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Carbon Sequestration Capacities of Different Land Cover Types and Climate Change

Nicole L. Melnick
Gettysburg College

Annabel Gorman
Gettysburg College

Adam F. Warren
Gettysburg College

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Abstract

Human-caused climate change creates a positive feedback loop that emits more carbon dioxide into the atmosphere instead of being sequestered in the Earth or its oceans. A major contributor to this feedback loop is deforestation in order to use land for agriculture and livestock. This study aims to investigate differences in carbon sequestration capabilities of forests, pastures, and cropland through soil and tree sampling in Gettysburg, Pennsylvania. The main hypothesis of this study is that forested land will be the most effective at carbon sequestration. The loss on ignition method (LOI) was used to determine the percent organic material in the soil for each land type. The soil in the forest sequestered the most CO2 per unit area at 0.012 tons/m2, followed by the pasture at 0.010 tons/m2, and finally the cropland at 0.009 tons/m2. When including the trees in the total carbon sequestered per unit area the carbon sequestered per unit area was 0.109 tons/m2 with average carbon sequestered per tree being 43644.4 pounds (21.8 tons). These results have implications for land management practices being used to mitigate climate change, as the different land covers sequestered significantly different amounts of CO2.

Keywords

Carbon, sequestration, climate, climate change, land cover

Disciplines

Environmental Indicators and Impact Assessment | Environmental Studies | Natural Resources and Conservation

Comments

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Carbon sequestration capacities of different land cover types and Climate Change

Annabel Gorman, Niki Melnick, and Finn Warren

ES 400, Environmental Studies Department

Gettysburg College

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Abstract

Human-caused climate change is creating a positive feedback loop that emits more carbon dioxide into the atmosphere instead of being sequestered in the earth or its oceans. A major contributor to this is deforestation and the loss of mature forest in order to use land for agriculture and livestock raising. This study aims to investigate the differences in carbon sequestration capabilities of forests, pastures, and cropland through soil and tree sampling in Gettysburg, Pennsylvania. The main hypothesis of this study is that forested land will be the most effective at carbon sequestration due to the carbon stored in its soil and trees. Using the loss-on-ignition (LOI) method, organic carbon was burned off soil samples from each of these land cover types and used to determine how much carbon these types of land cover sequestered. The forest was found to have the most CO_2 sequestered per unit area at 0.012 tons/m^2, followed by the pasture at 0.010 tons/m^2, and finally the cropland at 0.009 tons/m^2. When including the trees in the total carbon sequestered per unit area the carbon sequestered per unit area was 0.109 tons/m^2 with average carbon sequestered per tree being 43644.4 pounds (21.8 tons). These results have large implications for land management practices being used to mitigate climate change effects and creating more land cover types that sequester more carbon being emitted into the atmosphere.

Introduction

Over the last century, humans have been consuming the Earth's resources at ever greater rates. Forests have been flattened, mountains have been leveled, and even skies are full of smoke and smog. While these impacts might be easily recognized, the more dangerous human impact is completely invisible. Over the last 50 years, the amount of carbon released into the atmosphere on a yearly basis has increased by about 90% with carbon dioxide making up 76% of those emissions (EPA.gov, 2022). As a result of the increased concentration of greenhouse gasses in the atmosphere, the average global temperature has increased by 0.8°C since the 1900s (Lal, 2007). This transformation of a fundamental aspect of the climate system has already led to increased frequency and severity of natural disasters and increased the rate of biodiversity loss. While the impacts of climate change are already apparent they could be much worse. The amount of CO_2 being released and the amount actually accumulating in the atmosphere are not the same. This discrepancy is caused by natural carbon sinks such as the oceans and forests which absorb as much as 60% of the carbon currently being emitted into the atmosphere through a process called carbon sequestration (Lal 2007, Le Quéré et al. 2009).

