The impact of long-term land uses on organic carbon stocks in a landscape of similar soil texture classification in N. Ireland.

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Abstract

The appeal of nature-based atmospheric carbon removal solutions has gained prominence in recent years as countries seek to honor emissions reduction pledges. It has been estimated that soil carbon represents 25% of the total potential of natural climate solutions, roughly 6Gt of CO2-equivalent per year, and is an appealing way to increase carbon sinks while reducing emissions as it produces co-benefits via agricultural productivity (Bossio et al., 2020). There is, however, limited knowledge on the long-term effects that distinct land uses exert on soil organic carbon (SOC) stocks at varying depths in the context of temperate north Atlantic woodlands and grasslands. The aim of this study was to investigate whether significant differences in SOC stocks emerged after decades of consistent land uses within a single mixed farm property in the county of Londonderry, Northern Ireland. The farm is representative of five distinct land uses (grassland, willow production, silvopasture, 30-year woodland & 250-year woodland) providing a unique opportunity to compare the long-term effects of these treatments between fields of similar soil type (cambisols), soil textures (silt loam) and climactic conditions (cloudy, cool, and wet) in a cross-sectional chronosequential observational study. Our results have shown that land use, depth and their interaction significantly affect SOC densities (P< 0.05); that land use significantly affects SOC values at 0-15cm and 15-30cm depths (P< 0.05) however the effects at 30-60cm and 60-100cm are not statistically significant; that pH did not significantly impact carbon stock densities; and that land use changes associated with the planting of fast-growing trees (willows) resulted in substantial increases in total carbon stocks.

Introduction

The UK's ambitious emissions reductions target of 68% by 2030 (relative to 1990 levels) has placed enormous pressure on limiting emissions from all sectors of the economy. Only cutting emissions, however, would likely not be enough for the UK to meet its climate goals. It therefore becomes necessary to consider the role of nature-based carbon removal solutions to help the UK meet its climate goals. Atmospheric carbon sequestration in soils, however, is a complex process that is highly context-dependent. Understanding the dynamics of soil organic carbon (SOC) in relation to land use at increasingly local scales is needed for farmers and land managers to implement context-appropriate land use solutions aimed at increasing soil carbon sequestration.

This study aimed to contribute to the current understanding of soil organic carbon dynamics in response to land use change by:

1. Assessing if different long-term land uses impact SOC density;
2. Determining at what depths, 0-15cm, 15-30cm, 30-60cm, or 60-100cm, these impacts took place;
3. Evaluating the influence of pH on SOC density;
4. Investigating what land use changes contribute to significant increases or decreases in soil carbon stocks.

Site Description

Brook Hall Estate: a mixed-farm enterprise in the county of Londonderry engaged in renewable biofuel production (willow coppice), dry stock farming, and academic field-research.

- Area sampled: 32 hectares
- Soil texture: Predominantly silty loam
- Climactic conditions: Temperatures vary between 5°C to 18°C and is rarely below 1°C or above 21°C. Annual rainfall averages 860 millimeters per year.
- Land uses:

Willows (28 years)

Woodland (30 years)

Silvopasture (120 years)

Permanent grassland (200 years)

Woodland (250 years)

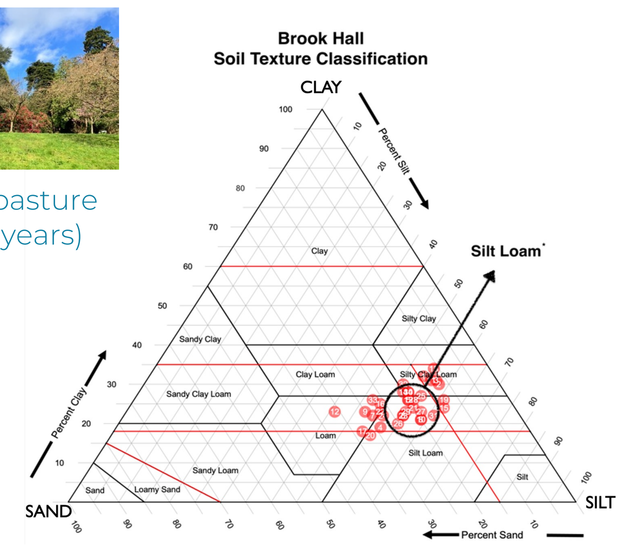

Figure 1: Soil texture classification of the different fields assessed in this study.

