

**Long-Term Soil Carbon and Nitrogen Analysis at the Calhoun
LTSE from 1962 to 2017**

By

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Executive Summary

The cycling of carbon (C) and nitrogen (N) through soil systems is fundamental to sustaining both human life and biodiversity. However, human activities, particularly agriculture and land-use change, have greatly impacted soil systems by depleting soil organic carbon (SOC) and soil organic nitrogen (SON). These actions have shifted soils from being carbon sinks to carbon sources. Since 1850, over 100 petagrams (Pg) of carbon have been released from soils into the atmosphere, making the management of soil organic matter (SOM) a critical component of sustainable development and climate change mitigation.

This study examines the long-term dynamics of SOC and SON within the Calhoun Long-Term Soil-Ecosystem Experiment (LTSE), located in the Sumter National Forest in South Carolina, USA. The site, which transitioned from historical cotton cultivation to secondary loblolly pine forests, offers a unique opportunity to investigate changes in soil properties over time. The study analyzed SOC and SON data collected from four soil depths (0–7.5 cm, 7.5–15 cm, 15–35 cm, and 35–60 cm) between 1962 and 2017. Soil samples were normalized to their 1962 values to account for spatial variability across the landscape. Segmented regression analysis was applied to identify breakpoints where SOC and SON dynamics shifted during this period. Additionally, the effects of clearcutting in 2007 were assessed by comparing SOC and SON changes in clearcut and intact plots both before and after harvesting.

Key Findings:

1. **Depth-Dependent SOC and SON Dynamics:**

SOC and SON exhibited distinct trends based on soil depth. In surficial soils (0–15 cm), there was a rapid decline in SOC and SON during the early years of reforestation, followed by a significant recovery in later years. In contrast, deeper soil layers (15–60 cm) experienced more prolonged declines before showing signs of recovery. In the deepest layer (35–60 cm), SOC has yet to accumulate throughout the study period, suggesting that deeper soils may be slower to respond to reforestation or other management practices.

2. **Nitrogen Depletion Greater Than Carbon Throughout Soil Depth:**

The temporal changes in SOC and SON followed a similar pattern of initial decline followed by accumulation, but the mechanisms driving these changes differed. The decline in SOC was largely due to insufficient organic matter inputs to compensate for decomposition. In contrast, the decline in SON was driven primarily by tree uptake, as nitrogen is a limiting nutrient for forest growth. This greater depletion of nitrogen throughout the soil profile indicates that it may take longer for SON to recover compared to SOC.

3. **Clearcutting Impacts:**

The anticipated effects of clearcutting in 2007 on SOC and SON were less significant than expected. SOC and SON concentrations in clearcut plots did not differ markedly from those in intact plots, suggesting that the input of organic matter from logging debris may have mitigated the anticipated loss of carbon and nitrogen following the harvest. This finding challenges the assumption that clearcutting always accelerates soil carbon losses, indicating that site-specific factors play a critical role in influencing outcomes.

The findings of this study have several important implications for soil management and forest restoration:

- **Depth Matters:**
The depth-dependent nature of SOC and SON recovery highlights the importance of considering soil depth in management practices. While surficial layers may recover more quickly, deeper soil layers may require additional interventions to restore carbon and nitrogen stocks effectively.
- **Long-Term Monitoring is Essential:**
The 55-year dataset from the Calhoun LTSE underscores the value of long-term monitoring for understanding soil dynamics. Short-term studies may fail to capture the full extent of SOC and SON changes, especially in deeper soils where recovery is slower and more variable.
- **Clearcutting and Debris Management:**
The relatively minimal impact of clearcutting on SOC and SON suggests that forest management practices that retain logging debris could mitigate carbon and nitrogen losses. This highlights the potential for debris management strategies to enhance soil restoration efforts following forest harvesting.

Approved

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Introduction

Carbon and nitrogen cycling through soil systems is fundamental to supporting billions of human beings and the Earth's biodiversity. Soils are in fact highly dynamic and influenced by topography, climate, time, geologic material, plants, and animals. In the Anthropocene, human influence has become another overriding factor in altering and forming soils (Richter, 2020). Among the most significant ways humans modify soils are agriculture and other land uses. Agriculture has been altering soils for nearly 12,000 years when it spread through the world and established a basis for human development (Ellis, 2021; Klein Goldewijk et al., 2011). Land use change and especially cultivation depletes soil organic carbon (SOC) and soil organic nitrogen (SON) and accelerates soil erosion. Over 100 Pg of C have been released from the soil into the atmosphere since 1850 with an annual rate of 2 Pg yr⁻¹ over 1980s, in comparison with a total of 760 Pg of C stored in the atmosphere (Houghton, 1999; Lal, 2004; Schimel, 1995). The loss of carbon from soils now exceeds the rate of carbon sequestration, turning soils from carbon sinks into sources of atmospheric CO₂ (Schlesinger, 1990). Therefore, effective soil management and restoration of soil organic matter and productivity are critical priorities for sustainable development.

Research has shown that converting agricultural lands back to native vegetation, either through natural succession or replanting, can effectively restore SOC (Post & Kwon, 2000; Schlesinger, 1990). The rate of and the time length for soil C to accumulate, however, are highly variable and depend on multiple factors such as soil properties, vegetation types, and land use history (Post & Kwon, 2000). In the early stages of forest development, SOC may decline as fresh organic matter inputs are insufficient to offset decomposition losses (Post and Kwon, 2000). Over time, as forests mature, SOC gradually rebuilds, but the rates of SOC accrual are very poorly quantified. The rate of soil carbon accumulation is influenced by environmental factors such as temperature, moisture and, soil depth, with evidence showing that SOC stocks below 40 cm can continue to decline even after a decade of reforestation (Post & Kwon, 2000; Quartucci et al., 2023).

