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Soil organic carbon accumulation in restored native prairies over time

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SOIL ORGANIC CARBON ACCUMULATION IN RESTORED NATIVE PRAIRIES OVER TIME

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Abstract

With the recent focus on the causes and effects of climate change, the relationship between agriculture and climate change has become an important concern. Conventional farming maximizes crop production at the expense of ecosystem services like soil carbon storage. As the human population grows, it is vital to develop practices that balance crop production and ecosystem services.

We investigated organic carbon accumulation in restored prairie soil over the course of a decade. Our goal was to determine how organic carbon levels and soil bulk density changed over time, and how that change was influenced by species diversity and soil depth. We hypothesized that more organic carbon would be stored in soil over time, and bulk density would decrease, both of which we found to be true. We also hypothesized that the amount of organic carbon stored would increase with greater species diversity (1-species, and 5-, 16-, and 32-species mixes) and it would decrease with soil depth. Our results showed us that species diversity has no noticeable effect on organic carbon levels, with the 5-species mix being the exception, as it stored very low levels of organic carbon. In both soil depths (0-7.5 cm and 7.5-15.0 cm), bulk density increased the first 5 years, then decreased drastically over the next 6 years, but when we compared 0-7.5 cm and 7.5-15.0 cm depths with each other, we found an overall decrease in the upper layer. We concluded that organic carbon accumulation increases over time in restored prairie soil regardless of species diversity or soil depth. As time passed, growing roots loosened up the soil, increasing and then decreasing bulk density.

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Introduction

Prairie restoration is a conservation effort to restore prairie habitat and support the wildlife that depend on them. This effort hugely benefits the planet and its rapidly changing environment. While traditional farming is essential for survival, it is also responsible for loss of organic carbon from the soil. When the way land is managed is altered, any escalation in soil organic carbon (SOC) levels represents “carbon sequestration” (Powlson et. al. 2011). By looking at the sequestration of SOC in soil from a restored prairie which was previously degraded through agricultural use, our project aims to see if land with low utility for farming anymore can serve other purposes that benefit the environment. This paper is based on the research that was carried out for the UNI Biology Department’s Summer Undergraduate Research Program (SURP) for summer 2021.

“Carbon sequestration” refers to the storage of atmospheric carbon in the soil. Sequestration of atmospheric carbon into SOC alleviates the effects of climate change. While agricultural use of land is crucial for mankind’s survival, it also has detrimental effects on the environment. Thus, it is important to establish a balance between detrimental farming practices and conversion of farmland to forests, grasslands or other forms that mitigate climate change. This can be solved by replanting vegetation on land that has already been degraded through farming, which cannot be used productively to grow food (Powlson et. al. 2011). While more effective methods to alleviate climate change may exist, SOC sequestration will allow farmers to make good use of land that is inhabitable for crops, which is both economically and environmentally beneficial.

Tillage is a method used in agriculture to prepare land. Heavy tillage depletes nutrients in the soil. A study found that conversion of conventional tillage (CT) soil to no-tillage (NT) soil causes SOC levels to rise in the top 10 cm of soil (Luo et. al. 2010). However, this same study found SOC levels decrease in lower soil layers in response to NT practices. Therefore, further investigation into the sequestration of SOC in the different layers of converted soil will lead to a better understanding of how reduction in farming practices affect soil carbon content, and therefore the environment.

More recently, it has been found that species diversity may play a role in increased SOC content of semiarid grasslands (Liu et. al. 2019). This suggested that this may also be the case in other types of grasslands and restored prairies. A while later, other researchers found that lands with higher species diversity manage to do this with the help of increased biomass from soil microbial organisms (Prommer et. al. 2020).

In other research, however, it has also been found that species composition is important as well (Sherrard et. al. 2019). This publication discussed that some plant species tend to deplete soil of various nutrients, depriving other species from obtaining nutrients, and thus, growth. In our study, this was an essential factor to consider. Species diversity was varied but species composition was considered as well. The focus, however, was to observe how SOC sequestration changed with time, as previously degraded land was allowed to prosper with restored native vegetation and no farming practices.

Studying C sequestration may be difficult due to various environmental factors, such as extreme weather conditions and pollution. It is also hard to obtain data from soil that is too deep or perform experiments that may take decades. Therefore, knowledge on C sequestration is limited. The goal of this research was to observe changes in SOC levels over a decade, by varying species diversity and soil depth. We also aimed to look at changes in soil quality by observing how soil bulk density changed.

Research Questions

This study addresses the following research questions:

- How much organic carbon accumulates in restored prairie soil over a decade?
- How does plant species diversity affect soil organic carbon levels?
- How does soil depth affect organic carbon accumulation?
- How does soil bulk density change over the course of a decade in restored native prairies?
- How does aboveground biomass affect soil organic carbon accumulation?

Hypotheses

In this study, I test the following hypotheses:

- Organic carbon content increases in soil over a decade.
- As species diversity increases, more organic carbon accumulates in soil.
- Upper layers of soil sequester more organic carbon than the layers immediately below them.
- Bulk density decreases as roots loosen up prairie soil over time.
- Soil organic carbon increases with aboveground biomass.