Materials

Data collection involved using Agricarbon's automated soil auguring services to extract cores to a depth of 1 meter, which were then stratified into four depth intervals (0-15cm, 15-30cm, 30-60cm, 60-100cm). Measurements of SOC stocks were reported for each stratified core. In-field pH measurements were taken at each sampling location at a depth of 5cm and 20cm using the Groline H981030 Soil pH Tester by HANNA instruments ®. Soil carbon measurements were quantified through elemental analysis by combustion at Agricarbon's laboratory. Samples were exposed to hydrochloric acid prior to analysis of organic carbon to allow for the removal of carbonates.

Land Use	Area Sampled (ha.)	Samples Extracted	Sampling Densities (samples / ha.)
Grassland	9.7	45	4.6
Willow Production	16.5	45	2.7
Silvopasture	2.9	30	10.4
30-year Deciduous Woodland	2.2	30	13.5
250-year Deciduous Woodland	0.8	30	35.7

Table 1: Total areas, samples and sampling densities for each land use at Brook Hall.

Methodology

Comparisons of SOC density were made between the different depth stratifications and land uses. SOC densities were computed at each depth according to the following equation:

Soil Organic Carbon Density [mg cm-3] = TBD x SOC x (TFFM/TDM) x 1000

Where TBD is the total dry bulk density [g cm-3]; SOC is the concentration of organic carbon present in the soil [%]; TFFM is the total fine fraction mass [g]; TDM is the total dry mass [g].

TBD, SSC, TFFM and TDM values that fell beyond 1.5x their respective inter-quartile ranges within each land use were eliminated to avoid potential biases resulting from outliers in any of these observed parameters.

Statistical analyses were carried out on R version 4.1.0. A two-way analysis of variance (ANOVA) was conducted to evaluate the significant effects of land use, depth, and their interaction on SOC densities using the 'stats' package. Model assumptions of homoscedacity and normality were assessed by visual assessment of diagnostic plots. Pairwise comparisons within each depth stratification were made using Tukey's HSD test. Separate one-way ANOVAs were conducted at each depth level to assess if land use significantly impacted SOC density at each depth. Pairwise comparisons within each depth strata were made using Tukey's HSD test to identify what pairs of land uses had mean SOC density values that were significantly different to each other. Finally, a two-way ANOVA was conducted to evaluate the effects of pH and land use on carbon stock densities. Significance of results was considered at p < 0.05 level for all tests.

Results

1. Land use significantly impacts SOC stock density.

A two-way ANOVA with interactions was used to assess if land use, depth or an interaction between land use and depth produce statistically significant differences in relative soil organic carbon stocks. Partial eta-squared (η^2) values for each variable have been computed to assess the effect size of each term in the model. It has been shown that both factors and their interaction had a significant effect (p < .001). The main effect of Land Use explained 9.16% of the total variance in SOC density. However, depth was shown to be a stronger predictor, explaining approximately 65.88% of the variation. This indicates that soil depth has a substantial impact on SOC density values, with deeper soil depths tending to have smaller carbon stock values compared to shallow layers. The interaction between land use and depth was also significant, accounting for 11.11% of the variance. This indicates that the effect of land use on SOC stock depends on the depth level and vice versa (the effect of depth on SOC stocks depends on the land use).

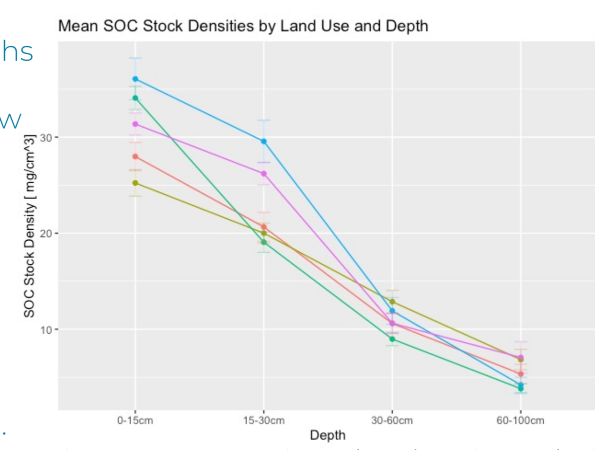

Figure 2: Interaction plot showing relationship between carbon stocks, land use and depth.