Due to the fact that biotic carbon sequestration is a free and naturally occuring ecosystem service the amount of research into the subject has been increasing. Numerous studies have constructed methods for determining the amount of carbon stored in many types of ecosystems (i.e. Xu et al. 2004, Pearson et al. 2007, Franzluebbers 2021, etc.). The most widely studied are forest ecosystems which have made multiple models for the purpose of measuring carbon sequestration in both the vegetation and the soil (Pearson et al. 2007, Franzluebbers 2021, Konen et al. 2002, and Nair 2011). While forests certainly sequester a large amount of carbon, around 33% of global CO_2 emissions, they are also becoming a less frequent land cover type (Lal, 2007). As forests are converted to other land use types even more CO_2 is emitted into the atmosphere which in modern times could be as much as $1.6 Pg C yr^{-1}$ (Lal, 2007). The necessity of understanding the carbon sequestration characteristics of other land cover types, particularly agricultural forms such as pasture, and crop land, has therefore never been more important. This information is required to obtain a more holistic sense of the net impacts of land cover change.

Some work has already been done in this regard. A number of studies have developed methods for quantifying carbon sequestration in meadows and pastures while cropland does not seem to have had as much focus in scientific literature (i.e. Xu et al. 2004, Skinner 2008, Zhang et el. 2022, de Koning et al. 2003, Nair 2011, etc.). These studies focus primarily on quantifying the amount of carbon sequestered with little attention paid to how these land cover types compare to one another.

The objective of this study is to investigate how carbon sequestration differs among three common land cover types in the American Northeast. It plans to calculate the amount of carbon sequestered in pasture, crop, and forested land in order to determine their relative efficacy as carbon sinks. The study area will be constrained to just one farm in order to limit confounding variables when comparing the different land cover types. The main hypothesis of this study is that forested land will be the most effective carbon sink followed by pasture and finally cropland.

Methods and Research Design

Samples were collected from three different land covers: pasture, crop, and forest. Within each land cover, a transect was drawn through the center of the area (Figures 1-3). The transect was drawn at least 20 m from the edge of each land cover type to minimize any potential edge effects. An auger was used to collect 12 samples at equal intervals along each transect at a depth of 0-30 cm, following the methods of Franzleubbers (2020).

In the forest land cover, the carbon sequestration in trees was also measured. At each interval along the transect, the two closest trees to each soil sample with a diameter at breast height greater than 10cm were measured, creating measurements for 24 total trees in the forest. To determine the carbon sequestered within each tree, the height and diameter at breast height

(DBH) of each tree were measured and used to sequentially calculate the green weight of the tree, dry weight of the tree, weight of carbon in the tree, weight of carbon dioxide sequestered in the tree, and the weight of CO_2 sequestered in the tree per year (University of New Mexico). The diameter of the tree was calculated by measuring the circumference of the tree and using the equation □ = □/□. The height of the tree was determined by measuring the distance of the observer to the tree (*d*), the angle from the observer to the top of the tree (*A*), and the height of the eyes of the observer. The equation used to determine overall height was *h* = □□□(□ ∗ □) + □□□□□□□□ □□□ *h*□□□*h*□ (Faculty of Forestry, 2019). To determine the CO_2 sequestered in the tree, the below equation was used.

CO_2 sequestered (lbs) = (0.33195)dbh^2*h (University of New Mexico)

To analyze the soil organic carbon content (SOC) in the soil, the loss on ignition technique was used. Each sample was placed in a 7mL container and then transferred to a crucible with a known mass. The wet bulk density was calculated using the wet mass of each sample prior to any combustion divided by the known 7mL volume. The mass of each sample was measured before being placed overnight in an oven set to 105°C to remove the water content. The samples were weighed again. The dry weight of each sample was used to determine the dry bulk density, using the same calculation as above. After a brief cooling period, samples were placed in a 550°C furnace for 4 hours. After 4 hours, the furnace was turned off, and the samples were allowed to cool overnight. The mass of the samples was measured one final time, and the SOC was calculated using the equation:

LOI(g/kg-1) = (original mass of soil sample - soil mass after combustion) / (original mass of soil samples)

which is consistent with that used in Konen et al. (2002)

LOI will also be used to determine the amount of CO_2 sequestered in the forest ground per year using the same methodology as in the pasture. Soil samples will be collected at regular intervals throughout the forest and dried in a furnace to burn all organic material from the sample. The equation from Konen et al. (2002) will be used here to determine the amount of carbon lost when in the furnace.