Methodology

SOC data collection:

This experiment was conducted over summer 2021 for the UNI Biology Department's Summer Undergraduate Research Program (SURP). Soil samples were collected from the Cedar River Ecological Research Site (CRERS) in summer 2021 to determine soil organic carbon. Figure A shows the fields that were sampled: fields A, B, and C. All 3 fields had Flagler sandy loam soil type, and there was a total of 16 plots. There were a total of four soil species-diversity treatment types: a 1-species switchgrass monoculture, a 5-species mix, a 16-species mix, and a 32-species mix treatment, with four replicate plots per treatment. Four repetitions were performed per plot, so 64 (4 x 4 x 4) total soil cores were collected. To obtain samples, soil coring was performed using a manual core or a trailer-mounted core to 15-cm depth. Each sample was divided into 2 layers (0-7.5 cm, and 7.5-15 cm), leading to a total of 128 soil samples being obtained. Datasets were also used from the same experiment conducted by Dr. Cindy Cambardella (US Dept of Agriculture) in 2009 and 2014 for comparisons. Cores were stored in a cooler on ice, then transported back to the lab.

Once in the lab, wet cores were weighed, then emptied out. The empty container for each sample was weighed, so that it could be subtracted from the total weight of the wet core, resulting in the weight of only wet soil.

Then, the soil samples were sieved to remove stones (>2mm), and the stones were weighed. The masses of the stones were subtracted from the weight of their respective wet soil samples. Their volumes were measured and subtracted from the volumes of their respective cores. For each sample, approximately 100 grams of wet soil was dried in an oven at 105º C for 48-72 hours, then their dry masses were measured to calculate soil moisture.

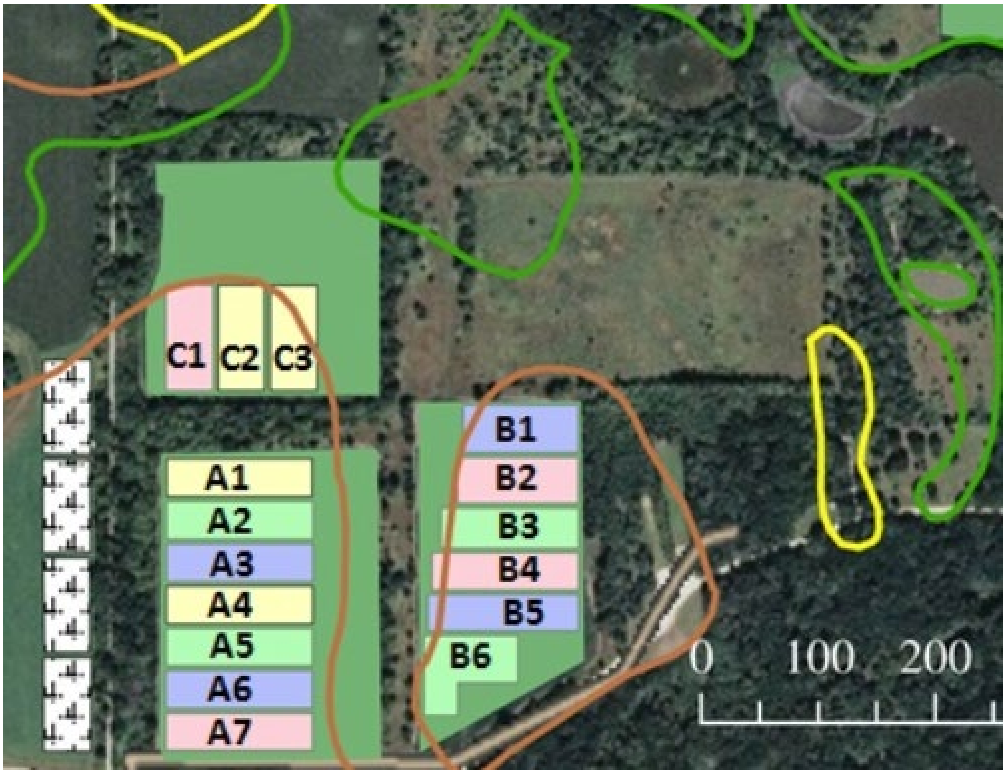

Figure A: Cedar River Ecological Research Site (CRERS) – fields A, B and C.

The soil moisture data for each sample was used to determine dry soil mass of the whole core. This dry mass was divided by the volume of soil to obtain bulk density for the whole core.

Once drying was done, the following step was to combust the samples and observe the change in mass. For every sample, 5-10 grams of dry soil was placed into a crucible and combusted in a muffle furnace at 500º C for 200 minutes and weighed. Weight change was calculated to find Loss on Ignition (LOI) (g C/g soil).

Bulk density and LOI values were used to calculate soil organic carbon on an aerial basis (g C/cm^3 of soil). Graphs were created to analyze the data collected.

Biomass data collection Methods:

Biomass data was collected from the Master's thesis of a UNI graduate student, Kathleen Madsen. Her thesis was titled "Productivity and community composition change in prairie biomass feedstocks." For her research, a total of 48 plots from the Cedar River Ecological Research Site were used for collecting data. However, in this thesis, only the biomass data of fields A, B and C have been used. In fields A, B and C, as mentioned earlier, there are a total of 16 plots, and soil type is Flagler Sandy Loam. There were 4 species-diversity treatments: 1-species monoculture, 5-species mix, 16-species mix, and 32-species mix. During the 10-year study period, there were a couple floods at the site, but none of them reached fields A, B and C. The fields were, however, burned in 2011 and 2014, and hayed every 3 years (2012, 2015, and 2018).

From the year 2010 to 2019, the average temperatures between April and October were calculated with the help of data from Waterloo Municipal Airport in Iowa, using NOAA's website. Rainfall data was obtained from the nearest recording weather station in Waterloo, to find average rainfalls for the individual years, and then overall for the ten years of study.

