PASTURES WITH MANAGED GRAZING HAVE MORE SURFACE-SOIL CARBON THAN ROW CROPS

by

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Table of Contents

List of Figures

Abstract

Under the ever-intensifying threat of climate change, agricultural practices that increase soil organic carbon (SOC) long-term provide an opportunity to offset greenhouse gas emissions, and of equal importance, to adapt to climate change. Well-managed grazing has potential to generate SOC increases, though gaps remain as to what "well-managed" is, particularly when it comes to combinations of grazing frequency and intensity and how they may impact different fractions of soil carbon. As those practices are identified, they require adoption with some level of permanence to achieve soil carbon sequestration. To address these knowledge gaps, a mixed-methods, paired-site design was implemented, which consisted of analyzing soil from pasture-row crop pairs and interviewing graziers about their management decisions and motivations. Results indicated that pastures had greater SOC in surface soils than row crop pairs, with no significant differences in subsurface soils. SOC was inversely related to the grazing rest period (i.e., grazing frequency) but had no significant relationship with residual height (i.e., grazing intensity). Particulate organic matter-carbon (POM-C), a less stable form of SOC, was similarly related to grazing management. Mineral-associated organic matter-carbon (MAOM-C), a more stable form of SOC, was not related to these management parameters. Higher SOC was observed with increased pasture age. Graziers expressed economic and non-economic motivations for using grazing and appeared committed to the practice. These results suggest that grazed, perennial pastures provide potential for SOC accumulation and hold promise for long-term use given the benefits afforded directly to graziers.

Introduction

The effects of climate change, both current and forthcoming, are daunting, but hope can be found in the soil. Soil carbon storage, a key function of soils, can help mitigate climate change and ameliorate its consequences globally (Wiesmeier et al., 2019), though environmental benefits of soil carbon also extend to other levels of spatial resolution. Nationally, increased soil organic matter, which is responsible for the increase in soil carbon, has the potential to reduce eutrophication in the Gulf of Mexico by minimizing runoff and soil erosion on Midwest agricultural land (Porter et al., 2015). Locally, benefits from more organic matter accrue directly to farmers. Improved water infiltration, water retention and increased productivity result (Paustian et al., 2019), all of which serve as adaptations to climate change. Improved management of agricultural land, including well-managed grazing of grasslands, is necessary for achieving substantial increases in soil carbon to reap these benefits (Lal, 2018).

Promoting improved land management practices that can build soil carbon is not without challenges. Industrial agriculture, the dominant system of food, feed, fuel, and fiber production in the United States, promotes increased farm size and yields, which often supersedes efforts towards sustainable land management (Houser & Stuart, 2020; Zimdahl, 2015). These high input systems result in polluted water (Glibert, 2020), soil erosion (Thaler et al., 2021), and biodiversity loss (Rosenberg et al., 2019) with ramifications for human health (Horrigan et al., 2002), but farmers remain entrenched in this system (Benton & Bailey, 2019). Farmers are at the mercy of those setting commodity prices (Zimdahl, 2015) while simultaneously remaining in a cycle of new technology adoption referred to as the "technology treadmill" or the "treadmill of production" (Gould et al., 2004; Levins &

Cochrane, 1996). In Wisconsin, dairy farmers are fighting to remain afloat as a record 10% of dairy farms were lost in 2019, a product of low milk prices with already narrow profit margins (Wisconsin Public Radio, 2020). Given these challenges, other systems must be considered, but overcoming barriers to this transition is not trivial.

Grazing offers an alternative feeding strategy

Grazing livestock, a type of improved management of agricultural land, offers an alternative to this problematic system (Spratt et al., 2021). Management-intensive grazing tends to be more profitable than confined dairy operations supported by industrial agriculture on a per acre and per cow basis (Dartt et al., 1999; Hanson et al., 2013). Greater profitability results from milk premiums and reduced expenses. Farmers of managed grazing operations, or graziers, also report significantly greater satisfaction with quality of life than farmers of small to mid-size confined dairy operations in Wisconsin (Lloyd et al., 2007). Accompanying these benefits is the positive effect of managed grazing on the soil. Grazing has been shown to increase soil carbon (Conant et al., 2017; Machmuller et al., 2015; Wang et al., 2016), but many factors influence whether the soil acts as an atmospheric net carbon source or sink under grazing.

The grazing system impacts soil carbon, with rotational grazing being superior to continuous grazing (Byrnes et al., 2018; Mosier et al., 2021). Other factors include grazing intensity (Zhou et al., 2017), grassland composition (Mcsherry & Ritchie, 2013), and climate, as well as interactions between all three (Abdalla et al., 2018). For example, when considering grazing intensity exclusively, a light grazing intensity has been shown to be necessary for increasing soil carbon (Zhou et al., 2017). However, when considering grassland composition and climate also, a high grazing intensity increases carbon accumulation within a C4-dominated grassland (Mcsherry & Ritchie, 2013) and a moist warm climate (Abdalla et al., 2018). As a caveat to these patterns, it should be noted that there is variation among studies as to the classification of high, medium and low grazing intensities (Abdalla et al., 2018). Thus, best management grazing practices for increasing soil carbon are context-dependent.

From studies in Wisconsin, evidence of the potential for grazing to increase soil carbon is mixed. In a 20-year study, no significant change in soil organic carbon (SOC) was found under rotational grazing of cool-season pastures across the entire soil depth (90 cm), despite an increase in the surface 15 cm (Sanford et al., 2012). None of the other cropping system treatments in this study, variants of grain and forage systems, experienced any SOC gains over this 20-year period, and some significantly lost SOC. In a two-year study of cool-season pastures, rotational grazing had greater potential for net carbon accumulation than continuous grazing, harvested hay and unmanaged pasture (Oates & Jackson, 2014). Rotational grazing had a significantly lower net carbon loss than the other treatments in one year and was the only treatment to have a positive net ecosystem carbon balance in the second year.

Understanding soil carbon quantity and quality matters

Aside from grazing management decisions, soil carbon accumulation may vary as a result of environmental factors out of graziers' control. Topographic position can influence initial soil carbon content, which can impact the magnitude of change (De et al., 2019). Temperature increases resulting from climate change are predicted to lead to carbon losses, even under conservative models (Crowther et al., 2016). These effects of temperature increase were considered as explanations for the mixed results of soil carbon under grazing in

Wisconsin (Oates & Jackson, 2014; Sanford et al., 2012). Precipitation events following droughts, which are expected to occur more frequently under climate change, have also been shown to increase carbon mineralization (Smith et al., 2017) as can elevated soil moisture (Huang & Hall, 2017). These trends further emphasize that optimum grazing practices will be context-dependent and should be studied across a variety of environmental conditions (Lyon et al., 2011).

While monitoring changes in the soil carbon quantity is important, equally so is the soil carbon quality, especially if managed grazing is to be used as a climate change mitigation strategy. Increasing soil carbon must be aimed at achieving some level of permanence, in other words, “sequestering” carbon. To reach this ideal, an understanding of long-term carbon storage is necessary, which requires a focus on the quality of soil carbon that is accumulating, though not as it was traditionally defined (Lehmann & Kleber, 2015). Previously, the molecular structure of compound classes within soil organic matter was implicated as the key determinant of persistence in the soil, but environmental factors, biotic and abiotic, have instead been recognized as largely contributing to soil carbon persistence (Schmidt et al., 2011). In particular, mineral associations with organic matter have been shown to contribute to longer mean residence times through providing protection from microbial decomposition (Lavallee et al., 2019), though there is potential for some of these associations to be destabilized (Jilling et al., 2018). Regardless, optimizing soil carbon quality would involve maximizing the amount of mineral-associated organic matter (MAOM), which has been shown to accumulate primarily from the incorporation of microbial necromass under perennial crops, part of the in vivo microbial turnover pathway (Zhu et al., 2020).

Given this understanding, Lavallee et al. (2019) argue for measuring particulate organic matter (POM) and MAOM pools when assessing soil carbon changes. These pools are characteristically different and can be separated via physical fractionation, which allows for comparison across studies. MAOM appears to be more abundant within grassland soils than POM, but MAOM tends to saturate because there are a finite amount of mineral surfaces in soil, while POM does not (Cotrufo et al., 2019). Despite limited mineral surfaces, however, some research suggests that this may not be a limiting factor. Specifically, associations can also occur between other organic matter fragments and the pre-existing MAOM, though the strength of those interactions may vary (Jilling et al., 2018). Consequently, grazing management decisions aimed at sequestering carbon should strive to increase MAOM if saturation has not yet occurred, though opportunities for further increases in MAOM may remain.

