handheld sensor was used to collect normalized difference vegetation index (NDVI) (Crop Circle ACS-430, Holland Scientific, Lincoln, NE) values from the growing crops around each collar location at the time of field respiration measurements. NDVI can be used to approximate alfalfa and corn yields in lieu of destructive sampling (Cazenave et al. 2019; Tagarakis and Ketterings 2017; Kayad et al. 2016); relationships between crop biomass and NDVI values were established for crops grown at the research station in 2019 (Wiesner et al., unpublished data).

Soil carbon fractions
As shown in Figure 2, soil samples for carbon fraction analyses were collected in the spring and fall. Three cores were collected with a soil probe (AMS, American Falls, ID) near each soil respiration collar, and composited in four sample depth increments (0-10, 10-20, 20-40, and 40-60 cm). Total carbon and total nitrogen were measured by dry combustion (Tru-Mac CN Analyzer, Leco, St. Joseph, MI), with soil organic carbon equal to total carbon on the sampled soils, or calculated after subtracting the inorganic carbon fraction for samples with a pH > 7.2 (Stott 2019; Sherrod et al. 2002). The labile carbon fraction was assessed for each depth increment using the permanganate oxidizable carbon (POXC) method (Weil et al. 2003).

Soil chemical analyses
Three cores were collected with a soil probe near each collar in the spring and fall, and composited by depth increments as shown in Figure 2. These samples were sent to the University of Wisconsin Soil and Forage Lab for routine soil nutrient analyses, including plant available P and K, pH, and soil organic matter.

Soil physical analyses
All soil physical samples were collected within 2 meters of the soil respiration collar, avoiding any disturbed areas, in the spring as shown in Figure 2. Depth increments were the same as for the soil carbon fractions. A fixed-volume soil hammer probe (AMS, American Falls, ID) was used to collect soil bulk density measurements near each collar location, dried at 105°C until constant mass, and the soil bulk density (ρb) calculated using the following formula, where bulk density is measured in g/cm^3, M_s is the weight of the dry soil sample in g, and V_s is the volume of the dry soil sample in cm^3:

$$\rho b = Ms/Vs$$

A soil probe was used to collect three soil cores which were composited by depth increment, and the soil processed in the lab to measure rapid particle size (Schindelbeck et al. 2016) and wet aggregate stability (Soil Survey Staff 2022).

Soil biological analyses
Soils were sampled near each location collar for biological analyses in the spring, summer, and fall (Figure 2). A soil probe was used to collect and composite three 10-cm depth soil cores, and these were bagged, put on ice in the field, and then stored in a -80°C freezer until ready for processing. After DNA extraction and PCR amplification, samples were sent to the University of Wisconsin Next Gen DNA Sequencing Core for sequencing of bacterial and fungal DNA.

Project Objectives	**Corresponding Results**
Evaluate & compare the performance of corn fields and alfalfa fields of varying stand age with respect to:	
1. Carbon flux	1. In 2019, young alfalfa stands (1-2 years) were a net carbon sink, while alfalfa stands >2 years old lost carbon at a rate of 100-200 g C/m^2 Corn silage fields were a net carbon sink in 2019 due to significant biomass accumulation, 1 harvest event, and rotation with perennial forages (i.e., alfalfa)
2. Soil health • Soil biological assessments • Soil carbon stocks • Soil physical assessments • Soil chemical assessments	2. No significant differences in soil health metrics by crop type due to within field variability. Landscape position likely a larger factor in affecting soil health outcomes for fields with a similar crop rotation and management history. • Alfalfa fields accumulated bacterial and fungal diversity with increasing stand age.

Results

Carbon flux
Alfalfa fields with stand ages of 1-2 growing seasons were a net carbon sink in 2019, while alfalfa fields with stand ages of 3-4 growing seasons lost carbon at a rate of 100-200 g C/m^2 annually (Wiesner et al. 2022). Corn silage fields had a positive field carbon balance due to high biomass production during the growing season and only one harvest event (i.e., export of biomass carbon). For 2019, approximately 60% percent of all farm emissions were mitigated by the 40% of the farm land base in permanent perennial cover, including pasture, grasslands, shrublands, and forests (Wiesner et al. 2022).