T-tests were performed for the percent organic material, wet bulk density, and dry bulk density between the pasture and forest, pasture and crop, and crop and forest land covers. T-tests were also performed to determine significance between the wet and dry bulk density within each land cover. An ANOVA test was performed for the percent organic material and the bulk densities among all three land covers.

To determine the total amount of carbon sequestered in each land cover, the equation

% organic material x bulk density x volume of soil

was used. This was calculated in grams, kg, and tons. The total carbon dioxide sequestered was normalized per unit area by dividing the result from the above calculation by the total area of each land cover. In the forest, the two above calculations were done with and without considering the carbon dioxide sequestered in the trees.

Results

Bulk Density

For the wet bulk density, the pasture had the highest average bulk density among the three land covers, with a mean value of 1.053 g/mL, followed by the forest with a mean bulk density of 0.983 g/mL, and finally crop with a mean value of 0.816 g/mL (Table 1). The dry bulk density found within the pasture was an average of 0.855 g/mL, with the forest at 0.734 g/mL, and crop at 0.669 g/mL. Within all three types of land covers, there was a significant difference between the wet and dry bulk density ($p<0.0001$) (Table 2). There was also a significant difference in the wet bulk densities between pasture and crop, pasture and forest, and forest and crop ($p<0.01$) (Table 3). Similarly, there was a significant difference in the dry bulk densities between pasture and crop, pasture and forest, and forest and crop (Table 4). When conducting an ANOVA test, a significant difference was found across all three land covers for both wet and dry bulk density ($p<0.0001$) (Table 5).

% Organic Material

For the percent organic material within each land cover, the forest had the highest percent organic material at 4.964%, followed by cropland at 3.885%, and pasture at 3.574% (Table 6) (Figure 4). There was a significant difference between the percent organic material in the forest and pasture ($p<0.0001$), as well as between the forest and cropland ($p <0.0001$) (Table 7). There was no significant difference between the pasture and cropland (Table 7) ($p = 0.0546$). Conducting an ANOVA test across all three land covers, a significant difference was found between the percent organic material in the pasture, crop, and forest land covers (Table 8) ($p = 0.0004$).

Total Carbon Sequestered

Using the areas of each land cover (Table 9) as well as the percent organic material and bulk density, the total amount of carbon dioxide sequestered was 674.64 tons in the pasture land cover, 535.58 tons in the cropland, and 65.14 tons in the forest (Table 10) (Figure 5). The forest had the highest CO_2 sequestered per unit area at 0.012 tons/m^2, followed by the pasture at 0.010 tons/m^2, and finally the cropland at 0.009 tons/m^2 (Table 10) (Figure 6).

Carbon Sequestration in Trees

In the forested land cover, 24 trees were measured. The average carbon sequestered per tree was 43644.4 pounds (21.8 tons), with a standard deviation of 65875.9 pounds (32.1 tons) (Table 11). The total carbon sequestered in the 24 trees was 1047465.4 pounds, or 523.7 tons (Table 11). Factoring this into the carbon sequestered in the forest land cover, the combined soil and tree sequestration is 588.9 tons, compared to the 65.14 tons in the soil alone. The carbon sequestered per unit area is 0.109 tons/m^2 factoring in both the trees and the soil, a factor of 10 greater than the 0.012 tons/m^2 in the soil alone (Table 12)

Discussion

Bulk Density

Bulk density is the primary measurement used to indicate soil compaction, meaning the mass of soil present in a given volume (Deen and Kataki, 2002). Soil bulk density is used when calculating soil organic carbon content (SOC) to normalize for the mass of the soil that is actually present at the site (Deen and Kataki, 2002). There was a significant difference in the bulk densities between the pasture, forest, and crop land covers, with the pasture having the highest bulk density, followed by the forest, followed by the crop land cover. This means that the soil was compacted the most in the pasture, thus there was the largest amount of soil mass in the same volume of soil.

These findings are confirmed by other studies investigating soil bulk density. A study conducted by Peterson et al. (2002) found that increased cropping was associated with a decreased bulk density, which is consistent with the cropland cover having the lowest bulk density of the land covers. One possible reason why the pasture may have had the highest bulk density is compaction from livestock grazing.