Between 2010 and 2019, plant biomass samples were collected from the months of August through November. For each plot, ten random quadrats were obtained. Drying was performed for every quadrat to a constant mass, by heating at a minimum of 65° C over 72 hours. Weight change was recorded afterwards, in grams. For the years 2010-2016 and 2019, biomass data for each quadrat was organized by functional groups (C_4-grasses, C_3-grasses, forbs, legumes, and unseeded species). Then, the biomass data for every quadrat was added together to give a total for each plot.

Data analysis:

We used analysis of variance to determine whether time, depth, or vegetation diversity significantly influenced C concentration (LOI), bulk density, and soil organic C content. Linear regression was used to further determine the relationship between aboveground biomass and soil organic carbon content. Assumptions of the models were assessed using QQ-plots of the residuals to ensure normality and homescedasticity.

Results

Figure B demonstrates change in LOI with time. We observed that carbon concentration increased more rapidly in years 6-12 than years 1-5. As more time passed, the amount of dead and decaying organic matter increased, making the soil richer in organic carbon, which in turn helped accelerate plant growth, creating even more decaying organisms. This explains why a curve exists instead of a straight line. For all 4 treatments, the deeper soil layer stored lower amounts of organic carbon, especially in the first 5 years. This can be explained by the fact that there is more dead and decaying matter on and closer to the surface of the soil than deeper below. Species diversity does not seem to have a significant effect on the bottom soil layer, but on the top layer, greater diversity seems to lead to higher organic carbon levels. The 5-species mix, however, has the lowest stored carbon in both layers. This indicates that species composition needs to be considered.

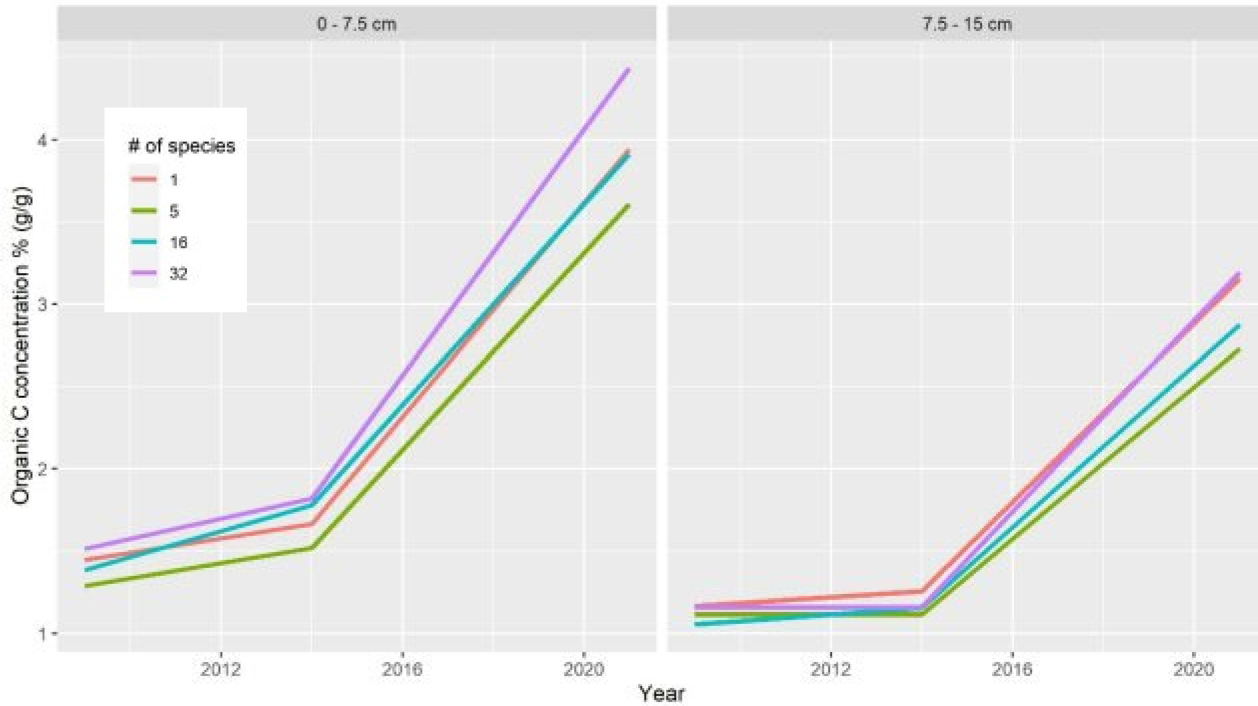

Figure B: Graphs of LOI (g C/g soil) against time (2009, 2014, 2021). 0-7.5 cm (left), 7.5-15 cm (right).

Soil bulk density, however, had an overall decrease in both layers over time (Figure C). In the top 7.5 cm of soil, bulk density did not change much the first 5 years, but strongly declined in the 6 years that followed. In the bottom 7.5 cm layer, there was a general rise during the first 5 years, but a strong decline during years 6-12. This demonstrated that soil compaction, which is found from bulk density, dropped as prairie soil was loosened by growing roots.