Soil health
Alfalfa fields accumulated bacterial and fungal diversity with increasing stand age, with alfalfa stands in their second or third growing season having higher soil microbial abundance than soils in first year alfalfa stands or corn fields (Figure 3).

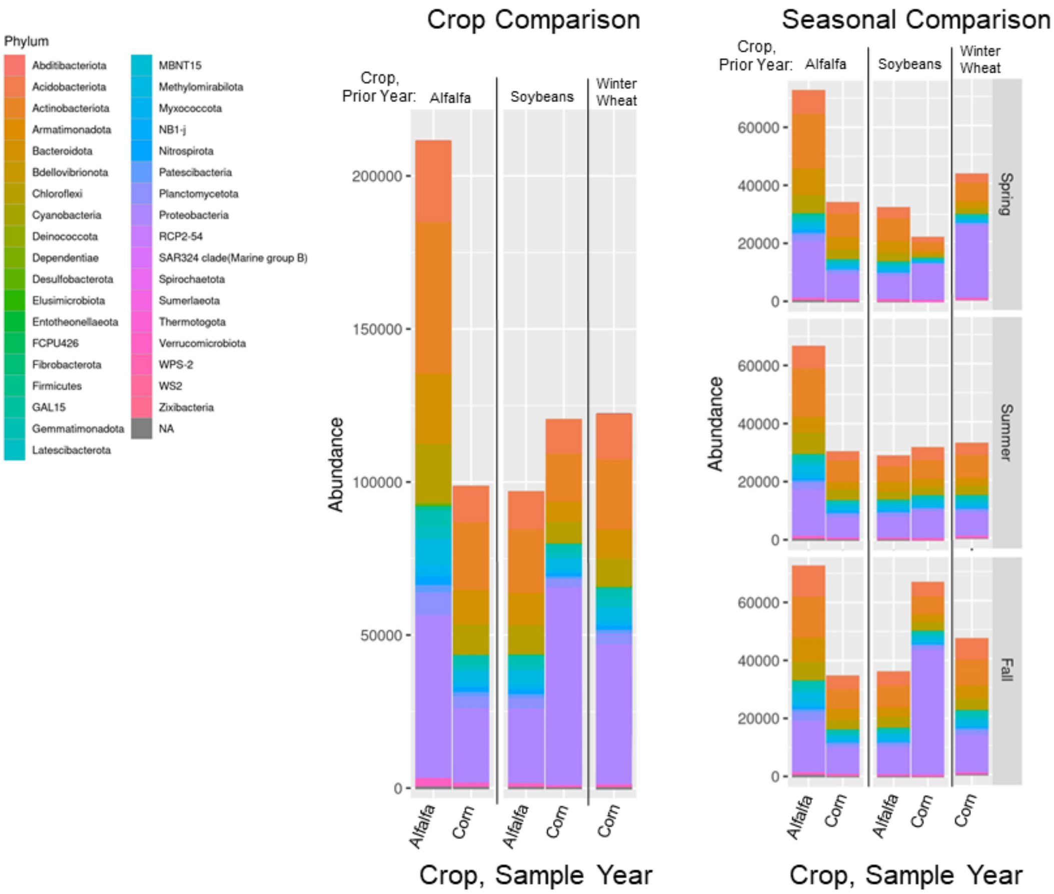
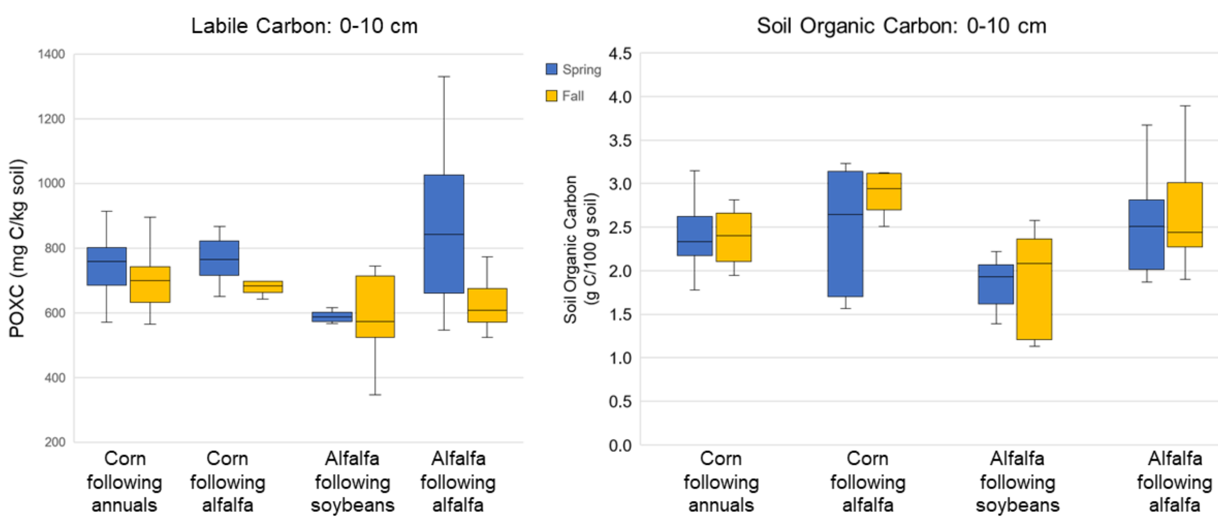