2. Impact of land use on SOC stock density is not significant at depths exceeding 30cm

Separate one-way ANOVAs were used at each depth stratification to assess the isolated contribution of land use to SOC stocks at each depth.

Depth	F-statistic	Df	P-value	Effect size (η^2)
0-15cm	8.25	4	4.58e-6	0.1737
15-30cm	10.45	4	1.36e-07	0.1973
30-60cm	2.144	4	0.0778	0.0506
60-100cm	2.3	4	0.0647	0.0918

Table 2: Results from a separate one-way ANOVAs at each depth stratification assessing the contribution of land use to observed differences in SOC stocks.

The results from the separate one-way ANOVAs are compatible with the trends observed in interaction plot in Figure 1. Land use produced significant effects (P<0.05) on SOC stocks at 0-15cm and 15-30cm but not at 30-60cm and 60-100cm. The proportion of the variance in SOC stocks explained by land use, measured by the eta-squared (η^2), at 0-15cm and 15-30cm is 17.4% and 19.73%, respectively.

These results disprove our second hypothesis. We have shown (P<0.05) that the effects of land use on carbon stocks were significant (P<0.05) at depths up to 30cm and insignificant at depths exceeding 30cm. However, when looking only at the significant depths, 0-15cm and 15-30cm, land use had a greater effect on carbon stocks at 15-30cm than at 0-15cm.

3. At a depth of 0-15cm, the effect of pH on carbon stock density is insignificant

A two-way ANOVA assessing the impact of land use and pH on SOC density was conducted on a subset of the data that contains SOC density values for the 0-15cm depth stratification. The eta-squared (η^2) values of land use, pH and pH:land use were 0.174, 0.003, 0.007, respectively. Only land use was shown to be statistically significant (P<0.001). These results were surprising given that increases in soil pH beyond 7.5 have been shown to negatively impact SOC (Yu et al., 2014) while soil acidification increases SOC content by decreasing the rate at which organic carbon decomposes (Zhang et al., 2020). Perhaps the limited ranges of pH observed in this study were not wide enough to capture the relationship between pH and SOC over the full range of plausible soil pH values.

4. Tree planting increases SOC stocks under different land use transitions

To assess the effects size of the SOC stock variations between the land use changes present at Brook Hall, we have computed the percent change, absolute differences, Cohen's d values, as well as the average rate of change in SOC stocks over their respective transition times. Cohen's d is a measure of the effect size of the transition. Its value tells us how many standard deviations lie between mean values of the groups being compared and is an indication of the practical significance of the results. Effect sizes < 0.2 were considered small; effect sizes ≥ 0.2 but < 0.8 were considered medium, and effect sizes ≥ 0.8 were considered large.

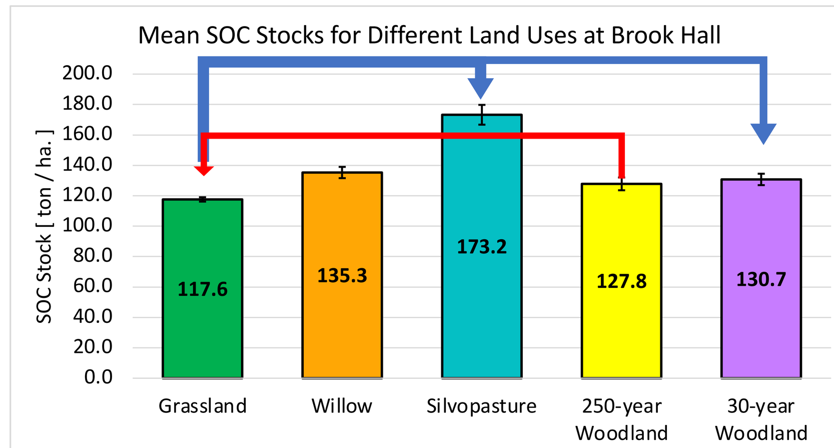

Figure 3: mean SOC values for each land use with standard error bars.