Total Carbon Sequestered

Significant differences were found in the percent organic material in the forest, pasture, and cropland, meaning that the soil in the forest sequestered more carbon than that of the pasture or cropland. Despite this, before scaling the different values to be per unit area, the forest was calculated to have sequestered the least carbon in the soil (Table 10). This is because it also covered the least area on the property that was sampled. When changed to be compared to the pasture and cropland on the same scale, the forest sequestered 1.4 times more carbon than the cropland and 1.19 times more than the pasture (Table 10). The forest soil was able to sequester the most carbon due to the increased biomass in forests above and below ground, although more carbon is returned to the soil through root growth and turnover rather than aboveground biomass (Ussiri et al., 2006). When considering only soil, the pasture's carbon sequestration abilities were close to those of the forest, but, by converting the pasture to a forest, it would improve soil structure, develop soil quality, and increase root biomass and organic carbon sequestration (Ussiri et al., 2006). This study by Ussiri et al. (2006) also confirms that pasture sequesters less carbon than forest although the pasture sampled in the present study had about ten times more carbon found in the soil than the Ussiri et al. study. Based on observations of the study sites and the results that the pasture sequestered more carbon than the cropland a further question to study could be why this is. The pasture in this study was relatively unmaintained and had high grasses as well as some shrubs and other plant species. Schulp et al. (2008) also studied the carbon sequestration capability differences between pasture, cropland, and forest in the European Union and found that pastures (especially less maintained pastures) sequestered more carbon than cropland. The biodiversity found in the pasture as opposed to the cropland could impact the soil's organic carbon levels due to a wider variety of plants that increase root biomass and soil quality which will ultimately contribute to more carbon sequestration. Wang et al. (2020) confirms this from their study where they concluded that there will be a decrease in carbon sequestration due to the loss of species diversity in grasslands

The cropland sequestered the least carbon in the soil which is likely due to the time of year these samples were taken. Since this study was conducted at the end of winter, the corn plants in the field were all dead and cut, or corn stover. The fact that these plants were cut and dead resulted in a nitrogen deficit in the soil (Kim et al., 2009). A nitrogen deficit in the soil can influence the amount of carbon stored and its emissions (Xu et al., 2004) meaning that as less nitrogen is being emitted from the soil, less carbon is able to be sequestered in it (Xu et al., 2004).

Carbon Sequestration in Trees

By adding the total carbon sequestered by trees to the forests' overall carbon sequestration abilities, the carbon sequestration abilities of the forest increase by about ten times more than when just the soil is considered. An average of about 21.8 tons of carbon were stored in each tree (Table 11). Trees sequester so much carbon because they are composed of carbon-made glucose and, as they grow, they store carbon in their wood as well as roots (Aguirre et al., 2009). Ultimately, the forest soil and tree carbon values were combined to create a more complete representation of the carbon that is sequestered in a forest which resulted in the carbon sequestration abilities of the forest dramatically increasing. M.G.R. Cannell (1999) did not directly confirm these findings but did build on them by stating that the addition of woodland to an area will increase the carbon sequestration capabilities of the soil. By factoring the trees into the forest's total carbon sequestered per unit area, the pasture and cropland values fell shorter as it's more than twelve times larger than both at 0.109 toms/m^2 (table 12). It is important to note that carbon sequestration rates can vary based on tree species, type, age, soil type, climate, topography, and management practices (Aguirre et al., 2009).

Relevance to Climate Change

In the modern world, the conversion of land cover from forest to agriculture is becoming increasingly common. Chakravarty et al. (2012) predicted that by 2022, the rate of deforestation could double. Consequently, there is a need to learn how such large-scale changes will impact the future. The greatest cause of deforestation is agricultural settlement so comparing the level of carbon sequestration in two of the most common agricultural land cover types to forested land will shed light on how these practices will impact the future (Chakravarty et al., 2012). Models predict that as more land is converted from forests to agriculture, and the existing forests become older, the amount of carbon sequestered by the terrestrial biosphere will decrease by 4% (Schulp et al., 2008). In addition, the act of cutting down forests, growing crops, and raising cattle all worsen climate change by emitting more greenhouse gasses (Bennett, 2017). Not to mention the fact that removing trees from an ecosystem alters systems as basic as the water cycle leading to untold complications (Bennett, 2017). The present study contributes to this growing body of work which shows that the conversion of forests to agricultural land has significant negative impacts on not only the local ecosystem but potentially the whole biosphere.