Figure 3. Soil biological sequencing results. Color key indicates bacterial and fungal phyla identified in the samples. Left figure compares soil biological community by crop type (all seasons). Right figure compares soil biological community by crop type in spring, summer, and fall.

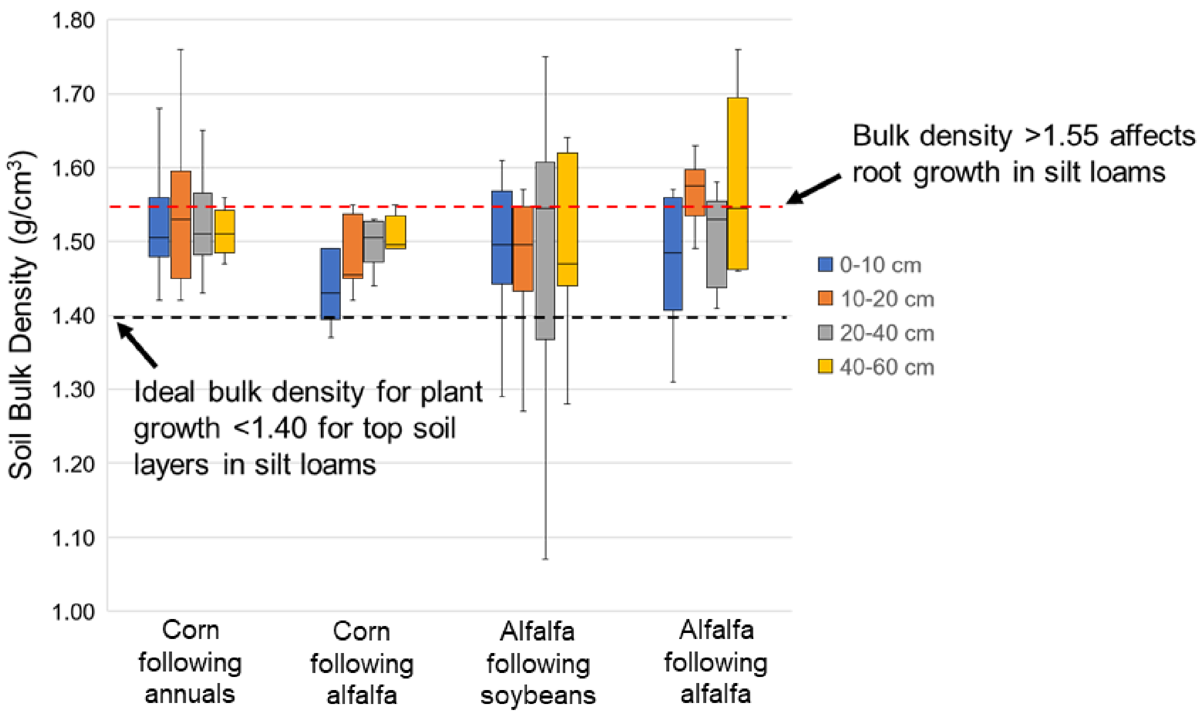
No significant differences in labile carbon (POXC) or soil organic carbon (SOC) were detected by crop type, at any depth. Figure 4 shows a summary comparison of both POXC and SOC for the 0-10 cm depth increment by crop type.