Forest management practices following reforestation or afforestation further impact soil composition and properties through the redistribution of soil organic matter (SOM), disturbance of soil biological communities, and soil compaction (Marshall, 2000). Practices such as clearcutting and salvage harvesting have been shown to accelerate the decomposition of SOM, leading to SOC loss and increased nutrient leaching (Bowd et al., 2019; Dahlgren & Driscoll, 1994; Fujii et al., 2021). However, in the short term, clearcutting can increase microaggregate formation and SOM due to the input of slash residues (Siebers & Kruse, 2019).

Among various approaches to estimating change in SOC over time, the long-term experiment is one of the most effective methods to understand how soils respond to land use changes and management practices (Richter et al., 1999; Richter & Yaalon, 2012). This study examines one of the most widely recognized long-term soil study sites, the Calhoun Long-Term Soil-Ecosystem Experiment (LTSE) in the Sumter National Forest, South Carolina, USA. The Calhoun LTSE investigates soil changes associated with the transition from historical cotton cultivation to secondary forest. Unlike the majority of land use and soil studies, which sample only the top 15 or 30 cm of soil (Richter et al., 2015), the Calhoun LTSE provides a deeper understanding of mineral soils, with samples consistently collected to a depth of 60 cm.

This study utilized data from the Calhoun LTSE to analyze the dynamics of SOC and SON at various soil depths following the replanting of loblolly pine, as well as the impacts of clearcutting on soils

in the Piedmont region. Based on previous research, the study hypothesized that SOC and SON followed similar trends: depletion during the early stages of forest development, followed by gradual accumulation as the forest matures. Instead of simply estimating the accumulation rate via fitting continuous linear or nonlinear regressions, this study applied segmented regression to detect the age of the forest when the SOC and SON changes flipped. Segmented regression has been shown to be a powerful tool to study soil-plants interaction involving combinations of mechanisms with differing slopes (Shuai et al., 2003). Additionally, the study expected the onset of increases to be depth-dependent, with deeper soils showing delayed and slower accumulation. The study also anticipated that clearcutting accelerated SOC loss and nitrogen leaching.

Methods

Study area and sample collection

The Calhoun Long Term Soil-Ecosystem Experiment (LTSE) is situated within the Sumter National Forest in the Piedmont region of South Carolina, USA (34.608° N, 81.724° W). This site has been profoundly affected by a historical agricultural land use pattern characterized by the clearing of mixed-hardwood forests during the European settlement, about 150-year cotton cultivation leading to soil erosion and significant losses of soil C, followed by agricultural abandonment and loblolly pine replantation. The soils of the study sites are composed of Cataula series soils and derived from granite and gneiss (Richter & Markewitz, 1995). Soil profiles exhibit a sandy loam or loamy sand texture in the A and E horizons, extending to depths of 30 cm, while the B horizons reach depths of 2 to 3 m and are rich in kaolinite and sesquioxides. (Richter & Markewitz, 2001).

The Calhoun LTSE originated from a US Forest Service study on loblolly pine productivity and tree spacing. The experiment utilizes a randomized block design consisting of four blocks over a slopes less than 3% with varying degrees of soil erosion. Each block contains four 0.1-ha plots with different loblolly pine planting spacings (6', 8', 10', and 12'), totaling 16 plots. Since 1962, soil samples have been consistently collected from these 16 plots at four soil depths (0-7.5 cm, 7.5-15 cm, 15-35 cm, 35-60 cm) at intervals ranging from 4 to 9 years (in 1962, 1968, 1972, 1977, 1982, 1990, 1997, 2005, 2010, 2017). Air-dried samples from each depth increment were archived separately, and subsamples were pulverized of soil C and N analysis through an elemental analyzer. Comprehensive details regarding sample processing, laboratory analysis, and quality control protocols can be found in Mobley et al. (2015).

Statistical analysis

All analyses were conducted using R (R Core Team, 2024). Table 1 summarizes the number of composite soil samples collected per year, depth, and plot. The effects of spacing and block was assessed using an ANOVA test. The difference between 2010 and 2017 measurements was evaluated via paired t-test or Mann-Whitney U test based on the result of normality tests. The alpha significance level of all the statistical tests conducted in this study was 0.05.

To examine long-term changes in C and N in each of the four soil layers, segmented regression, also referred to as piecewise regression, was applied using the R package 'Segmented' (Muggeo, 2024)

identify and estimate the presence and value of a breakpoint. According to Muggeo (2003), the segmented linear regression model identified the value of breakpoint(s) by minimizing the residuals through:

$$y = \begin{cases} \beta_0 + \beta_1 x & \text{if } x \leq \tau \\ \beta_0 + \beta_1 x + \beta_2 x & \text{if } x > \tau \end{cases}$$

Where y is the response variable (e.g., soil C or N), x is the predictor variable (e.g., year), β_0 is the intercept, β_1 is the slope before the breakpoint, β_2 is the change in slope after the breakpoint (so slope after the breakpoint is equal to $\beta_1 + \beta_2$), and τ is the breakpoint. In this context, the breakpoint represents the year when the slope of C and N changed.