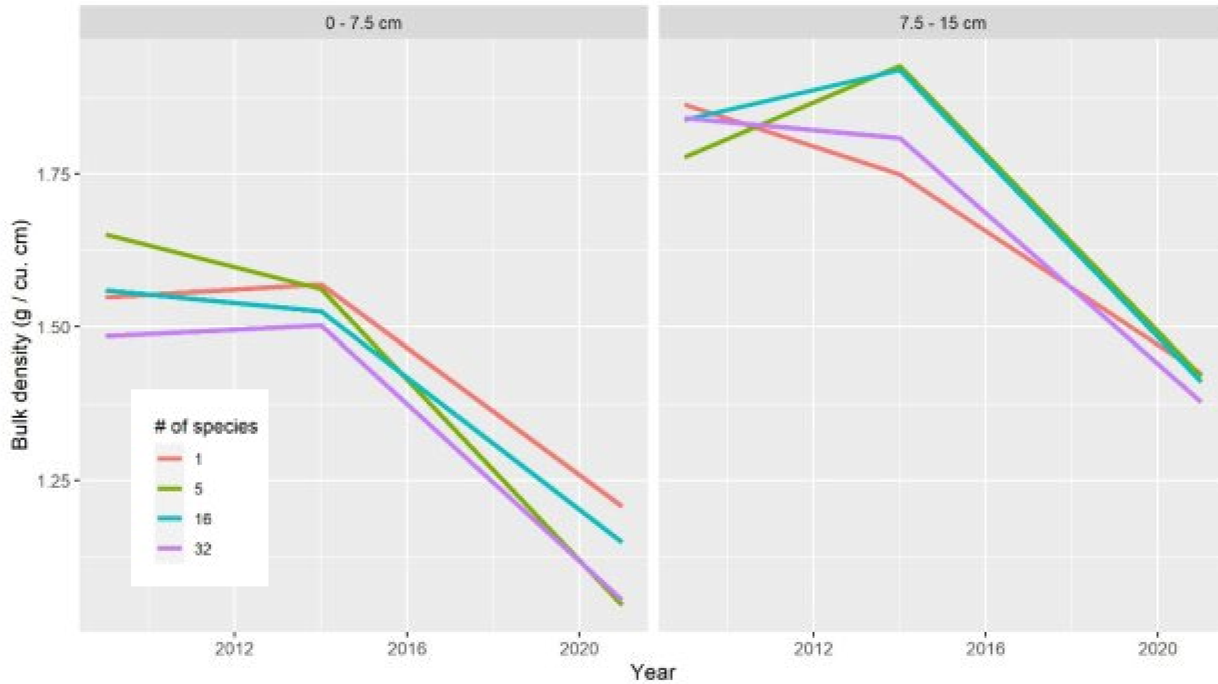

Figure C: Graphs of bulk density (g soil/cm^3 soil) against time (2009, 2014, 2021). 0-7.5 cm (left), 7.5-15 cm (right).

Organic carbon on an aerial basis rose over time and accelerated in years 6-11 (Figure D). Few differences exist between the diversity treatments (except the 5-species treatment on the top layer). The 5-species treatment has the lowest quantity of stored carbon in both layers. This demonstrates that while species diversity does not significantly affect organic carbon sequestration in soil, the difference in the 5-species mix for the top-soil may have been caused by particular species within the mix rather than the number of species.

The 5-species mix was dominated by big bluestems and little bluestems, both of which are strong competitors for nitrogen in the soil. They both draw down most of the nitrogen in the soil, so the 5-species plots are the most nitrogen-depleted plots. Other species have a harder time growing in those plots, leading to less growth, and thus, less decayed organic matter. This emphasizes the argument that species composition is an important factor to consider.

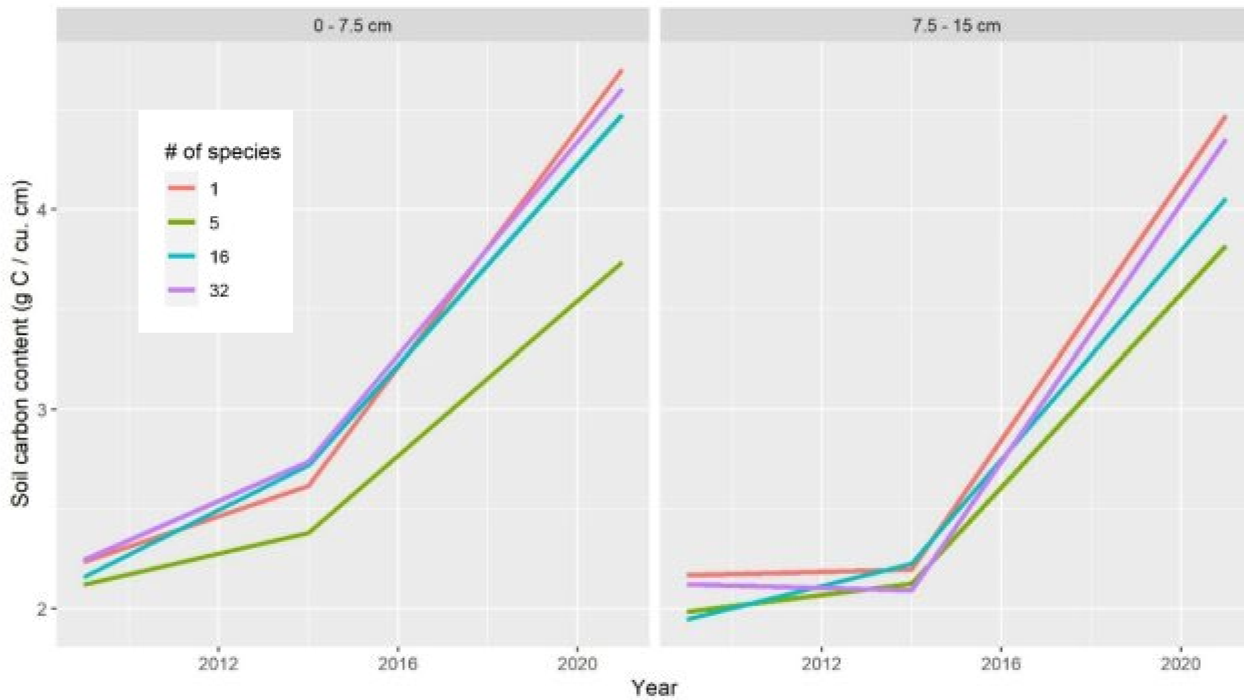

Figure D: Graphs of soil organic carbon on an aerial basis (g C/cm^3 of soil) against time (2009, 2014, 2021). 0-7.5 cm (left), 7.5-15 cm (right).