Figure 4. No significant differences were detected for labile carbon (left graph) or soil organic carbon (right graph) by crop type for any soil depth (0-10 cm depth increment shown). Within-category variability was greater than differences between crop type.



No significant differences in soil physical samples, including wet aggregate stability or soil bulk density, were found by crop type at any depth. However, samples from all fields were found to have soil bulk density that was higher than the ideal for plant growth in silt loams, and in some cases higher than values that would impede root growth (Figure 5).

Figure 5. Soil bulk density comparison among field types for all depth increments. Samples were collected in spring 2021.



According to the soil survey geographic (SSURGO) database, all fields surveyed in this study were designated as silt loams. Although state soil survey maps are coarse and not meant to distinguish fine field-scale differences, a total of 11 of our 48 sampling locations had a soil texture that did not match the soil survey designation. All of the sites in which the rapid particle size test resulted in a "sandy loam" instead of a "silt loam" were located on hill summits or along paths of water flow after intense rain events - in other words, they have lost their topsoil. For sites where the lab texture designation was "silt" instead of "silt loam," 75% of those sites were on toeslopes or known gully deposition sites.

Discussion

Carbon flux and meteorological data were used to assess farm carbon balance of the study site in 2019. Alfalfa stands in their first and second growing season were a net carbon sink, while alfalfa fields >2 growing seasons were a net carbon source (Wiesner et al. 2022). Corn silage fields were a slight carbon sink in 2019, likely due to the accumulation of carbon in plant biomass, only one harvest event compared to the more intensive harvest schedule in alfalfa fields (i.e., 4 harvest events), and crop rotation for all fields, so that soil organic carbon losses associated with continuous corn silage production were not a factor (Gamble et al. 2021).

Topography and landscape position were significant factors affecting soil conditions for the surveyed sites. Long-term patterns of soil erosion which resulted in hill summit locations being categorized as sandy loams and toeslopes and other areas of topsoil deposition being categorized as silts, created significant within-field variability. Thus, crop type did not have a significant effect on soil health metrics, except for soil biological samples. Alfalfa stands of two and three years had greater microbial abundance and diversity than one-year-old alfalfa or corn silage fields.

For fields with a similar crop rotation and management history, it appears that crop type is not as important as landscape position in affecting soil health outcomes. However, inclusion of perennial forage crops within the crop rotation is likely an important factor in reducing soil organic carbon losses over time. Perennial cover in the study site contributed to a longer growing season, and greater carbon accumulation during the early and late parts of the growing season (Wiesner et al. 2022).

Additional research is needed to identify management practices that will increase carbon accumulation, or reduce carbon losses, from older alfalfa stands. It is possible that alfalfa-grass mixes may increase biomass production in both above- and below-ground vegetation in older stands, but studies are needed to evaluate the potential impacts on forage quality and productivity over time. Alfalfa varieties which allow for fewer cuttings with high productivity and forage quality may present an opportunity to increase net field carbon balance. Finally, there is significant uncertainty associated with estimates of field greenhouse gas emissions, particularly nitrous oxide, in both corn and alfalfa fields, and in situ measurements are needed to verify predictions recommended by the IPCC or other scientifically accepted models.

Further exploration of the dataset collected during this project is underway to assess the linkages among the measured soil health metrics for all sites, compare in situ field respiration and NDVI measurements between crop types, and to evaluate the relationships between landscape position and soil health. This work will be published in the peer reviewed literature in 2023, with acknowledgement of the U.S. Alfalfa Farmer Research Initiative of the National Alfalfa & Forage Alliance as the funding source.

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