The analysis was conducted on plots that were not harvested in 2007 (plots with spacings of 8' and 10') and included samples from all four soil depths, except for 1968, when only the two uppermost soil layers were sampled. To account for spatial variability among plots, C and N measurements were normalized to their corresponding values from 1962 in each plot. A paired t-test or Mann-Whitney U test was performed to compare the coefficient of variation (CV) between the normalized and original data, with the alternative hypothesis that normalization reduces the CV, thereby improving data consistency. The dataset with the smaller CV was then used for the segmented regression analysis.

Half of the plots (with spacings of 6' and 12') were clearcut in 2007 and replanted with pine seedlings in 2009. To evaluate the effects of clearcutting on C and N, samples collected in 1997 (10 years prior to harvest), 2005 (2 years prior to harvest), 2010 (3 years post-harvest), and 2017 (10 years post-harvest) were analyzed to evaluate effects of harvest. Measurements from other years were normalized to the 2005 values, the closest pre-harvest year, to account for inherent spatial variability across plots. The C and N measurements from both clearcut and intact plots at the same soil depth and year were assessed for normality via Shapiro-Wilk Normality Test. If both datasets were normally distributed, a t-test was conducted to determine if there was a statistically significant difference from zero. If either dataset did not meet normality assumptions, a Mann-Whitney U test was performed to test the same hypothesis. This comparison was repeated for each year and each soil depth.

Results

Long-term soil C and N analysis

Changes in soil C from 1962 to 2017 varied by soil depth (Figure 1). Previous studies analyzing data from 1962 to 2010 demonstrated that temporal changes in C were best modeled by linear regression (Mobley et al., 2019). Measurements in 2017 did not significantly differentiate from 2010 measurements based on the result of the paired Mann-Whitney U test ($p = 0.0879$). The 95% confidence interval of the paired difference between 2010 and 2017 C measurements ranged from -0.003% to 0.068 %. The percentage here is not the percentage of C in the soil but is the percentage of its first measurement in 1962. Same with N. Normalization significantly reduced the averaged CV from 0.27 to 0.19 ($t = 4.83$, $df = 29$, $p < 0.0001$), resulting in a smaller variability of measurements in the 0–60 cm (Table 2). Soil C concentration was highest in the uppermost layer, decreasing with depth until below 15 cm (Figure 1). The two surficial layers exhibited a decline in C concentration followed by an increase, as hypothesized, yielding a negative slope prior to the breakpoint year and a positive slope after it. However, this trend was absent in the deeper layers. In the 15–35 cm layer, C exhibited a slight positive slope before the breakpoint year, followed by a

pronounced increase, while C in the deepest layer (35–60 cm) continued to decline during forest development (Figure 2).

This study hypothesized a depth-dependent relationship in the rebuilding of soil carbon, predicting that deeper soils would have a later breakpoint year and a slower rate of decline and accumulation (Figure 3). However, only the surficial layer exhibited a distinct response, with a rapid initial decline in C during the beginning 12 years of forest development, followed by earlier accumulation. While the accumulation rates of C in the upper three layers did not differ significantly with an average rate of 0.014% per year, the deepest layer did not show evidence of C accumulation during the measurement period (Figure 3).

Similar to C, changes in soil N from 1962 to 2017 varied by soil depth (Figure 4). Previous studies found that changes in N concentrations in the 0–7.5 cm and 7.5–15 cm layers were best fit by quadratic models, whereas N in the 15–35 cm and 35–60 cm layers were best fit by linear regressions (Mobley et al., 2019). Measurements in 2017 did not significantly differentiate from 2010 measurements based on the result of the paired Mann-Whitney U test ($p = 0.1048$). The 95% confidence interval of the paired difference between 2010 and 2017 N measurements ranged from -0.0001% to 0.0026%. Normalization significantly reduced the average CV of all N measurements in 0–60 cm from 0.26 to 0.18 ($p < 0.0001$). Segmented regression revealed significant slope changes in the temporal change of N across all four soil layers over time (Table 3). As hypothesized, N concentrations in all layers exhibited a decrease followed by a period of accumulation (Figure 5).

Along with the hypothesis that N would exhibit depth-dependent characteristics similar to C, the uppermost layer showed a more rapid decline in N concentration than the deeper layers, followed by an earlier accumulation, while N in the deepest layer reaccumulated in a slower rate than more surficial layers (Figure 3). Compared with C, all layers showed a more rapid decline in N concentration than C during forest development. N in the upper layer reaccumulated later than C but reaccumulated earlier in the subsoils (Figure 3).

The temporal changes in the C/N ratio differed from those of C and N. Normalization did not significantly improve the CV ($p = 0.9983$), so the original data were used for further analysis. The C/N ratio was generally higher in the surficial layers compared to the deeper layers (Figure 6). Significant slope changes in C/N across all depths were predicted by segmented regression (Table 3). Unlike C and N, the C/N ratio increased early in forest development, peaking around the stand age of approximately 30 years, followed by modest declines (Figure 7). A clear depth-dependent trend in the C/N ratio was not evident. The breakpoint year and rate of decline after the peak did not significantly differ among the four soil layers (Figure 9a & 9b). However, the rate of increase at the beginning of forest development was faster in the two uppermost layers compared to the deeper layers (Figure 9c).

Harvest effect analysis

Neither the t-test nor the Mann-Whitney U test detected a significant difference in C and N concentrations between clearcut and intact plots, both before (at 1997) and after the harvest (at 2010 and 2017) (Tables 4 & 5). Both C concentrations in the two uppermost layers and N concentrations in the most surficial layer exhibited declines in 2017 in both clearcut and intact plots, indicating a broader site-wide change (Figures 9 & 10).