Limitations

The primary limitation of the present study is the restricted scope of the sampling. Soil samples were taken from only one farm in the Gettysburg, Pennsylvania area and therefore can not be readily extrapolated to other regions. This is particularly inconvenient as the greatest rate of conversion from forested land to agricultural settlements is occurring in the tropics and has slowed significantly in temperate climates (Chakravarty et al., 2012). Additionally, the forested area that was sampled was relatively young, and therefore many trees had to be ignored because they were too small for the sampling requirements of this study. This potentially led to an overestimation of the carbon sequestered in the trees as the average tree size would be larger than in reality. Future studies could expand the sampling area to get more robust results and focus on a tropical region to gather more information on the most impacted areas.

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Tables and Figures

Figure 1: Google Earth Pro screenshot depicting the study sight and pasture transect where samples were collected. The sampling transect is shown in green and the 20m buffers are shown in red.

Figure 2: Google Earth Pro screenshot depicting the study sight and cropland transect where samples were collected. The sampling transect is shown in green and the 20m buffers are shown in red.

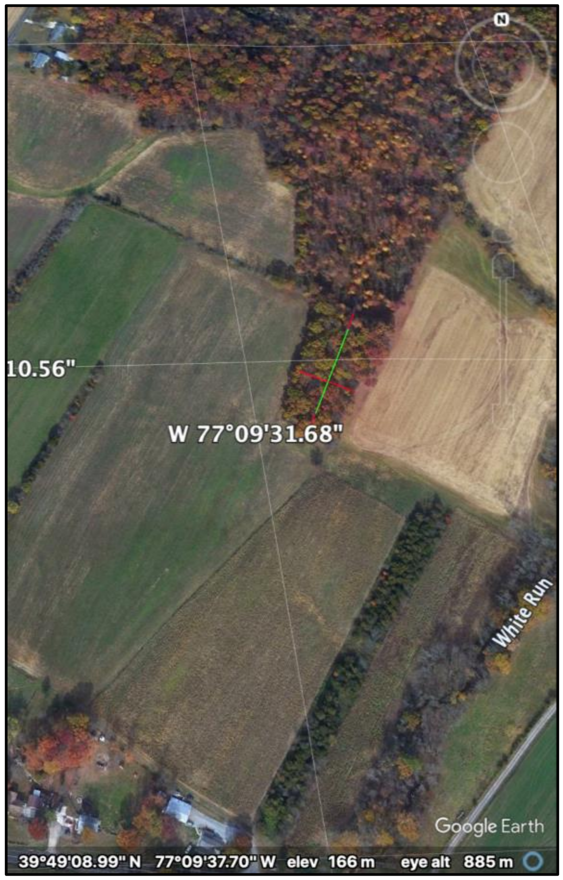

Figure 3: Google Earth Pro screenshot depicting the study sight and forest transect where samples were collected. The sampling transect is shown in green and the 20m buffers are shown in red.