Carbon will only be sequestered if pastures remain in place

Even if changes in management are shown to impact soil carbon quantity and quality, those practices must then be adopted by farmers for the benefits to be realized. Consistent predictors of farmer adoption of conservation practices are limited, but include environmental attitudes and environmental threats (Knowler & Bradshaw, 2007; Prokopy et al., 2019). In grazing systems, perceptions about the ease of use as well as the usefulness of grazing have been shown to be important for adoption (Schaak & Mußhoff, 2018). Equally important is long-term use of grazing practices to ensure soil carbon accrual is maintained. Beyond initial adoption of grazing, continued use of beneficial grazing practices is the goal, but literature on the maintenance of conservation practices is more limited.

Determinants of the continued use of soil and water conservation practices in developing countries have been shown to include actual profitability with intrinsic motivation also considered to be important (de Graaff et al., 2008). Other literature supports the potential role of intrinsic motivation in conservation behavior long-term (De Young, 1985; Mills et al., 2017), though interactions with extrinsic motivations occur as well (Mills et al., 2018; Van Herzele et al., 2013). Given that grazing systems have been shown to be profitable (Hanson et al., 2013) and offer satisfaction with quality of life (Lloyd et al., 2007), grazier experiences might provide insight to the linkages between these benefits and the continued use of well-managed grazing.

To better understand the role of grazing management in SOC accumulation, I explored how soil organic carbon quantity (i.e., soil carbon stocks) and quality (i.e., POM and MAOM carbon) 1) differed between grazed pastures and row crops, 2) varied along gradients of grazing intensity and frequency, and 3) related to other management and environmental variables. I also explored grazier perspectives to understand how they might relate to continued use of grazing practices.

Methods

I engaged Wisconsin graziers in two stages: 1) interviews about their grazing management practices and motivations and 2) collecting soils on their pastures and nearby row crop sites. Interview data provided insight into the complexities of each farm and each grazier's experience. Soil samples were analyzed to examine changes in soil carbon across management gradients.

Participants

Before contacting graziers, an institutional review board (IRB) proposal was submitted to the Education and Social Behavioral Science IRB at UW-Madison. The proposal was approved with exemption status. Following approval, graziers throughout southern and central Wisconsin were invited to participate in this research via phone or email communication. Of the 65 graziers initially contacted, 33 completed all aspects of the research study. Graziers were identified through snowball sampling, including contacts made through Wisconsin grazing networks, after beginning with graziers known to the research team. Initial inclusion criteria to participate in the research were:

i. Must be a Wisconsin grazier
ii. Must have a cool-season pasture established and grazed for at least three years
iii. Must have a nearby row crop reference site on a similar soil type that represents the land use of the pasture before it was established

No livestock requirements were part of the inclusion criteria, so the farms visited raised a variety of grazing animals, though primarily beef cattle and dairy cows. Following this initial screening and determining potential participants' interest, farm visits were scheduled.

Site selection

Of the 33 farms visited, pasture and reference sites were identified at all but two farms, on which only pasture sites were identified. Since some farms had multiple fields sampled, 47 pastures and 36 reference sites were sampled in total. All reference sites consisted of annual row crop rotations, either on the grazier's land or their neighbor's land. Common crop rotations included strictly corn and soybean rotations or corn, sometimes soybeans also, with a small grain and/or alfalfa. The graziers were actively involved in identifying the pasture and row crop site on their farms by sharing the cropping history and past renovations on the land. Using this background information as a baseline, the compared areas of pasture and row crop fields were also selected based on similarity in topographic position, slope, and aspect. The paired fields were as close geographically as possible, with the proximity ranging from just over the fence line to ~5.6 km. To ensure the pasture and crop field were on similar soil, soil maps were used initially, followed by in-field visual comparisons. Soil similarity was later confirmed by analyzing the soil texture using near-infrared spectroscopy and x-ray fluorescence (Zhang & Hartemink, 2020). Based on each of these qualities, paired fields were ranked on their comparability to serve as a guide for data interpretation.

Soil sampling

Ten, 30-cm deep, 2-cm diameter soil cores were collected from both the pasture and reference sites between July and October 2020. Samples were collected in a “W” pattern over an area of ~20 to 400 m^2. Soil cores from each site were split into 0 to 15- and 15 to 30-cm depth increments. The 10 samples from each depth were combined and homogenized to generate one composite sample per depth per site. Additionally, two bulk density soil samples, one at the 0 to 15-cm depth and the other at the 15 to 30-cm depth, were taken near the center of each sampled area using a hammer core, which contained metal sleeves that were 7.4 cm in diameter and 7.5 cm in height. After each core was extracted from the ground, the metal sleeves containing the soil core were removed from the hammer core, the soil was cut flush with the end of the sleeves, and the sleeves were capped. Soil samples were kept on ice in the field and stored at 4°C in the lab until processing.

Participant interviews

To supplement the soil data, semi-structured interviews were conducted with the graziers to better understand how their pastures and animals were managed. Questions about management included when the pasture was established, the grazing intensity and frequency used, and species composition of the pasture. Grazing intensity was operationally defined as the residual height after a paddock was grazed. Grazing frequency was operationally defined as the days of rest before grazing a paddock again. Intensity and frequency were given particular focus. The interviews also included open-ended questions about the graziers' motivations for their current grazing management practices and continued use of those practices. Those questions were important for understanding the likelihood of the continued use of grazing. All questions appear in Appendix A. I audio-recorded all interviews. The interviews were then transcribed with help from the research team and Descript transcription software. Graziers were randomly assigned a pseudonym for identification to maintain confidentiality.

Soil processing and analysis

Within one week of sample collection, each sample was sieved to 2 mm and roots greater than 2 mm were removed. The sieved soil was sub-sampled to fill a 50-mL Falcon tube ¾ full. Falcon tubes were placed in a freezer at -20°C until further processing. The remaining soil was allowed to air dry.

<u>Texture</u>

Soil texture was assessed on air-dried soils via near-infrared spectroscopy and x-ray fluorescence to predict sand, silt, and clay content for each sample, which were used to classify soil texture. Soil texture was then used to compare pasture and row crop pairs. Sites with dissimilar soils, defined as soils of a different soil texture classification, were excluded from soil carbon comparisons. Exceptions included 6 pairs in which one of the two samples fell on the border of a classification, so that the pairs appeared different despite being close together in soil texture.

Bulk density

Bulk density soil cores were removed from their metal sleeves and placed in pre-weighed aluminum pans. The soil was dried at 55°C until the mass stopped decreasing. Sample weights were then recorded with the pan weight subtracted out. Next, the dried soil was passed through a 2-mm mesh sieve to remove gravel. Gravel was weighed and bulk density was determined as:

$$(\text{Soil dry weight} - \text{gravel weight}) / (\text{Soil core volume}) = \text{BD } (g/cm^3)$$

Total soil carbon and nitrogen

Soils samples were analyzed by dry combustion on a Flash EA 1112 elemental analyzer to determine total organic carbon and total nitrogen. To prepare samples, approximately 1 cm^3 of air-dried soil was transferred to microcentrifuge tubes and homogenized. From the homogenized soil, 25 mg were added to tin capsules and rolled to close. Rolled tins were submitted for C/N analysis. Inorganic carbon in these samples was presumed to be negligible with confirmation provided as described below (see *Inorganic Carbon*). Therefore, total soil carbon is henceforth labeled soil organic carbon (SOC). The bulk density measurements and SOC mass percent output were used to calculate SOC stocks in units of Mg C/ha for each depth increment.

Mineral-associated organic matter carbon and particulate organic matter carbon

POM and MAOM were separated as in Cotrufo et al. (2019). Briefly, dried soil samples were dispersed with glass beads and 0.5% sodium hexametaphosphate. Samples were then rinsed over a 53-µm sieve. The sample remaining on the sieve contained the POM fraction and the sample, which passed through, contained the MAOM fraction. The POM and MAOM were washed into pre-weighed tins, dried, and weighed. Samples were transferred to microcentrifuge and centrifuge tubes for grinding and storage, respectively. To determine the carbon present in each fraction, the same procedure for determining total organic carbon via elemental analyzer was followed, though the mass used varied based on estimations of the soil carbon mass percent. To determine the POM-C and MAOM-C quantity, the percentage that each fraction contributed to the original soil sample by mass was calculated. Those percentages were then applied to the SOC stocks to calculate the POM-C and MAOM-C stocks.

Soil inorganic carbon

Field history was reviewed for each farm to determine the date of the most recent lime application, which may suggest the presence of inorganic carbon. Pasture samples with lime application in the previous 5 years were identified and tested using an adaptation from Sullivan et al. (2018). All row crop samples were tested since lime history was unknown. Briefly, homogenized soils were placed into well plates and ~0.4 mL of %5 acetic acid were applied. Positive controls were included. If samples effervesced, which was indicative of inorganic carbon, further analysis was performed. Effervescence was only observed in the positive controls, but not any of the pasture or row crop samples. Because none of the pairs appeared to have detectable amounts of inorganic carbon, total soil carbon was assumed to be equivalent to soil organic carbon.