Discussion

Long-term C and N Response to Forest Development

The response of soil C and N concentrations to forest development is strongly depth-dependent. Carbon concentration is generally higher in surficial soils compared to subsoils (Jobbágy & Jackson). At the early stages of forest development, C declines across all depths due to the lack of fresh organic matter inputs, where decomposition occurs faster than the rate of organic matter deposition. The surficial soils contain higher microbial activity, leading to a faster decomposition rate, as reflected by the steeper decline in C. Over time, as the forest matures, the surficial layers are more biologically active than the subsoil (Dove et al., 2021; Hao et al., 2021).

However, the input of organic C, such as fallen leaves, woody debris, and fine root turnover, eventually exceeds decomposition rates in the surficial layers resulting in carbon sequestration. Previous studies showed that the major input of soil C was from canopy litterfall, small amounts from turnover of fine roots, and least from the dissolved organic carbon (D. D. Richter et al., 1999). The subsoil obtained much less carbon than the topsoil over time, so the accumulation is delayed as soil depth increases. In the deepest layers, no significant C accumulation was observed over the measurement period. The surficial soil is mainly composed of light-fraction C, derived from fresh organic matter, while the deeper soils contain a higher proportion of recalcitrant C, which is more resistant to decomposition (Mobley et al., 2015). Thus, the overall rate of C decline is slower in deeper layers than the most surficial layer.

N follows a generally similar pattern of initial decline and later accumulation in the surficial layers, but the driving mechanisms contrast greatly. During the early stages of forest development, N is mineralized from organic matter to meet the aggrading forest's large and increasing demand of N (Richter et al. 2000). Although tree roots extend throughout the upper 60cm, fine roots, responsible for most nutrient uptake, are most concentrated in the surficial layers (Gale & Grigal, 2011; Hendrick & Pregitzer, 1996), resulting in a greater uptake of N at shallower depths and more rapid initial declines. As the forest matures and net biomass N accumulation reaches its peak at stand age 25-35 years (Richter et al., 2000), accumulation of the majority of N begins as the forest's N demand decreases. N in the surficial layer accumulated earlier than the peak of N in the aboveground biomass because the high microbial activity resulting in a faster return to compensate the tree uptake. This accumulation of N lagged and is not as rapid in the deeper soils.

The C/N ratio, unlike C and N individually, first increases and then decreases, indicating that N changes more intensively than C. The faster decline of N than C contributes to the increase in C/N at the beginning stage. The age at which C/N peaks coincides with the peak in aboveground tree biomass (Markewitz et al., 1998; Richter et al., 2000), while its later decline aligns with N accumulation in the soil. This suggests that changes in C/N are primarily driven by N dynamics and secondarily by C, and N is the limiting nutrient of the tree growth in the Calhoun. The peak C/N ratio reflects the typical values for pine-dominated forests, while the subsequent decline indicates a transition from pine to mixed forest stands since C/N is closely related to land cover and species composition (Blanco et al., 2023; Getino-Álvarez et al., 2023). Although C/N ratios are depth-dependent, the timing of changes in C/N appears to be relatively consistent across soil depths, suggesting that C/N dynamics are more closely linked to broader process across depths (Ostrowska & Porębska, 2015).

Impact of Clearcutting

In contrast to previous studies, clearcutting did not result in significant net changes in carbon loss or nitrogen. Clearcutting massively disturbs the forest-soil C and N stores/pools and cycles and adds large

quantities of organic debris (logging slash) to the forest floor. Decomposition and mineralization of logging debris, especially over the decade following logging (2007 to 2017) has been substantial. Therefore, an absence of change in SOC and SON must be interpreted as an absence of a net change in the mineral soil. Unlike prolonged agricultural disturbances that last for many decades, the clearcutting event occurred only once, followed by replanting within two years. The resilient nature of recalcitrant C and N in the soil may have allowed these pools to withstand the disturbance with minimal long-term impacts.

Forest Management Implications

The study demonstrated that six decades of reforestation increased soil C stocks in surficial soils (Figure 4). However, N concentrations have not fully returned to pre-reforested levels by the end of the measurement period (Figure 6). The temporal changes in soil C and N have some similarities in initial decline followed by accumulation, but the driven mechanisms are different. The decline of C is mainly due to the input that has yet to compensate for the decomposition, but the decline of nitrogen is driven by the tree uptake as the limiting nutrient to forest growth (Richter et al., 2000). This also leads to a larger depletion on N pool throughout the soil depth than C, thus a longer time to recover.

In general, the surficial soil layer shows the most dynamic behavior, with an earlier breakpoint year, faster decline, and more rapid recovery of both C and N compared to deeper soil layers. As soil depth increases, the accumulation of both C and N is delayed, with slower, and in some cases, negative rates of change. Even though results highlighted the transition from carbon source to carbon sink in surficial three layers and is able to offset the losses in the deepest layer, previous study found that most of C accumulation is light fraction carbon, but the majority of losses are those associated with clay and silt (Mobley et al., 2015). The slower rates of recovery underscore the bioavailability of soil N at depth. Reforestation has shown to greater impacts on subsoils through enhanced microbial activity and SOM decomposition (Mobley et al., 2015). Thus, the findings emphasize the need for careful management of subsoils during terrestrial restoration efforts, as disturbances may have long-lasting effects to these deeper layers which are understudied than upper layers (Richter et al., 2015).

Moreover, this study highlights the importance of long-term soil monitoring as a key method for systematically tracking soil responses to land-use changes. Understanding if and when reforestation can fully restore soil productivity is especially significant in the context of global food security, where intensive agricultural practices have degraded soil over time. Continuous monitoring can help determine the capacity of reforestation to reverse such damage and whether it can play a role in supporting sustainable land management.