The graph for 0-7.5 cm of soil is generally steeper than the graph for 7.5-15 cm of soil. This indicates that the top layer of soil accumulated organic carbon more rapidly than the soil beneath it.

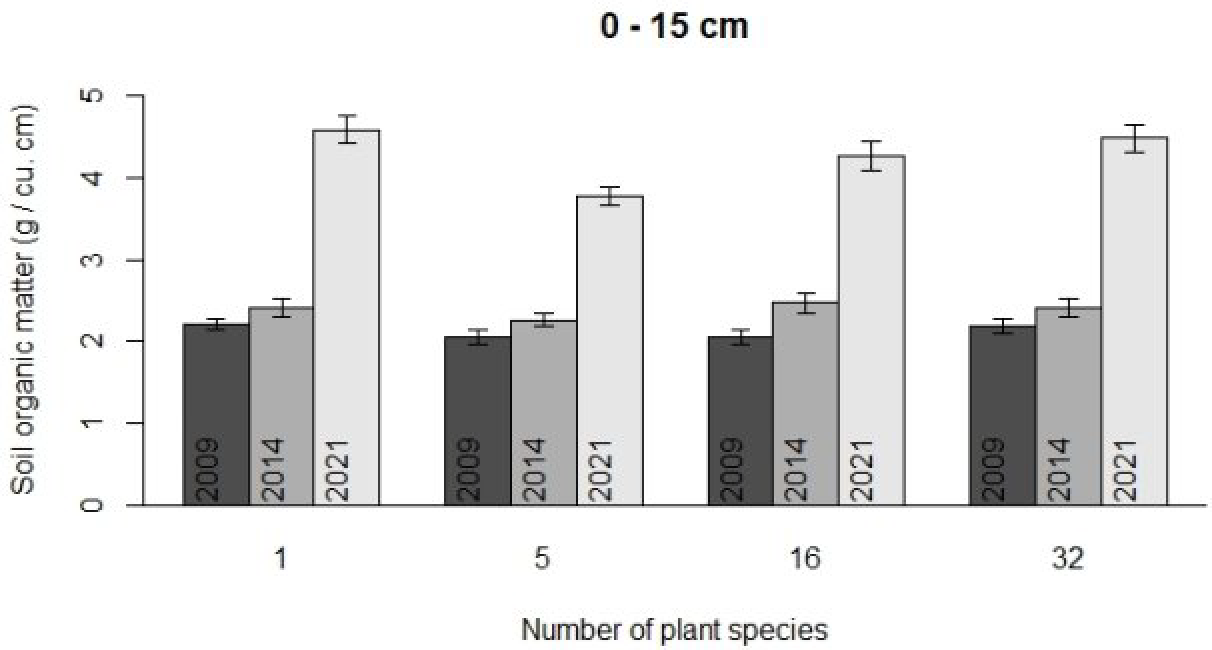

Figure E: Bar graph of soil organic carbon on an aerial basis (g C/cm^3 of soil) against species treatment for 0-15 cm of soil depth.

Finally, Figure E is a bar graph for the SOC content of both layers summed together, showing differences between each treatment over time. Throughout both soil layers, rapid soil carbon storage occurred in years 6-12 in all diversity treatments except the 5-species grass mixture, where less carbon was sequestered presumably because of the big bluestems and little bluestems.