Data analyses

Row crop SOC was subtracted from the paired pasture SOC for both depth increments. Three fields from two sites were initially excluded from this calculation because they did not have a row crop comparison. Others were not rotationally grazed and excluded. Additional sites were excluded from the analysis because differences in soil type, topographic position, slope, or drainage were observed. Finally, some sites had incomplete data and could not be included in this analysis. In total, 27 and 24 paired sites remained to be analyzed within the 0 to 15-cm and 15 to 30-cm depths, respectively. A paired t-test was used to compare the differences in total SOC among the pasture-row crop pairs within these two depth intervals. A paired t-test was also run on the paired data without making any exclusions. While the magnitude of the difference changed slightly, the relationship of SOC differences remained (Figure S1). All other analyses only used data from the 0 to 15-cm depth.

To better understand the variability in the SOC differences among the sites, those differences were also examined across management gradients of grazing intensity, i.e., residual height, and frequency, i.e., length of rest period, using simple linear regression. One point appeared to strongly leverage the observed relationships. Therefore, the same analyses were run with that data point removed. The general trends between SOC and grazing intensity and frequency remained the same with the exclusion (Figure S2). However, the significance of the relationship with grazing frequency changed. In response, the carbon analyses for that soil sample outlier were re-run, but similar carbon results were returned so the data-point remained. The relationship between SOC and intensity was also examined when only using data points that corresponded to a typical grazing frequency (i.e., 20 to 35 days), but this did not change the relationship (Figure S3). Finally, sandy sites appeared to be responding differently than other soil types, so sandy loam sites, which had the highest sand content of all the samples, were removed. Removing sandy sites improved the model so the remaining 24 points were analyzed. Similar relationships were observed when total pasture SOC was used as the response variable instead of SOC differences. Following the analyses of SOC, POM-C and MAOM-C were also examined across the grazing management gradients with sandy sites excluded.

Because of the observed and anticipated impacts of soil type and pasture age on SOC, linear mixed effects models were used to explore the effects of management while accounting for variation introduced by those variables. Grazing intensity and frequency were specified as fixed effects while pasture age and soil type were specified as random effects. Similar relationships between SOC and grazing intensity and frequency were observed when using these models. However, none of the linear mixed effects models significantly differed from the simple linear regression models. Therefore, only the statistics from the simple linear regressions are reported and interpreted.

Simple linear regression was used to explore relationships between pasture age with the SOC difference, total pasture SOC, and the ratio of POM-C to MAOM-C. Pasture age was recorded as each grazier's estimation of the time since the pasture was first established. Given uncertainties in the ages of the oldest pastures by the graziers, 100 years was the maximum recorded age. The relationship with the SOC difference was limited to the subset of well-paired sites and as a result, had few long-term pastures sites. In contrast, all data could be included for comparing total pasture SOC because the value was not dependent on the quality of any pairing. However, using total pasture SOC did not control for initial site differences in SOC. Therefore, both SOC values were compared to pasture age so that initial site differences were better controlled for with SOC difference values and more long-term sites could be included with total pasture SOC values. When analyzing both the changes in SOC and the POM-C to MAOM-C ratio with pasture age, sandy loam soils appeared to be outliers just as with the management relationships. Given the limited number of sandy sites, and to remain consistent, all samples classified as sandy loam were removed from all linear regression analyses. Again, 24 points remained. Sandy clay loam soils, another high sand soil, were also removed from the total pasture SOC linear regression. Because that regression contained all available pasture samples, it was the only analysis in which sandy clay loam soils were present.

Regression tree analysis was used to further explore which management decisions or environmental conditions explained the most variability in total pasture SOC, the SOC difference, and MAOM-C/POM-C pools. Grazing intensity, grazing frequency and pasture age were included as the management variables. Environmental variables included percent sand, percent silt, percent clay, carbon to nitrogen ratio, and site latitude. Regression tree output for MAOM-C and POM-C mirrored results observed from the previous linear regressions (Figure S4). Output for the SOC differences did not produce meaningful results and was not included.

Interview analysis

In the interview data, open coding was used to identify themes in questions with relevance for exploring continued use. Three questions given particular focus were as follows:

i. Why have you continued to use grazing?
ii. Have you had any moments where you considered stopping grazing?
iii. Have you experienced any atypical events that have stopped you from using these typical practices?

Results

Soil organic carbon greater in pasture surface soils

Pastures had 10.67 Mg SOC more per hectare in the surface 15 cm of soil compared to their row crop pair ($t = 4.38$, $p < 0.001$, Figure 1). However, not all pasture surface soils had higher carbon than their row crop pair (Figure 2). Within the 15 to 30-cm depth, no significant difference was observed in SOC between the pasture-row crop pairs ($t = -0.13$, $p = 0.55$, Figure 1).

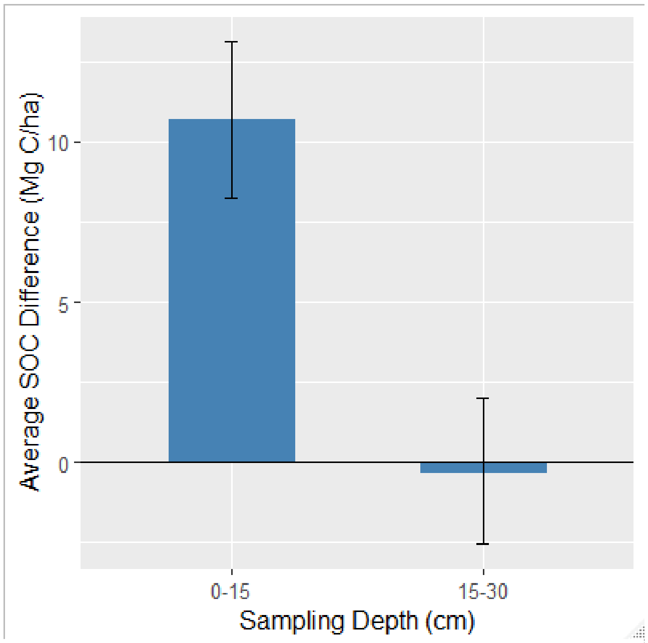


Figure 1. Mean (+/- SE) soil organic carbon difference between pasture-row crop pairs for the a) 0 to 15-cm, n=27 pairs and the b) 15 to 30-cm, n=24 pairs depth increments.

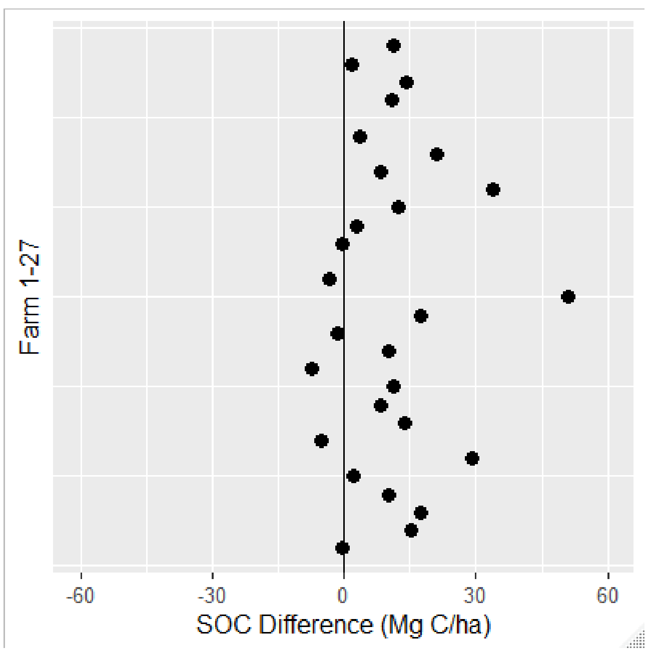
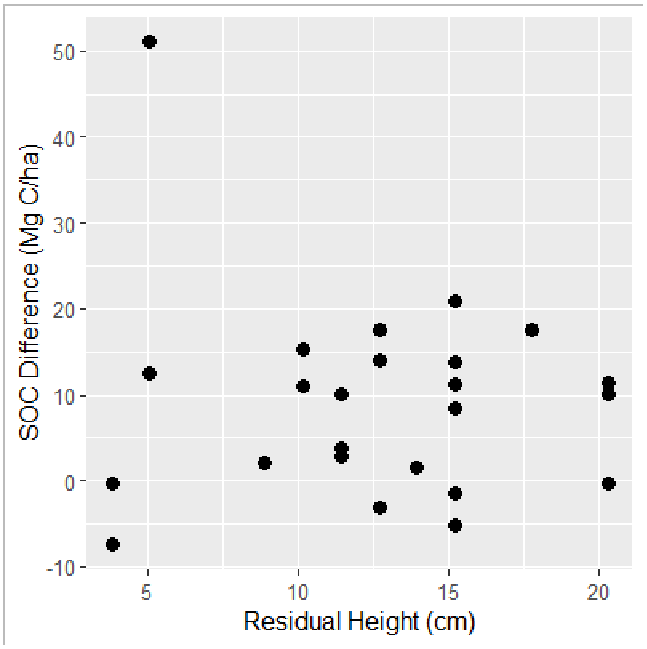


Figure 2. Individual differences in SOC between pasture-row crop pairs at the 0 to 15-cm depth, n=27 pairs. All pastures are rotationally grazed, but management intensity varies.