The impact of one-time clearcutting remains inconclusive based on this study. It would be valuable to extend monitoring efforts to assess the effects of more frequent harvesting practices, which are more representative of real-world forestry operations. This approach could provide insight into how current forest management practices either support or alter soil health. More importantly, among about 250 global LTSEs reviewed by Richter and Yaalon in 2012, only 10% of those studied forest soil, and even less are currently operating. This study also calls for more LTSEs focusing on forest soils. Such findings would be crucial for guiding sustainable forest management strategies, particularly in balancing timber production with the long-term preservation of soil quality and ecosystem resilience.

Citations

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Figures and Tables

Figure 1. The average C content in percentage (a) and after normalization (b) changes by depth over years. The error bar stands for one standard error.

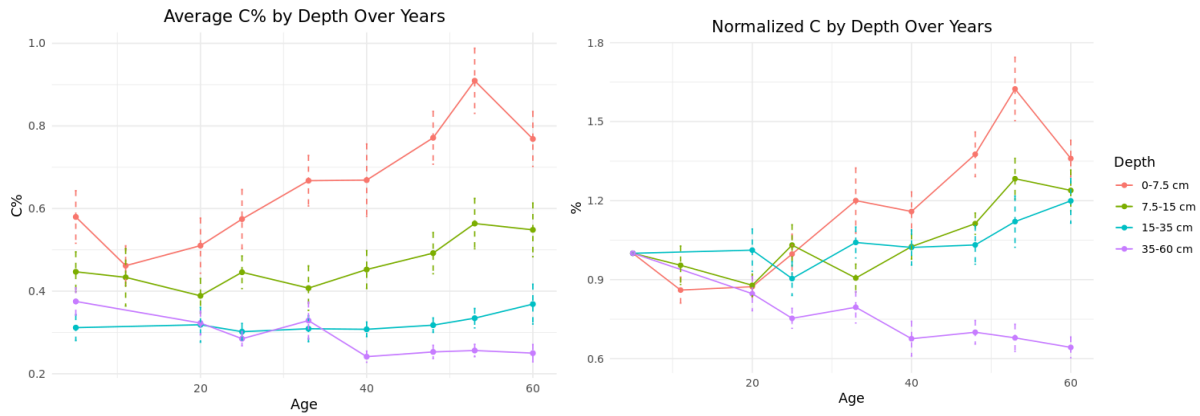


Figure 2. The distribution of normalized C of each depth over years. Blue line is the fit predicted by segmented regression, and the read dash line indicates the breakpoint year.

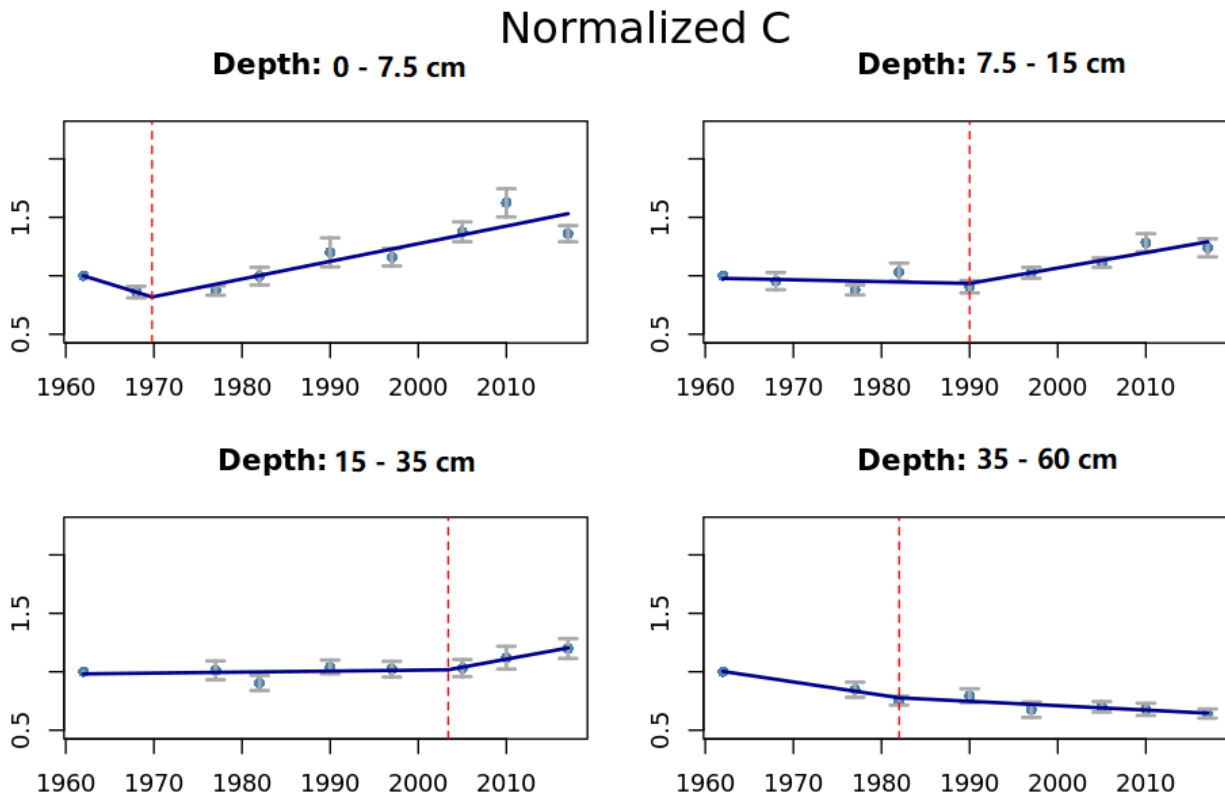


Figure 3. The breakpoint year (left), the slope before the breakpoint year (middle), and the slope after the breakpoint year (right) of normalized C by soil depths predicted by the segmented regression. The red solid lines indicate a slope of 0.