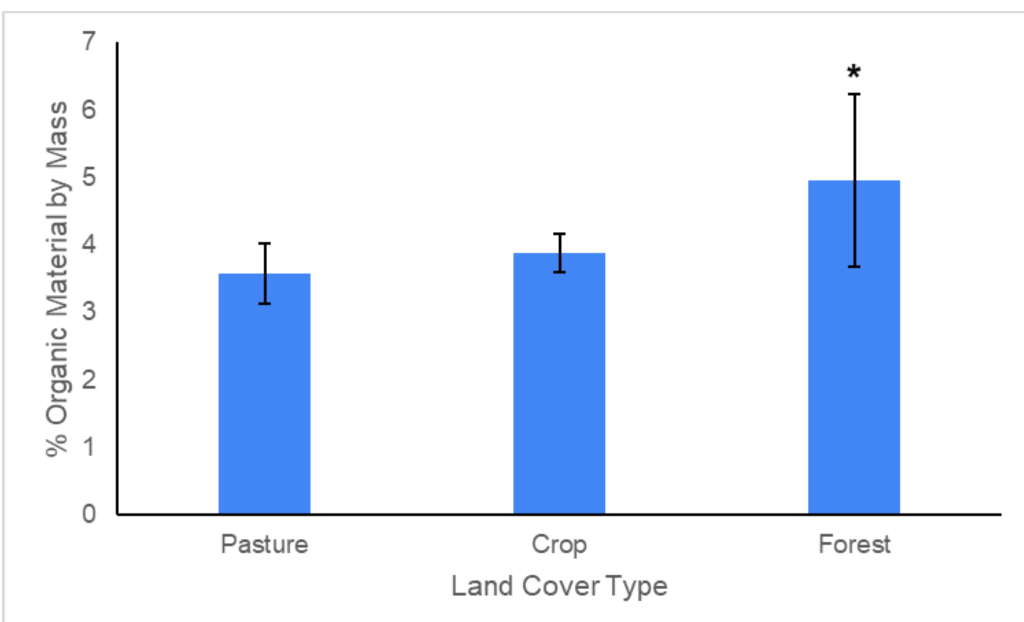

Figure 4: comparison of the percent organic material by mass for pasture, crop, and forest land cover. Error bars show ± 1 standard deviation and asterisk denotes significance (between forest and crop, and forest and pasture).

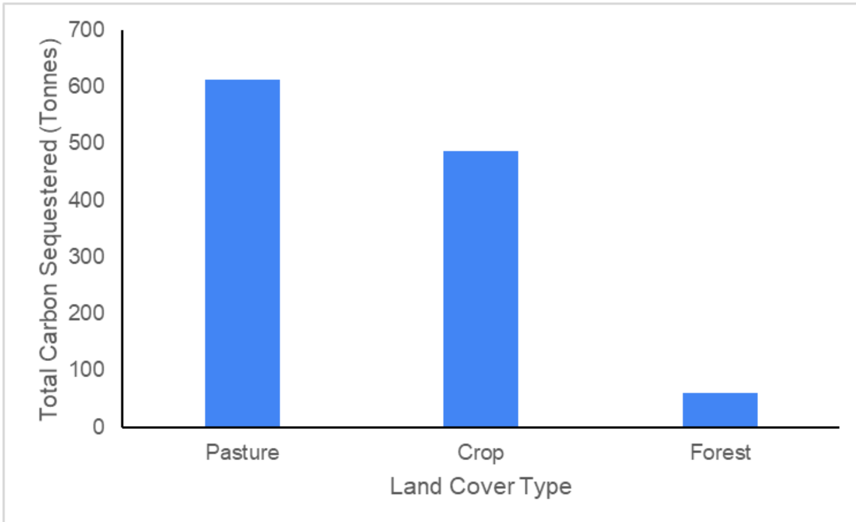

Figure 5: comparison of the total mass of carbon sequestered (in metric tonnes) for pasture, crop, and forest land cover.

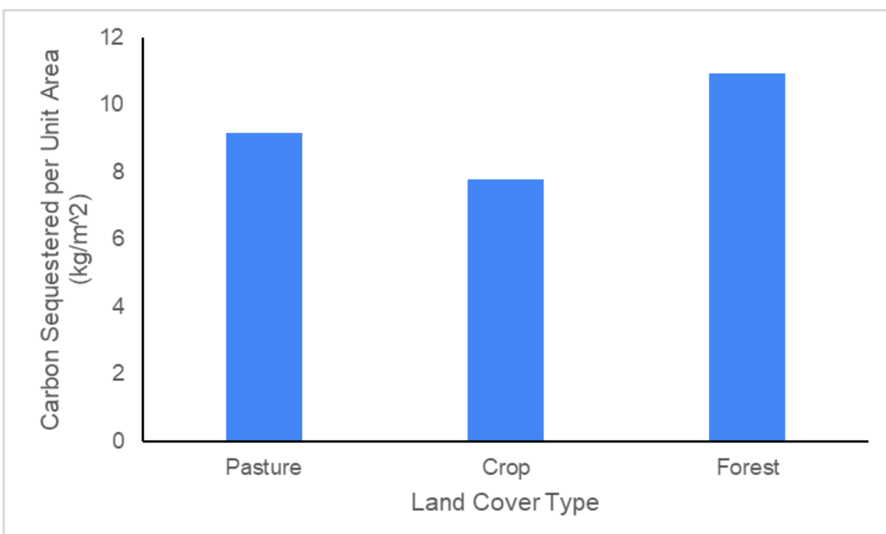

Figure 6: comparison of the mass of carbon sequestered per unit area (in kg/m^2) for pasture, crop, and forest land cover.