Grazing intensity and frequency exhibit limited impact on SOC dynamics

Grazing intensity was not significantly related to the SOC differences (*p* = 0.66, Figure 3a). Grazing frequency, however, had a significant, inverse relationship to the SOC differences (R^2 = 0.39, p = 0.004, Figure 3b).



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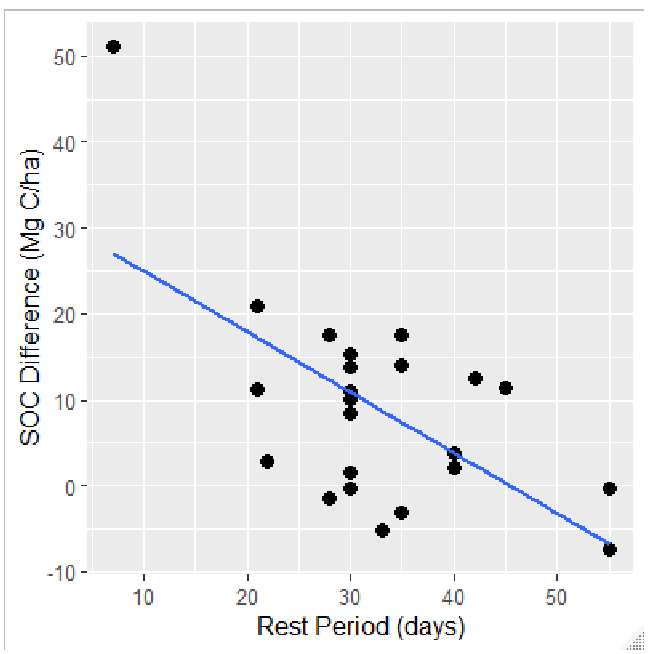
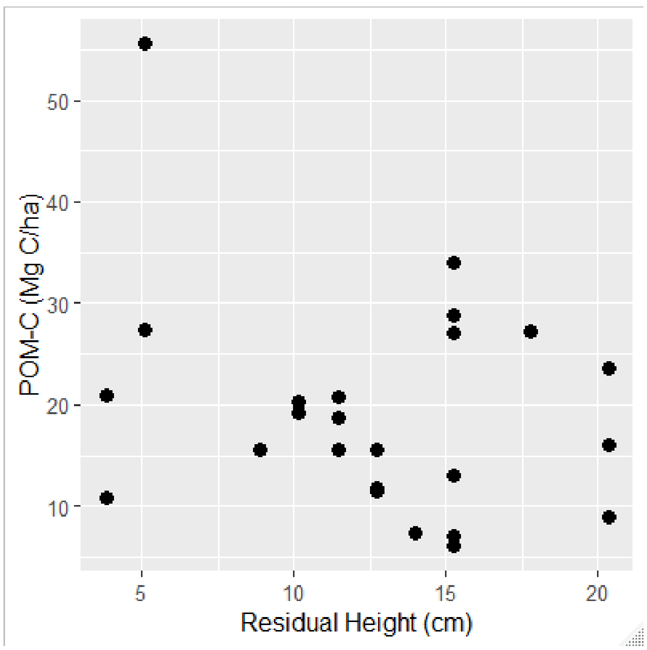


b)

Figure 3. Differences in SOC between pasture-row crop pairs across management gradients of a) residual height after grazing and b) number of days before grazing a paddock again.

POM-C but not MAOM-C similar to SOC under management gradients

POM-C had a slight inverse relationship with grazing intensity, but the relationship was not significant (p = 0.23, Figure 4a). A significant inverse relationship was observed between POM-C and the rest period (R^2 = 0.27, p = 0.01, Figure 5a). These trends are similar to those observed with SOC. MAOM-C, however, did not appear to be responsive to either grazing management parameter (p = 0.95, Figure 4b; p = 0.77, Figure 5b).

a) 

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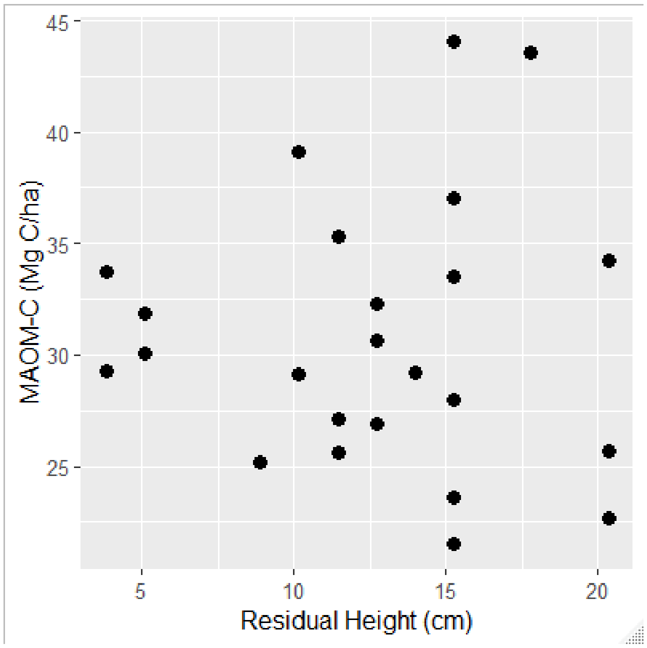
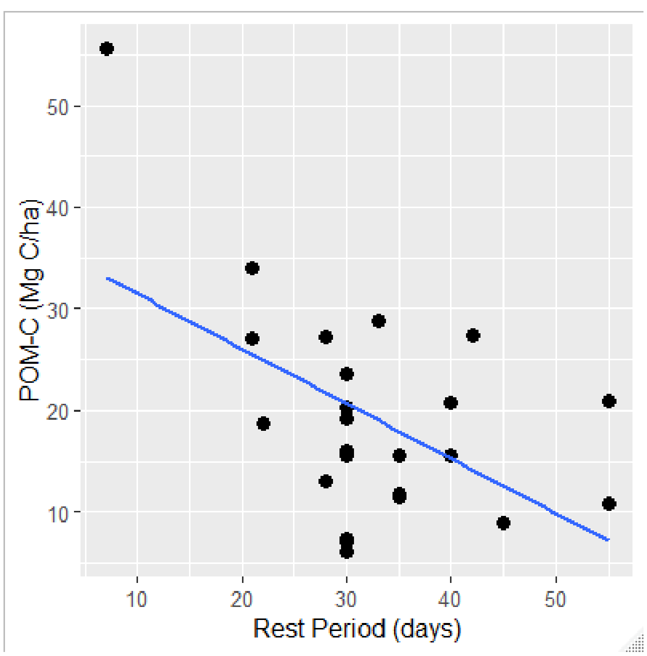
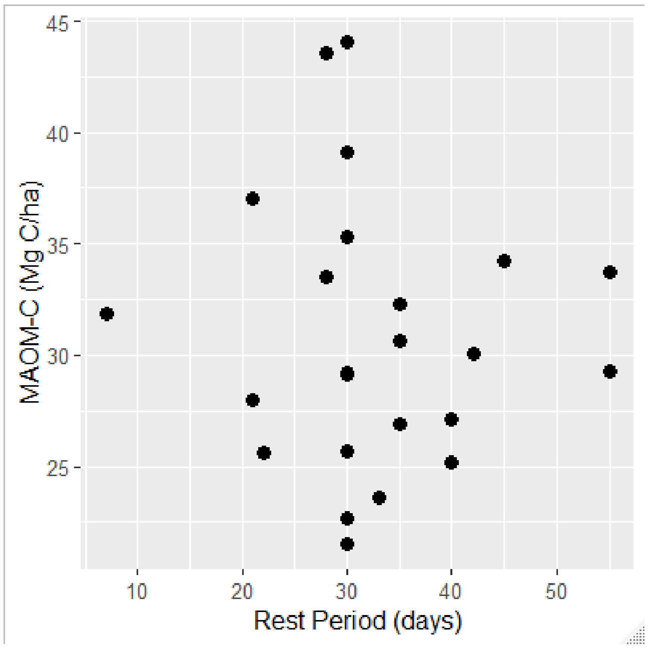


Figure 4. Relationship between residual height after grazing and a) particulate organic matter carbon (POM-C) and b) mineral-associated organic matter carbon (MAOM-C).

a)



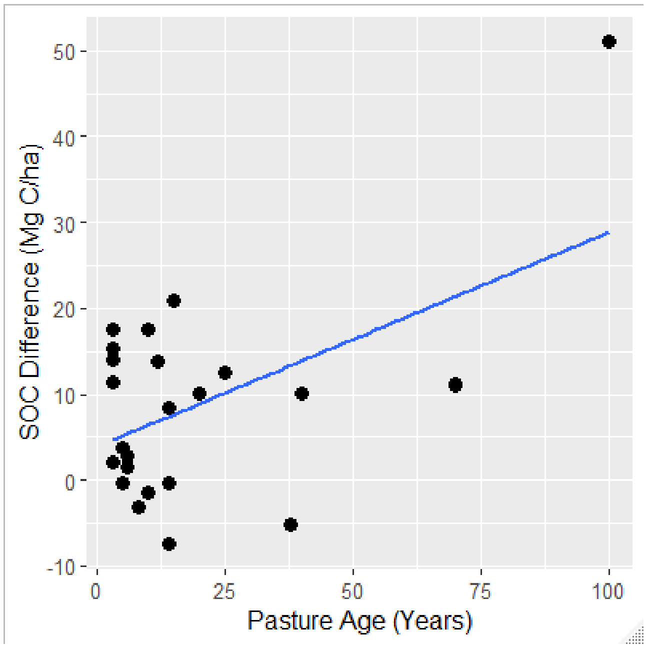


b)

Figure 5. Relationship between the rest period between grazing events and a) particulate organic matter carbon (POM-C) and b) mineral-associated organic matter carbon (MAOM-C).