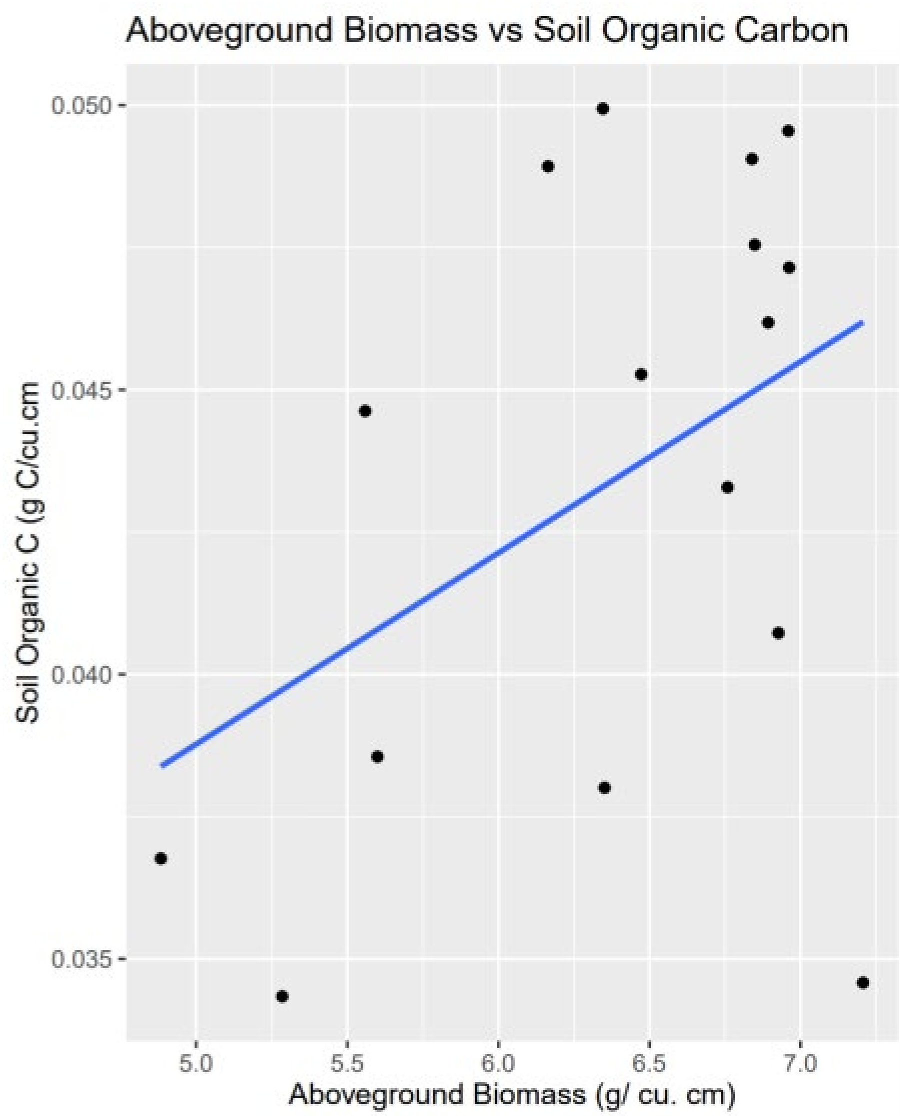

Figure F: Graph showing linear regression line between soil organic Carbon (g/cm^3) and aboveground biomass (g/cm^3), which suggests a linear relationship between the two variables.

Figure F suggests that there is a linear relationship between soil organic carbon and aboveground biomass. This graph does not take species diversity into consideration, to display the overall relationship between aboveground biomass and SOC content.

Figure G was created to take species diversity into account. It demonstrates the linear relationship between aboveground biomass and soil organic carbon, but with species diversity in mind. The 5-species graph stands out the most from the other graphs. 5-species plots have the lowest soil organic carbon and aboveground biomass levels, and they seem to be positively correlated with each other.

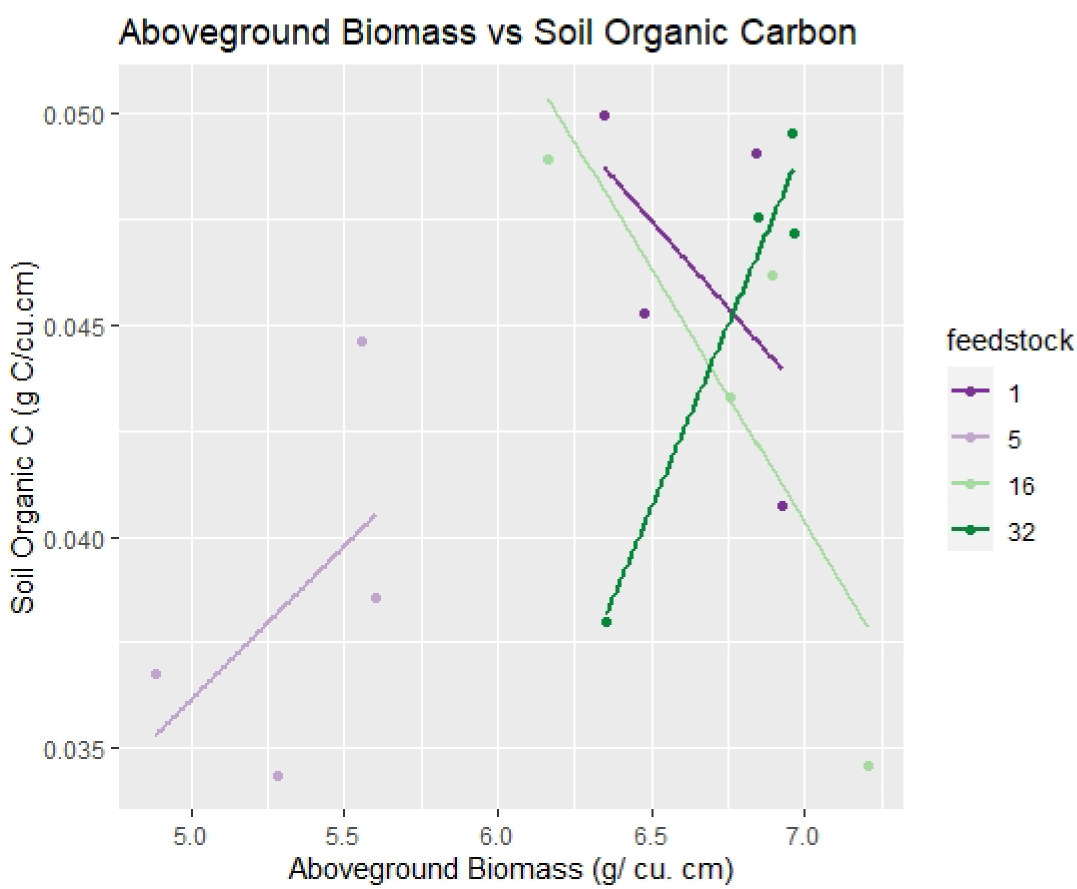

Figure G: Regression lines showing the relationship between soil organic carbon (g/cm^3) and aboveground biomass (g/cm^3) with respect to number of species in the plot.