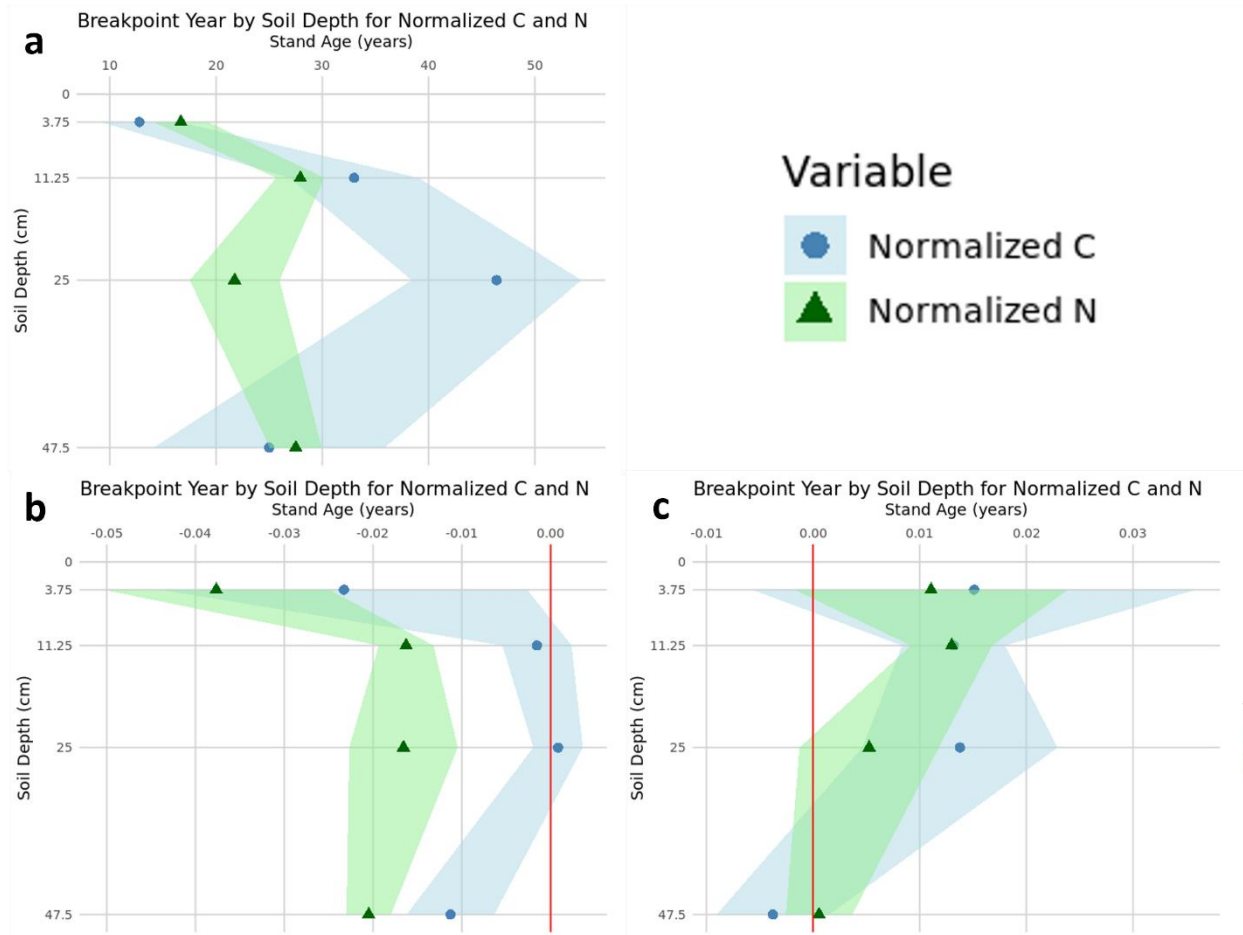


Figure 4. The average N content in percentage (a) and after normalization (b) changes by depth over years. The error bar stands for one standard error. The black line on figure (b) indicates the original value in 1962, which also equals to 1.