Pasture age positively correlated with SOC and POM-C to MAOM-C ratio

Another management parameter, pasture age, was significantly correlated with SOC (Figure 6), both when considering SOC differences and total pasture SOC. Specifically, a significant positive relationship was observed with SOC differences across pasture age gradients ($R^2 = 0.29$, $p = 0.01$, Figure 6a). A similar relationship was observed for total pasture SOC, which contained more sites ($R^2 = 0.40$, $p < 0.001$, Figure 6b).



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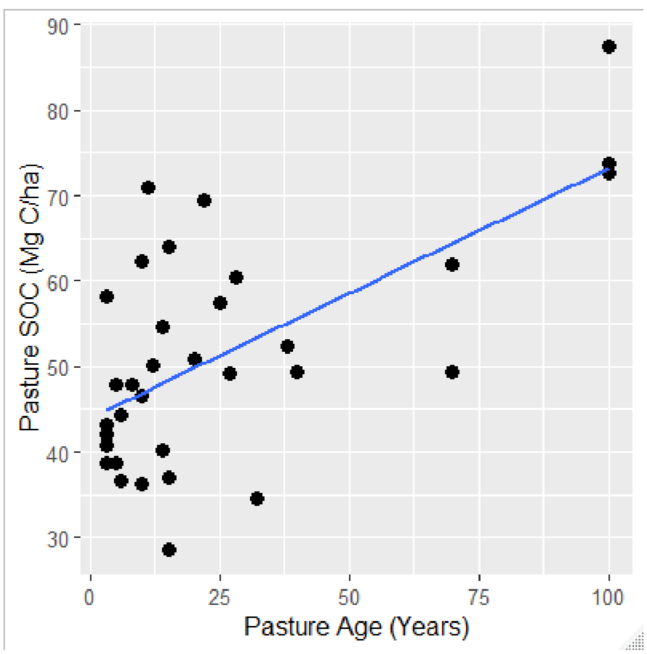

b)

Figure 6. Relationship between pasture age and SOC when carbon is represented as a) the SOC difference between pasture-row crop pairs or b) the total amount of SOC present in pastures.

Additionally, the ratio of POM-C and MAOM-C was significantly correlated with pasture age ($R^2 = 0.61$, $p < 0.001$), such that as age increases, the ratio increases (Figure 7).

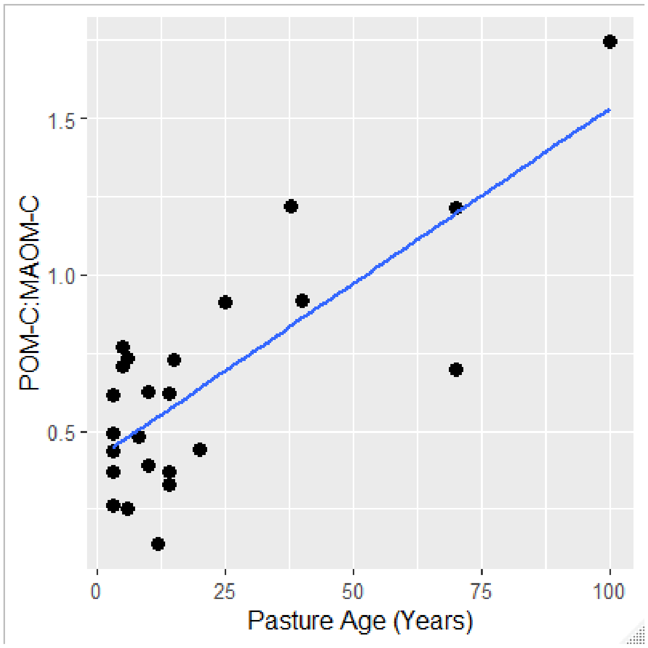

Figure 7. Relationship between pasture age and ratio of POM-C to MAOM-C.

Pasture age and SOC had strongest relationship

When using total pasture SOC as the response variable, pasture age emerged as the only variable which split the data to minimize variance (Figure 8). Older pastures were associated with more soil carbon.

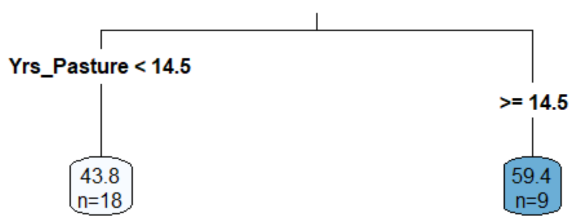

Figure 8. Regression tree analysis output for total pasture SOC. The included variables are as follows: grazing intensity, grazing frequency, pasture age, % sand, % silt, % clay, C:N, and site latitude.

Grazier attitudes demonstrate commitment to beneficial grazing practices

I explored responses related to the continued use of grazing practices, expressed as grazing motivations and commitment to the practice. While benefits of grazing are known (Conant et al., 2017; Hanson et al., 2013; Lloyd et al., 2007), they have not been explicitly related to the continued use of grazing. Other studies outside the context of grazing have linked profitability (de Graaff et al., 2008) and intrinsic motivations (Mills et al., 2017) to continued use. I also considered disruptions from extreme weather events to grazing practices, as they may have implications for the commitment to grazing long-term. Other research has demonstrated a relationship between extreme weather events and increased adoption of conservation practices (Druschke, 2013), though this research considers the impact after grazing, a conservation practice, has already been adopted. Both explorations were critical to understanding the long-term use of grazing, which is an essential part of soil carbon sequestration.

Grazing was profitable and personally beneficial

In this research, the graziers appeared very motivated to continue using their grazing practices, with many providing more than one justification. These included both economic and non-economic motivations. In considering economic motivations for continued use, the graziers highlighted profitability. For Jay, the profitability of grazing was a primary motivator as it provided the ability to continue with the practice, in particular reflecting, “we can continue to farm because of it, because of the money that we do save” (5/20/2020). The graziers also expressed that grazing was more profitable than conventional agricultural practices. This included row crop agriculture, with Jeremy sharing “most years, we make the most money per acre on our grazing acres as opposed to row crops” (3/9/2020). It applied to conventional dairy as well, as Thomas said it “gives you a lower cost to milk, so it increases your margins on your milk, on what you make over your expenses compared to conventional dairy” (5/12/2020). Therefore, one of the motivations for continued grazing seemed to be that it was profitable overall, and even more so than other systems.

The graziers expressed non-economic motivations, including intrinsic motivations, through a variety of explanations. Intrinsic motivations ranged from enjoyment to lifestyle benefits to environmental benefits. Enjoyment was found in different ways, from “lightbulb moments” as Ronald discovered benefits to his animals, the environment, and his family (5/4/2022) or in how grazing provided Roy options for experimentation which was reinforced through “favorable outcome[s]” (4/29/2020). Lifestyle benefits included minimizing time spent on heavy machinery and positive impacts for children and families in that it “teaches them very good values and morals” as part of “a small family farm” (Alex, 3/9/2020). These graziers found personal value in farming this way, not just monetary value.

Previous literature has considered the significance of each attitude or motivation individually when examining relationships with adoption or continued use (de Graaff et al., 2008; Prokopy et al., 2019), but the combination of the different benefits were important for many graziers. Sean and Dennis referred to the “triple bottom line” when talking about benefits of grazing. Sean defines this as the “social impacts, economic impacts, [and] environmental impacts” (6/24/2020) and Dennis referred to the benefits “financially, biologically, [and] ecologically” (7/20/2020). Russell found enjoyment in grazing “just because of all the benefits of it” citing animal health, good land use and the organic standard (7/30/2020). These responses demonstrated that there was no one overarching benefit but having multiple benefits at once made grazing appealing.