In R, an ANOVA table was obtained for this linear model. Table 1 shows the ANOVA table for the model in Figure G. The p-value obtained demonstrates that a significant linear relationship between soil organic carbon and aboveground biomass seems to exist.

	Df	Sum Sq	Mean Sq	F value	p-value
Biomass	1	8.223×10^{-5}	8.22×10^{-5}	3.1234	0.099
Residuals	14	3.6857×10^{-4}	2.63×10^{-5}		

Table 1: ANOVA table for the linear model between soil organic carbon and aboveground biomass.

For the linear model, a Q-Q Plot of residuals was also constructed (Figure H). The Q-Q plot shows a straight line, demonstrating an approximately normal distribution.

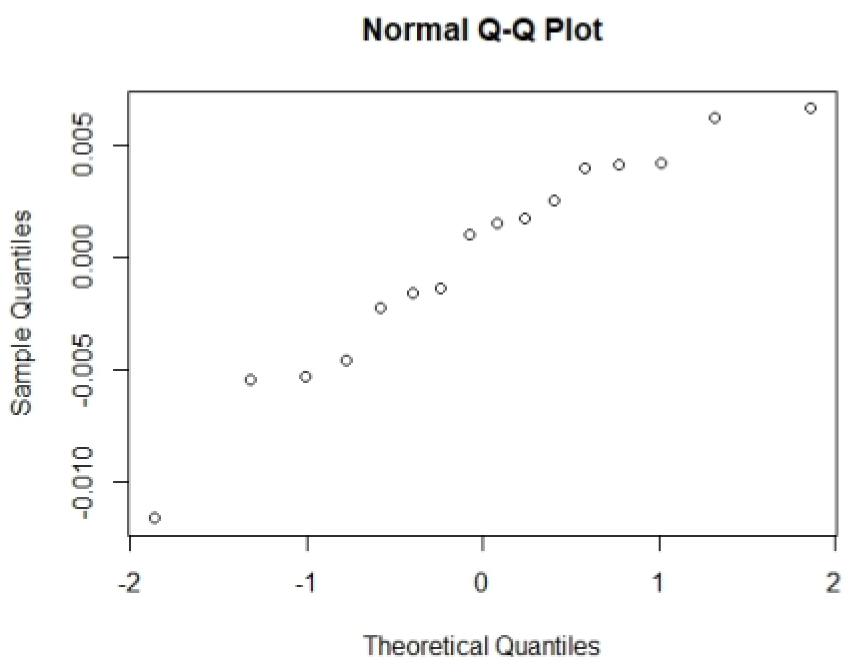

Figure H: Q-Q plot for linear model between soil organic carbon and aboveground biomass.

	Df	Sum Sq	Mean Sq	F value	p-value
Biomass	1	8.223×10^{-5}	8.22×10^{-5}	5.7267	0.044
Feedstock	3	6.537×10^{-5}	2.18×10^{-5}	1.5176	0.283
Biomass: Feedstock	3	1.883×10^{-4}	6.28×10^{-5}	4.3720	0.0423
Residuals	8	1.149×10^{-4}	1.44×10^{-5}		

Table 2: ANOVA table for the linear model between soil organic carbon and aboveground biomass, soil organic carbon and species-diversity treatment, and soil organic carbon and the interaction between aboveground biomass and species-diversity treatment.

Another ANOVA table was constructed to study the effect of species-diversity treatment on the relationship between aboveground biomass and soil organic carbon. Table 2 demonstrates the effects of aboveground biomass, species-diversity treatment, and the interaction between biomass and species-diversity on soil organic carbon. The p-values for the main effect of biomass and for the interaction between biomass and diversity (feedstock) are significant.

A QQ-plot was created for this linear model (Figure I). A normal distribution is demonstrated based on the straight line that is observed.