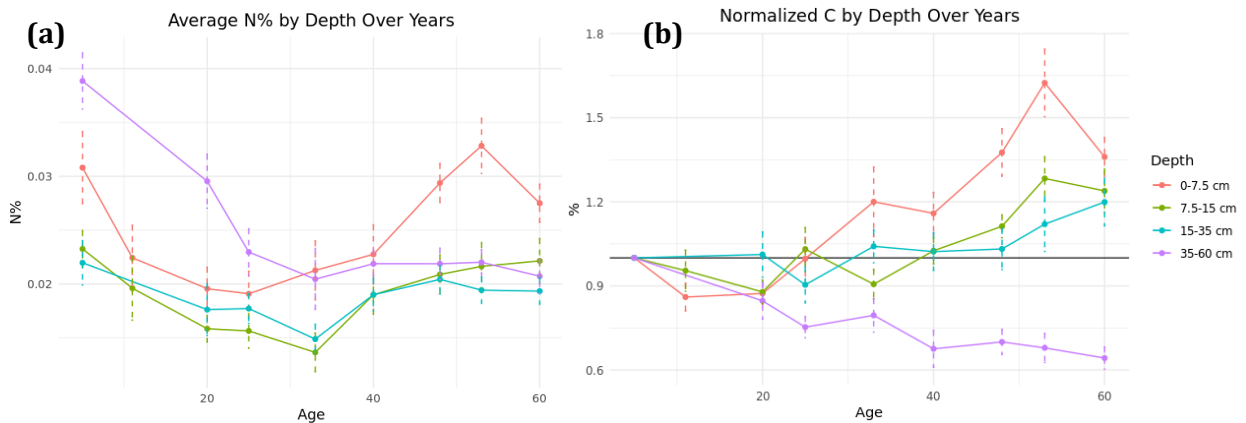


Figure 5. The distribution of normalized N of each depth over years. Blue line is the fit predicted by segmented regression, and the red dash line indicates the breakpoint year.

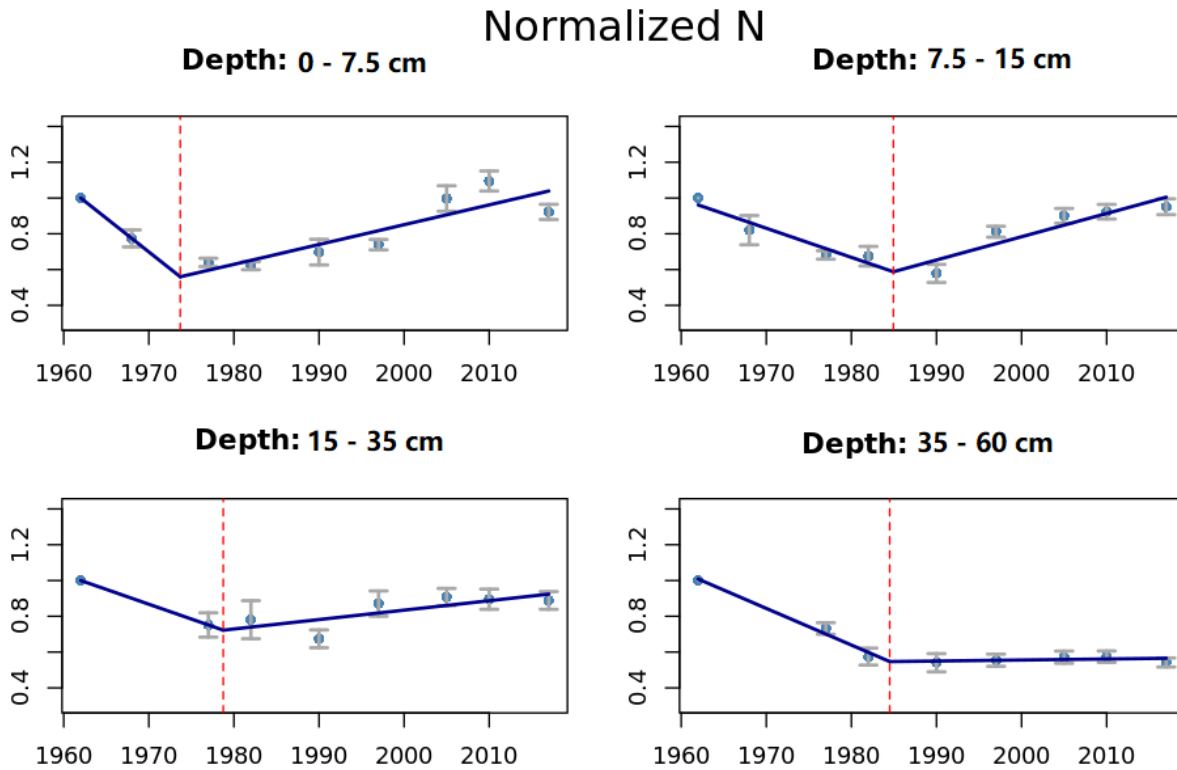


Figure 6. The average C/N ratio (a) and after normalization (b) changes by depth over years. The error bar stands for one standard error. The black line on figure (b) indicates the original value in 1962, which also equals to 1.

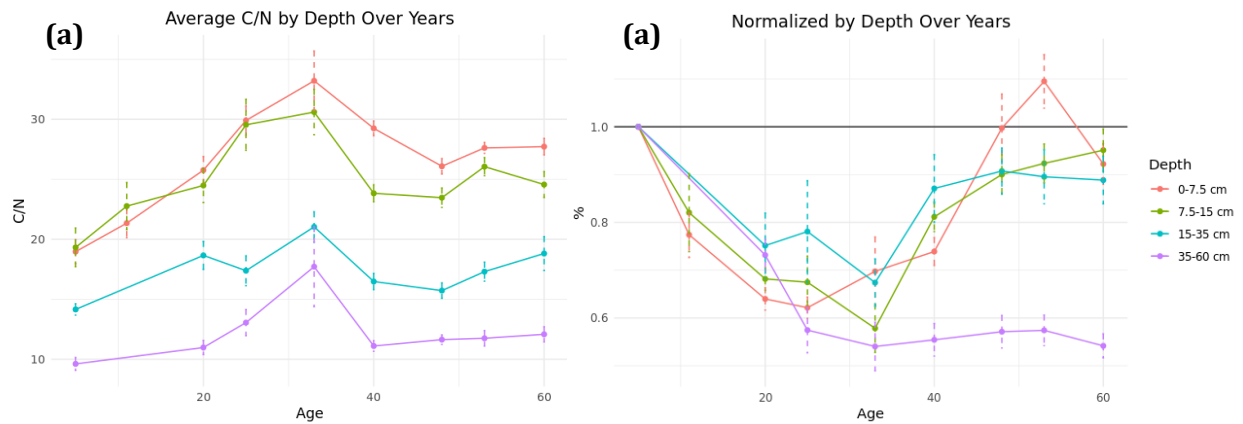


Figure 7. The distribution of C/N of each depth over years. Blue line is the fit predicted by segmented regression, and the red dash line indicates the breakpoint year.