Table 1: Mean Wet and Dry Bulk Density for Different Land Covers

Land Cover	Mean Wet Bulk Density	Standard Deviation (wet)	Mean Dry Bulk Density	Standard Deviation (dry)
Pasture	1.053	0.109	0.855	0.087
Crop	0.816	0.083	0.669	0.070
Forest	0.938	0.075	0.734	0.063

Table 2: T-Tests for Wet and Dry Bulk Density u

Land Cover	T	df	p
Pasture	4.29	22	<0.0001
Crop	4.68	22	0.0001
Forest	7.21	22	<0.0001

Table 3: T Tests for Wet Bulk Density between land covers

Land Covers	T	df	p
Pasture and Crop	6.02	22	<0.0001
Pasture and Forest	3.02	22	0.0062
Crop and Forest	-3.78	22	0.0010

Table 4: T-Tests for Dry Bulk Density between land covers

Land Covers	T	df	p
Pasture and Crop	5.79	22	<0.0001
Pasture and Forest	3.92	22	0.0007
Crop and Forest	-2.41	22	0.0248

Table 5: ANOVA parameters for Bulk Density

Condition	SS	df	MS	F	p
Wet	0.3385	2	0.1693	20.83	<0.0001
Dry	0.1254	2	0.1077	19.69	<0.0001

Table 6: Average percent Organic Material in different land covers

Land Cover	**% Organic Material**	**Standard Deviation**
Pasture	3.574	0.450
Crop	3.885	0.284
Forest	4.964	1.282

Table 7: T-Tests % Organic Material across land covers

Land Covers	**T**	**df**	**p**
Pasture and Crop	-2.03	22	0.0546
Pasture and Forest	-7.076	22	<0.001
Crop and Forest	-30.09	22	<0.0001

Table 8: ANOVA Parameters for percent organic material across land covers

SS	**df**	**MS**	**F**	**p**
12.7761	2	6.383	9.94	0.0004

Table 9: Area of Each Landcover

Land Cover	**Area (m^2)**	**Depth (m)**	**Volume (m^3)**
Pasture	66718.8	0.3	20015.6
Crop	62329.4	0.3	18698.8
Forest	5404.6	0.3	1621.38

Table 10: Total Carbon Dioxide sequestered in each land cover

Land Cover	**CO2 Sequestered (kg)**	**CO2 Sequestered per unit area (kg/m^2)**	**CO2 Sequestered (tons)**	**CO2 Sequestered per unit area (tons/m^2)**
Pasture	612033.6	9.17	674.64	0.010
Crop	485876.0	7.80	535.58	0.009
Forest	59091.1	10.93	65.14	0.012

Table 11: Carbon Dioxide Sequestered in a sample of 24 Trees

Average CO2 Sequestered per Tree (pounds)	Standard Deviation (pounds)	Total CO2 Sequestered among Trees (pounds)	Average CO2 Sequestered per Tree (tons)	Standard Deviation (tons)	Total CO2 Sequestered among trees (tons)
43644.4	65875.9	1047465.4	21.8	32.9	523.7

Table 12: CO2 sequestered including trees

Land Cover	CO2 Sequestered (kg)	CO2 Sequestered per unit area (kg/m^2)	CO2 Sequestered (tons)	CO2 Sequestered per unit area (tons/m^2)
Pasture	612033.6	9.17	674.64	0.010
Crop	485876.0	7.80	535.58	0.009
Forest (soil only)	59091.1	10.93	65.14	0.012
Forest (soil **and trees**)	534221.4	98.85	588.9	0.109