The importance of multiple benefits appeared in the interplay between the motivations for continued use and the initial motivations for adopting grazing, as they were not perfectly aligned. Thomas considered “liking the idea of pasture” as most important for initial adoption, but financial benefits as critical to continued use, stating “if it had not cut costs, I probably would not have stuck with it” (5/12/2020). With Cory, safety and enjoyment were initial considerations, but what motivated her to continue were the environmental benefits sharing grazing is “actually super cool because I’m a huge environmentalist” (8/4/2020). Continuing to find benefits while implementing grazing practices seemed to be important to long-term use.

Graziers are strongly committed to grazing

With the benefits the graziers experienced from grazing, most never considered stopping, with some providing very strong responses. Billy demonstrated strong commitment by offering an implausible circumstance for stopping of “minus 60 degrees temperature all year” (3/17/20). Others considered no alternatives. Sean said, “there’s no other way” to farm besides grazing (6/4/2020), and for Thomas, if the option was to stop grazing, “it’d be time to throw in the towel and quit farming” (5/12/2020). Furthermore, this distinction appeared between considering stopping and the actual intent not to graze. This became evident when George expressed that he considered stopping “probably every day” (7/23/2020). However, when asked more explicitly about circumstances that would make him stop, George said, “I would quit farming first”. Others expressed similar sentiments given the challenges of farming yet when it came to not grazing, Jeffrey had “not seriously considered it” (7/31/2020) and Cory never considered replacing it “with a different farming method”

(8/4/2020). This suggested that these graziers are strongly committed to the practice with few who had seriously considering stopping grazing.

Extreme weather creates disruptions, but some graziers can adapt

Despite these strong commitments, extreme weather events did present challenges. Disruptions came from both excessive rainfall and drought. Too much rain limited accessible acres as Taylor recalled "there's certain parts of the farm we just have to fence them out of when it's too wet" (6/1/2020). Impacts extended beyond single farms too. Carl shared how excessive rainfall "has changed a lot of the grazing dynamics for people in that zone right here" (6/11/2020). For others, drought was instead an issue, which also limited acres for grazing. In Jimmy's experience, "I had to quit grazing just because I didn't have any pasture because it was all dried up" (5/11/2020). Fortunately, others found they could adjust their grazing practices to adapt to weather events. Adjustments for Cory included moving animals to "shaded fence rows" in response to higher temperatures and using "higher and lower areas" depending on rainfall (8/4/2020). Justin turned to "[eating] the grass a little bit shorter" to help "slow us down" under drought conditions (6/23/2020). For Douglas, another option was to move the animals and "keep them in the free stall barn" to deal with rain and heat (5/11/2020). These adaptations illustrate the ways in which grazing can be an adaptive system, but acreage, landscape, and infrastructure might make adapting more feasible on some farms than others.

These results indicate that graziers have found grazing to be beneficial, and often for multiple reasons. This has translated to a strong commitment to maintaining their grazing practices. However, extreme weather events created challenges, though there may be options to adapt.

Discussion

Under rotational grazing, management decisions related to grazing intensity and frequency seemed to be less important for soil carbon differences than the agricultural system that was implemented, specifically whether it was perennial pasture or annual row crops. Pastures evidently had more carbon than their row crop pairs on average, making them the most promising agricultural strategy for accumulating soil carbon, or at the very least, minimizing soil carbon losses. Given the positive relationship between soil carbon differences and pasture age, which suggested accumulation was occurring, planting and maintaining perennial pastures all across the landscape is needed. The need for maintaining pastures was further supported by the accumulation of POM-C, the less stable fraction of SOC, over MAOM-C. There are major challenges to this paradigm shift towards more perennial agriculture (Benton & Bailey, 2019), but grazier experiences and commitments provide hope.

SOC responses do not indicate a one-size-fits-all approach to grazing management

Grazing intensity was not an important determinant of SOC differences in these sites and grazing frequency was only weakly correlated. This has implications for on-farm management. Despite a significant inverse relationship with grazing frequency, the relationship was highly leveraged by a few data points, which when excluded, made the relationship no longer statistically significant. Also, neither intensity nor frequency appeared as explanatory variables in regression tree analyses; only pasture age and soil texture appeared to explain SOC differences. The inherent productivity of the site may be a confounding variable too, which would explain the significant relationship with grazing frequency. Sites with greater productivity and related higher SOC could enable farmers to use a higher grazing frequency, i.e., a shorter rest period. On the other hand, less productive pastures would need a longer rest period. Thus, rather than SOC differences being driven by the grazing frequency, the frequency could instead be a response to inherent differences in productivity and soil carbon.

Stronger relationships may have been observed if more extreme grazing practices were included, such as continuous and/or overgrazing. However, these data did not encompass a full range of grazing frequencies and intensities as self-selection bias was likely present. Knowing that this work would compare grazing management systems, we assumed graziers would be more likely to participate if they felt they had implemented well-managed grazing. While there was some variability, most graziers employed more moderate grazing practices, with residual heights mostly between 8 and 20 cm and rest periods between 20 and 40 days. In addition, continuously grazed sites had been removed prior to data analysis to limit interpretations to rotationally grazed sites. These constraints, however, made the results more applicable to the managed grazing practices observed on the landscape in Wisconsin.

Previous studies have observed relationships between soil carbon and grazing intensity (Abdalla et al., 2018; Mcsherry & Ritchie, 2013; Zhou et al., 2017) and frequency (Byrnes et al., 2018; Mosier et al., 2021). In particular, higher SOC has been observed under a light grazing intensity in cool-season pastures (Mcsherry & Ritchie, 2013) and longer rest periods (Mosier et al., 2021). However, those finding were based on meta-analyses (Abdalla et al., 2018; Byrnes et al., 2018; Mcsherry & Ritchie, 2013; Zhou et al., 2017) that identified broad patterns across regions or strictly limited paired sites which minimized variability (Mosier et al., 2021). Given these differences in spatial resolution and variability, along with the exclusion of more extreme management practices, we might expect small shifts in management to have less of an impact as was shown in this research. In addition, we considered grazing intensity as a continuous variable. This differed from the categorical comparisons in the meta-analyses, which can vary in their definitions (Abdalla et al., 2018). Therefore, in this region within the observed ranges, shifts in grazing intensity and frequency were observed to have little or no relationship with soil organic carbon quantity or quality. The minimal response of SOC to these different grazing intensities and frequencies is an important finding for graziers. Rather than turning to ‘recipe’ style farming with a prescribed grazing intensity and frequency, they can adopt practices best-suited to their agroecosystem without jeopardizing potential soil carbon gains.

More important than how pastures were managed was whether the pastures existed or not

Higher SOC in grazed, perennial pastures under various management demonstrated the importance of this agricultural system. Differences in SOC between pastures and row crops are consistent with previous literature (Diederich et al., 2019; Machmuller et al., 2015). Increased perenniality (McGowan et al., 2019; Sanford et al., 2021) and integration of livestock (Oates & Jackson, 2014) under pasture management compared to the row crop fields likely contributed to these results. In this research, the changes in SOC observed under grazing were limited to the surface 15 cm of soil. SOC differences in the surface soils only may reflect where most of the roots are concentrated (Cougnon et al., 2017), which provide carbon inputs, and can be limited in growth from grazing (Johnson & Matchett, 2001). Greater surface SOC is consistent with a meta-analysis of grazed sites (Wang et al., 2016) and prior long-term research of grazed, cool-season pastures (Sanford et al., 2012), though Sanford et al. (2012) found the SOC increases in the surface soils under grazing were not significantly different from baseline SOC measurements. Other studies, however, have observed differences at greater depths (Mosier et al., 2021). Differences in these findings may reflect differences in the methodology, and as previously mentioned, variability. A paired-site design was used in both this research and research by Mosier et al. (2021), which does not include baseline SOC measurements. Mosier et al. (2021) also significantly minimized variability when selecting paired sites and ensured consistent management practices had been employed for longer amounts of time. These constraints may have contributed to observed differences at greater depths, while such differences were not present in this or other research (Sanford et al., 2012; Wang et al., 2016).

A paired-site design does have some limitations as problems with space-for-time substitution are well known (Sanderman & Baldock, 2010). As a result, although pastures had more carbon than row crop sites, an alternative explanation is that pastures have simply maintained their soil carbon while the row crop fields have lost carbon as Sanford et al. (2012) have observed. However, the direction of SOC change may be inferred from interpreting SOC relationships with pasture age.

While pastures overwhelmingly contained more SOC in the surface soils on average, for some pairs, SOC was greater in row crop fields. One consideration is that the row crop comparisons were diverse, consisting of a variety of crop rotations and tillage practices, with some identified as organic and others as conventionally managed. Unique crop rotations, especially if livestock were integrated into the management, might be part of the explanation for these differences. Also, SOC accumulation is a slow process, so some pastures may not have been established long enough for the differences to occur, especially when considering the tillage history. Aside from current management, similarities in prior land use is an important component in paired studies as it can contribute to legacy effects (Sikora, 2020).