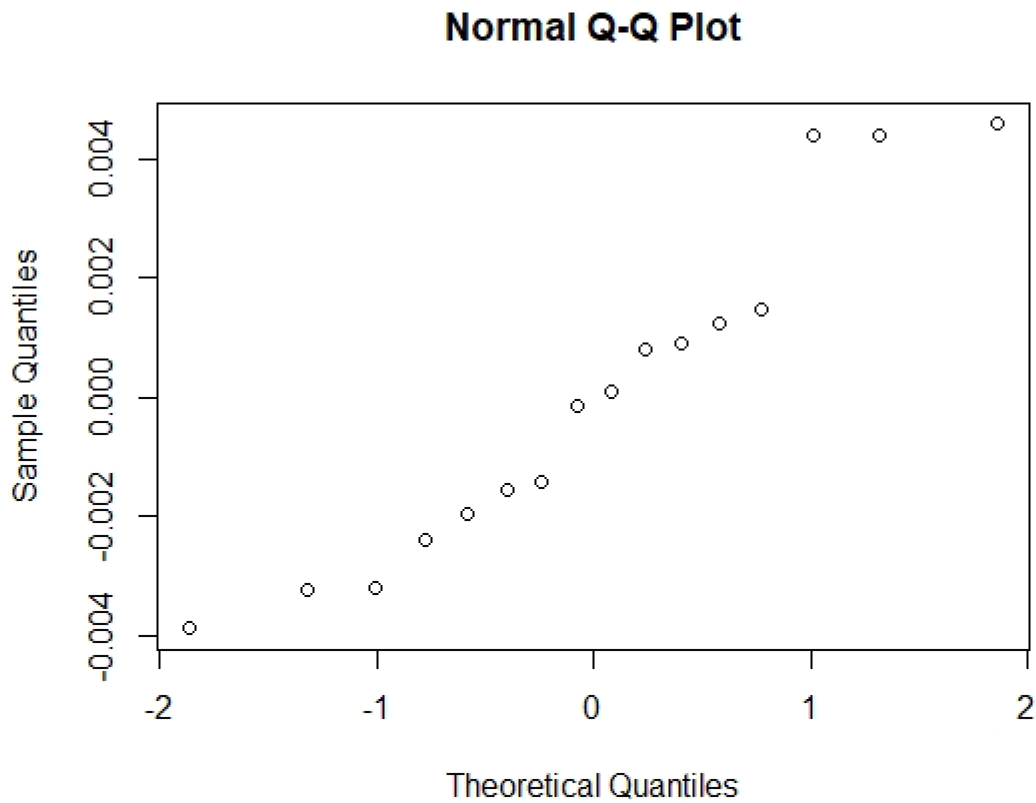

Figure I: Q-Q plot for linear model between soil organic carbon and the interaction between aboveground biomass and species-diversity treatment.

Discussion

Based on the results, it is evident that a large and accelerating amount of SOC is accumulated in prairie soil over time. This suggests that native prairie plantings are an effective way to sequester carbon, and long-term plantings are better than short-term temporary prairies.

Deeper layers seem to store less organic carbon than layers closer to the surface. This can be explained by the idea that most soil organic carbon comes from plant decay matter, and there is a greater amount of litter and decay closer to the surface of the soil than in the deeper layers. This study only sampled the top 15 cm, but future studies should sample even deeper layers. A deep corer was used to collect soil down to a meter for some locations, but those data have not yet been analyzed, and more can be learned in the future from that approach.

There seemed to be no emerging patterns when it came to species-diversity treatments. The 5-species treatment plots, however, stored the least amount of organic carbon, perhaps because those plots contained big bluestems and little bluestems, both of which are strong competitors for nitrogen in the soil. They take up all the nitrogen in the soil, causing other species to become nitrogen-deprived. Thus, these plots have less overall plant growth, and therefore, less litter and decay matter, which are the main source of organic carbon in the soil. This also means that species composition (specifically which species have been planted) is perhaps more important than the species-diversity treatments (the number of different species in the feedstock) used when it comes to accumulation of organic carbon in the soil over time. This implies that when planting prairies for carbon sequestration, special attention should be given to designing a seed mix that will promote SOC accumulation.

It is also evident that bulk density is a dynamic variable that is also influenced by changes in vegetation and soil depth. Future studies ought to consider bulk density, and not just the Loss on Ignition (LOI).

It is also discernible that aboveground biomass and belowground carbon have a clear relationship, and this could also be influenced by the relationship between aboveground and belowground biomass. Belowground biomass is dependent on aboveground biomass, and it is available at the expense of aboveground biomass. A plant must choose between investing in its aboveground parts (such as stem and leaves) and belowground organs (such as the roots). In high nutrient soils, they invest more on aboveground biomass, while in low nutrient soils, they invest more on belowground biomass (Wilson & Tilman 1991). While no pattern has emerged from the number of species in a plot, it is obvious that species composition plays a big role in biomass and accumulation of soil organic carbon.

Conclusions

Prairie restoration is a conservation effort that has the capacity to reduce the effects of climate change. When various conventional farming practices are carried out, organic carbon can be lost from soil, releasing atmospheric carbon dioxide - a key player in climate change. By sequestering organic carbon back into soil from the atmosphere by converting degraded land into prairies, it is possible to mitigate the effects of climate change.

This experiment found that plant species diversity does not significantly affect sequestration of organic carbon in the soil. Rather, it is more important to look at the specific species involved. However, overall, more organic carbon is stored in restored prairie soil over time, and more carbon is sequestered in surface soil than the layers beneath it. Soil compaction is not lowered initially but drops over the years as growing roots loosen up prairie soil. As aboveground biomass increases, a greater amount of organic carbon also accumulates in the soil.

Future research on C sequestration in restored prairies should focus on both species-diversity as well as the species composition. It might also be better to carry out these studies in locations with less extreme weather conditions, or more stable environmental conditions, possibly in warmer climates. Functional groups and invasiveness of species are important variables to consider. Other variables that may need to be investigated are temperature, rainfall, pollution levels in the environment, geographical location, or animal habitation.

This research demonstrates that grassland restoration and conservation efforts do improve environmental outcomes by sequestering C in soil. Restoration of agriculturally degraded lands through prairies has tremendous potential to return organic carbon back into degraded soil, so this highlights the importance of investing in soil conservation if we want to abate (or even reverse) global warming and climate change. If future research in this area studies the effects of geographical location, it may even be found that some regions of the world can sequester organic carbon back into soil at faster rates than others – which would create a need for more restored prairies in those areas, given the goal is to mitigate the effects of climate change.

Soil organic carbon research is not only important for the benefit of the planet, but also commercially in agriculture as well. Lands with higher organic carbon content have potential for better agricultural yields (Oldfield et. al. 2019), so restoration efforts should benefit both the farming industry as well as the economy as a whole.

While it is possible to move from one region of the planet to another when the need arises, it is impossible for humanity to move to another planet when the Earth loses its unique, idiosyncratically livable environment. As sea levels rise and the detrimental effects of climate change become more disruptive as well as discernible, it is our role to do the most we can to leave a better world for future generations, before the consequences of human activity become irreversible.

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