While the magnitude of the differences between total carbon stocks varied depending on the land use change, it was apparent that changes associated with tree-planting resulted in increases in SOC stocks. Such was the case when transitioning grassland into woodlands and grassland to silvopasture. The opposite trend appears to be true as removing trees, such as when transitioning 250-year-old woodland to grassland, resulted in a modest decrease in SOC stocks.

Years of current land use	Former land use	Current land use	% change	Difference (ton / ha.)	Rate of change (ton / ha. / year)	Cohen's d	Effect size
34	Grassland	30-year Woodland	11%	13.2	0.39	0.35	Medium
120	Grassland	Silvopasture	47%	55.2	0.46	1.08	Large
200	250-year Woodland	Grassland	-8%	-10.2	-0.05	0.26	Medium

Table 3: Impacts of specific land use changes observed in this study

Conclusion

This study illuminates the profound impact of land use on soil organic carbon (SOC) stock density. Our findings demonstrate the significance of both land use and depth, as well as their interaction, in influencing SOC levels. Additionally, our results revealed the pivotal role of silvopasture in contributing to enhanced SOC sequestration. We posit that silvopasture contributes to enhanced SOC stocks due to the complex root architecture created by grasses and trees cohabiting the same land. This diversity-driven phenomenon underscores a fundamental principle—monocultures, whether of grass or trees, fall short when compared to the SOC sequestration capacity of a diversified ecosystem by allowing carbon to be sequestered at various depths simultaneously.

Notably, this study also found that the influence of land use on SOC stock density diminishes beyond a depth of 30 cm. Through meticulous depth-wise analysis, we observed that land use significantly affects SOC stocks up to 30 cm depth but loses its significance beyond that threshold. At significant depths (0-15 cm and 15-30 cm), land use demonstrated a substantial effect, with 15-30 cm depth exhibiting a greater influence on carbon stocks than the shallower 0-15 cm depth.

Surprisingly, at a depth of 0-15 cm, we observed that pH did not significantly impact carbon stock density, contradicting existing literature. Despite expectations based on previous studies linking soil pH to SOC content, our findings suggest that the observed pH range in this study may not have been broad enough to capture the pH-SOC relationship comprehensively. Further research with a wider pH range is warranted to explore this relationship more comprehensively.

Lastly, our investigation underscores the potential of tree planting in augmenting SOC stocks during land use transitions. Analyses of SOC stock variations revealed that tree planting, evident in transitions from grassland to woodlands and grassland to silvopasture, consistently resulted in increased SOC stocks. Conversely, removing trees, such as in the transition from 250-year-old woodland to grassland, led to a modest decrease in SOC stocks. The practical significance of these transitions was elucidated through effect size measurements, highlighting the beneficial effect of afforestation on SOC stocks across various land use changes.

In sum, this study sheds light on the multifaceted interplay between land use, depth, and pH, providing valuable insights for sustainable land management practices that can foster enhanced soil carbon sequestration. The positive impact of diverse root structures within silvopasture advocates for promoting functionally diverse ecosystems to bolster SOC stocks, reinforcing the importance of thoughtful land use planning and management in the pursuit of a sustainable future.

Recommendations

The comprehensive soil carbon baseline produced because of this study have laid the foundation for future experiments to be conducted at this study site. Since the data on soil carbon is quite variable, even within each land use, future observational studies could seek to explore the causes or correlations associated with these variabilities. One interesting aspect to explore could be the effect that tree species have on localized carbon stocks. By sampling under the canopies of different tree species, it may be possible to determine the individual contribution of each species to the soil's ability to sequester carbon.

The soil carbon baselines resulting from this study can also serve as experimental control values for each land use to test the effects of specific treatments on soil carbon. In the grasslands, for instance, it is possible to assess the impact of introducing herbs and legumes into pastures by dividing the grasslands into fields where different treatments can be applied (herbs and legumes vs. perennial rye grass). The effect of grazing patterns on soil carbon can also be assessed by comparing set stocking vs. rotational grazing systems. It may also be worthwhile to consider the impact that different species of livestock (sheep vs. cows) have on soil carbon. Similarly, the effect of tree planting density in relation to soil carbon sequestration may also be explored by experimenting with different planting densities in the willow fields and the 30-year woodland. These investigations could contribute to a more complete understanding of what might be driving differences in carbon stocks within similar land uses in the climactic conditions found in Northern Ireland.

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