While steps were taken to minimize this potential confound when identifying sites, the entire land use history may not be identical due to changes in ownership over time. However, since no significant difference in SOC was observed at the 15 to 30-cm depth, those differences, if any, were assumed to be negligible. While these factors may have influenced some of these sites, no consistent patterns have been identified across the row crop sites with more SOC. Future work will explore the nuances of these exceptions, but this does not negate the overall importance of perennial pastures.

Long-term establishment of pastures may lead to SOC accumulation

SOC positively correlated with pasture age, which suggests that soil carbon may be accumulating in pastures, though slowly. This supports the need for maintaining pastures long-term, especially given that pasture age was the only explanatory variable in the pasture SOC regression tree analysis. An increase in SOC over time aligns with previous research (Franzluebbers et al., 2012; Rowntree et al., 2020), but estimated rates differ. In particular, the slope of the relationship between SOC and pasture age might be inferred as the rate of soil carbon accumulation (0.25 Mg C ha^{-1} yr^{-1}). This contrasts with 10-fold higher estimates of SOC accumulation by others (2.29 Mg C ha^{-1} yr^{-1} (Rowntree et al., 2020) and 3.59 Mg C ha^{-1} yr^{-1} (Stanley et al., 2018)), though those rates are based on much shorter amounts of time (20 years (Rowntree et al., 2020) and 4 years (Stanley et al., 2018)). A more conservative estimate ranges from 0.04 to 0.21 Mg C ha^{-1} yr^{-1} (Chambers et al., 2016). Within this research, however, few long-term sites are highly leveraging the relationship. Thus, future work should continue to identify and sample long-term pastures, so that the relationship is more robust and contributes to the understanding of SOC accumulation over longer periods of time. This will provide more confidence in any derived rates for soil carbon accumulation, which is critical as carbon sequestration is incentivized and carbon neutrality is hinged upon it.

As outlined in the methods, sandy loam sites were excluded from comparisons with pasture age as they seemed to be responding differently than the other soils. This difference may be reflective of differences in SOC storage capacity in sandier soils (Wiesmeier et al., 2019). Future work will aim to include more sandy soils to better understand the unique patterns in this subset of samples.

POM and MAOM responded differently to grazing management

POM-C accumulation supports the need for pasture maintenance, though further insights can be gained from understanding this response. While MAOM-C was the dominant fraction in these sites initially, which is expected in grassland soils (Cotrufo et al., 2019), that relationship seemed to change with time. The ratio of POM-C to MAOM-C increased with pasture age, such that POM-C eventually dominated in some sites. This change in the ratio is supported by the differing response of POM-C and MAOM-C to grazing management practices, particularly that POM-C was much more responsive, a finding supported by previous research (Plaza-Bonilla et al., 2014). Furthermore, in regression tree analyses, POM-C differences were largely explained by pasture age, but only clay content emerged as an explanatory variable for MAOM-C. It may be that MAOM-C had reached saturation in most of these pasture soils. However, under European grassland and forest soils, saturation has been observed at 50 g SOC kg^{-1} soil (Cotrufo et al., 2019), or 5% SOC, which is greater than the SOC mass percent observed in nearly all of these sites. Therefore, if the relationship holds in Wisconsin soils, saturation has likely not occurred, which may suggest that MAOM-C was instead accumulating very slowly in these systems.

A widespread shift from annual to perennial agriculture benefits the soil and graziers

Understanding grazier experiences and motivations for their management practices may be a step towards soil carbon sequestration given the importance of continued use in maximizing and maintaining accumulated carbon. In particular, the reversibility of grazing adoption has been used as a critique of employing grazing to build soil carbon (Godde et al., 2020), though graziers in this research seem motivated to maintain their practices. As stated, the grazier participating in this research shared several economic and non-economic motivations for continuing with their grazing practices. Profitability was greater than confined dairy and row crop agriculture for some graziers. This aligned with previous work demonstrating the profitability of grazing compared to confined dairy (Hanson et al., 2013), and is consistent with research linking actual profitability to the continued use of conservation practices (de Graaff et al., 2008). Graziers also noted many personal benefits from grazing as influential in the continued use of their grazing practices. This aligns with research suggesting intrinsic motivation is an important factor for continued use as well (De Young, 1985; Mills et al., 2017). While individual motivations for continued use appeared, the combination of multiple benefits seemed to be an important aspect of grazing.

As further evidence of the connection between these benefits with long-term use, graziers expressed a strong commitment to grazing, which was demonstrated by the limited thought given to stopping. Nevertheless, challenges were still present, especially related to extreme weather events, which will only be exacerbated by climate change (Fischer & Knutti, 2015; Trenberth, 2008). Fortunately, grazing systems are more resilient than row crop systems and better positioned to adapt (Sanford et al., 2021). Some graziers even implemented their own adaptation strategies. Each of these benefits associated with grazing make it more likely to be a long-term practice, a critical component of making grazing a strategy for sequestering carbon.

On-farm research provides critical insights

An important consideration of this research is that it is being done on real farms. These data are therefore the results of a combination of measured variables and the graziers' retelling of their own practices. These graziers are responding to their environments and making decisions based on their own observations to determine the best practices for their land (Paine et al., 2000). They are adapting, adjusting, and experimenting, which means the practices are not always consistent. Knowing this complexity makes the results all the more exciting and also more generalizable (Lyon et al., 2011). Thus, this research offers insight into grazing systems collectively, while also reminding us that landscape changes occur one farmer at a time.

Conclusions

The potential for SOC accumulation is greater under rotationally grazed, perennial pastures than row crop production. Management of those pastures, however, is not as straightforward. Well-managed grazing is adaptive and seems to encompass a variety of grazing practices within these Wisconsin sites. This indicates that to achieve these soil carbon benefits, a paradigm shift in our current agricultural system is needed where perennial agriculture is dominant. Further research focused on exploring SOC fractions under row crop agriculture, inherent site productivity, and older pastures sites will contribute to our understanding of more specific management recommendations and guidelines.

Increasing the adoption of perennial pastures on the landscape does more than benefit the environment; it benefits graziers economically and personally. This is critical because farmer livelihoods should always be considered when promoting any agricultural system. Those benefits also make the prospects of long-term grazing management promising, which is essential for climate change mitigation. A future landscape of more well-managed, perennial pasture can provide a pathway to increased resilience without compromising farmers, animals, or the land.

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Supplemental Info

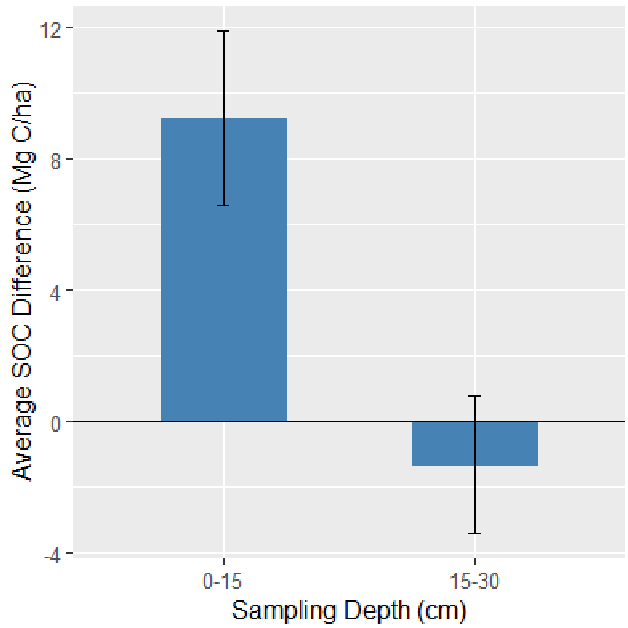
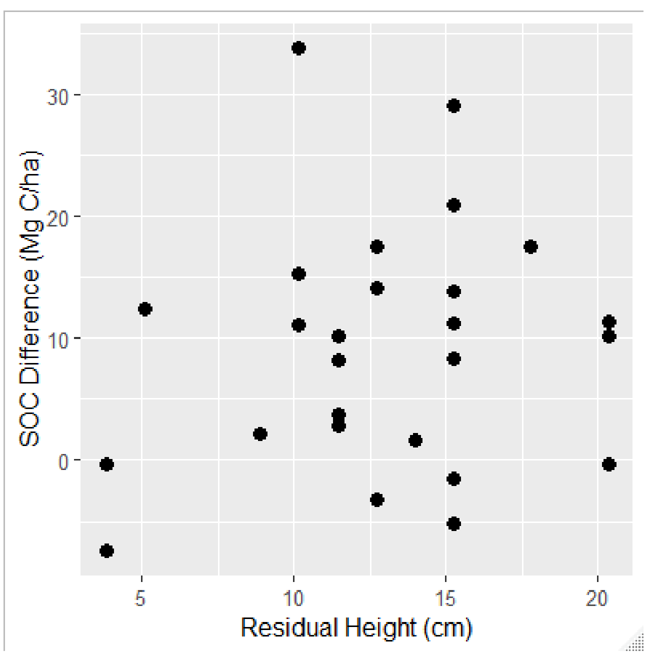
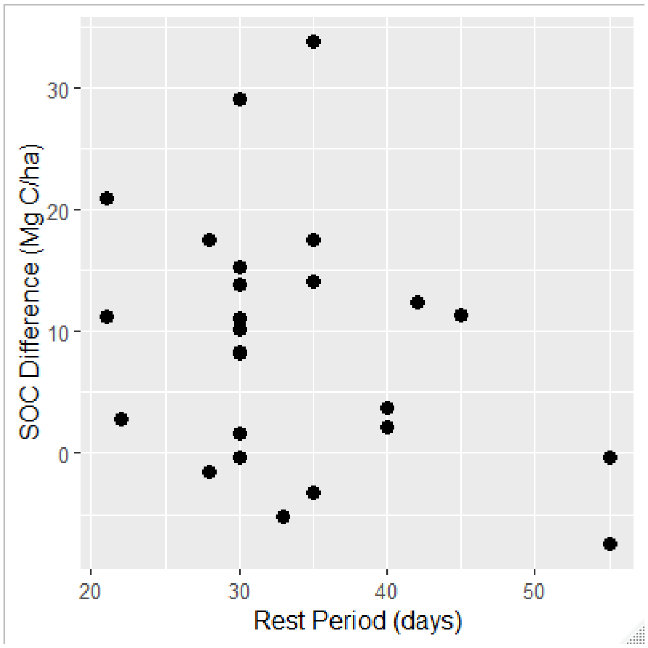


Figure S1. Mean (+/- SE) soil organic carbon (SOC) differences between pasture-row crop pairs. All paired sites are included. Pastures have significantly more SOC at the 0 to 15-cm interval ($t = 3.49$, $p < 0.001$) with no significant difference at 15 to 30-cm interval ($t = -0.62$, $p = 0.27$).



a)



b)

Figure S2. Differences in SOC between pasture-row crop pairs across management gradients of a) residual height after grazing and b) number of days before grazing a paddock again, but with the highest outlier removed. Neither intensity ($p = 0.43$) nor frequency ($p = 0.11$) were significantly related to the SOC differences.

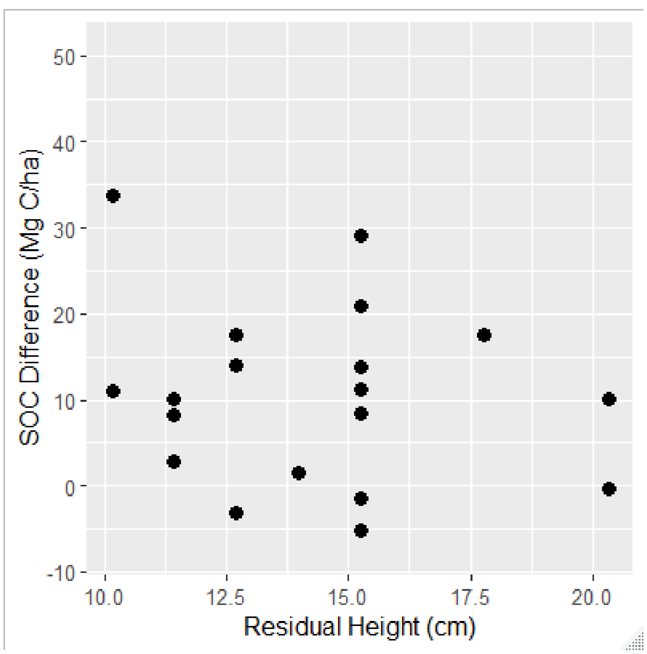
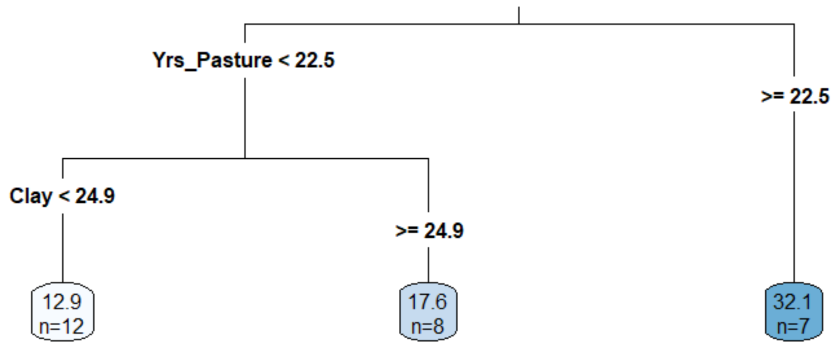


Figure S3. Difference in SOC between pasture-row crop pairs across a management gradient of the residual height after grazing. Data points included are only those which also correspond to a typical grazing frequency (i.e., 20 to 35 days). There was no significant relationship ($p = 0.46$).



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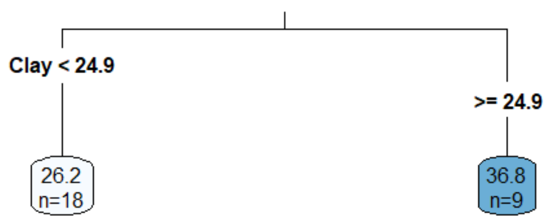

b)

Figure S4. Regression tree analysis output for a) POM-C and b) MAOM-C. The included variables are as follows: grazing intensity, grazing frequency, pasture age, % sand, % silt, % clay, C:N, and site latitude.

Appendix A

Background questions:

1. In what year were you born?
2. In what year did you begin farming, not including childhood years on your parents' farm?

Technical questions:

3. Roughly how many pasture acres do you graze?
4. Roughly how many and what kind of livestock do you graze?
5. Can you describe your pasture soil(s)?
6. Can you describe the typical water pattern in your pasture(s) throughout the season?
7. How long has your pasture been established?
8. What cropping system was here before this land was converted to pasture?
9. When was your pasture last renovated, e.g., the species composition drastically changed?
    a. How many times has your pasture been renovated?
    b. In what years?
10. What did you plant in your pasture?
11. What do you think is growing in your pasture?
12. What are the dominant grasses in your pasture?
13. What is the average percent cover of legumes on your pasture?
    a. If you feel like there is considerable variation, you can also provide a minimum and maximum value.
14. I want to understand a bit about your fertilizer routine.
    a. If applicable, what would you estimate is the average rate of nitrogen application?
    b. If applicable, what would you estimate is the average rate of phosphorous application?
    c. If applicable, what would you estimate is the average rate of potassium application?
15. Do you manage the pH of your pasture with liming?
    a. If so, when was your last application of lime?
    b. What was the rate?
16. Do you graze your livestock year-round?
    a. If not, what day do you typically start grazing for the season? What day do you typically end grazing for the season?
    b. Are your livestock receiving any supplemental feed during the grazing season?
17. What do you do with your animals in the winter, i.e., what is your winter feeding and housing strategy?
    a. Are they consuming forage on the ground, hay from haybales, etc.?
18. Are you practicing managed grazing or continuous grazing?
19. I understand that grazing intensity can vary, but I want to get a good sense of what is *typical*.

a. What is the minimum residual height after grazing?
b. What is the maximum residual height after grazing?
c. What is the average residual height after grazing?

20. I understand that grazing frequency can vary, but I want to get a good sense of what is *typical*.
    a. What is the minimum number of days before grazing a paddock again?
    b. What is the maximum number of days before grazing a paddock again?
    c. What is the average number of days before grazing a paddock again?
21. How frequently do you move your livestock from one paddock to another?
22. Have you grazed your livestock this same way since establishing your pasture?
    a. If not, what has changed?
    b. How long have you been managing the pasture the way you are now?
23. Have you experienced any atypical events that stopped you from using these *typical* practices?
    a. If so, how frequently?
24. Do you have any soil carbon data that has been collected on your farm previously?
    a. Is that something you would be willing to share?
25. Would you like me to follow-up with your results from the soil carbon analysis?
26. Is there anything else you think is important for me to know about your pasture management?

Social science questions:

27. How did you learn about how to implement grazing?
    a. Do you still rely on that same source of information?
    b. Are there others?
28. What was your top motivation for adopting grazing?
    a. Did you have any other motivators?
29. What is your top motivation for rotating your livestock the way that you do?
    a. Do you have any other motivators?
30. Why have you continued to use grazing?
31. Have you had any moments where you considered stopping grazing?
    a. If so, can you tell me about those?
32. Are there circumstances that would make you stop grazing?
33. Are there any changes you'd like to make to your management practices or are you happy with what your practices are doing for your livestock and farm?
34. Do you rent or own the pasture that is grazed?
    a. Do you feel that has influenced your decision to use grazing?
35. Do you talk to others about your motivations for grazing who are not currently using grazing?
    a. If so, what do you tell them?
36. Is there anything else you'd like to add? Are there any additional motivations to share or anything you think is also important for me to know?