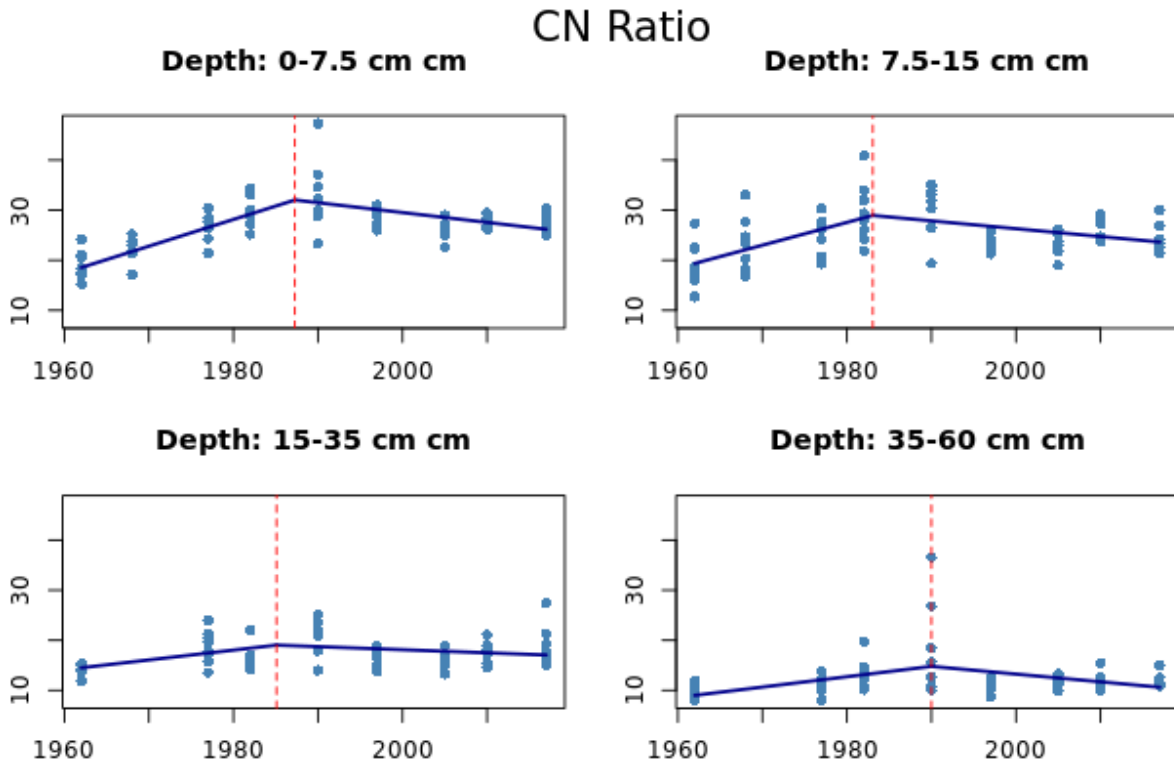


Figure 8. The breakpoint year (a), the slope before the breakpoint year (b), and the slope after the breakpoint year (c) of original C/N by soil depths predicted by the segmented regression. The red solid lines indicate a slope of 0.

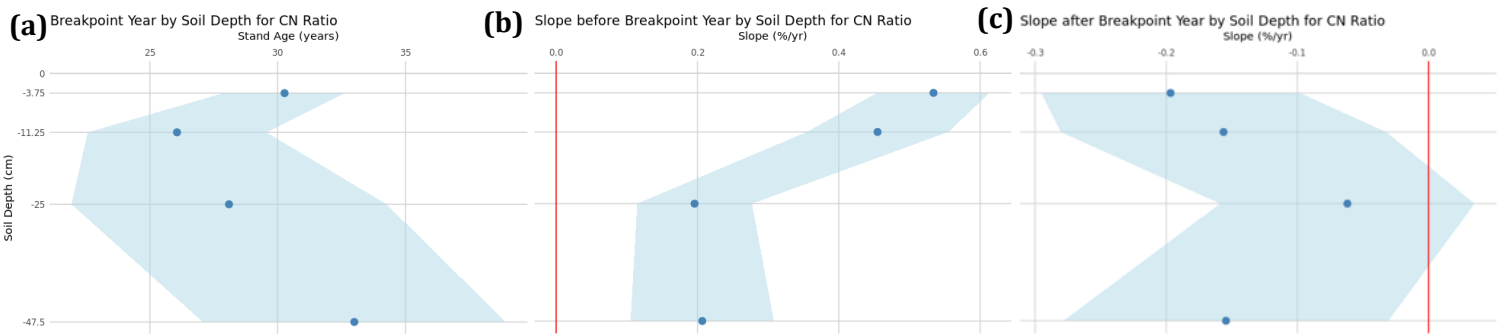


Figure 9. Boxplot of C (normalized by the concentration in 2005) in clearcut plots and intact plots by depth.

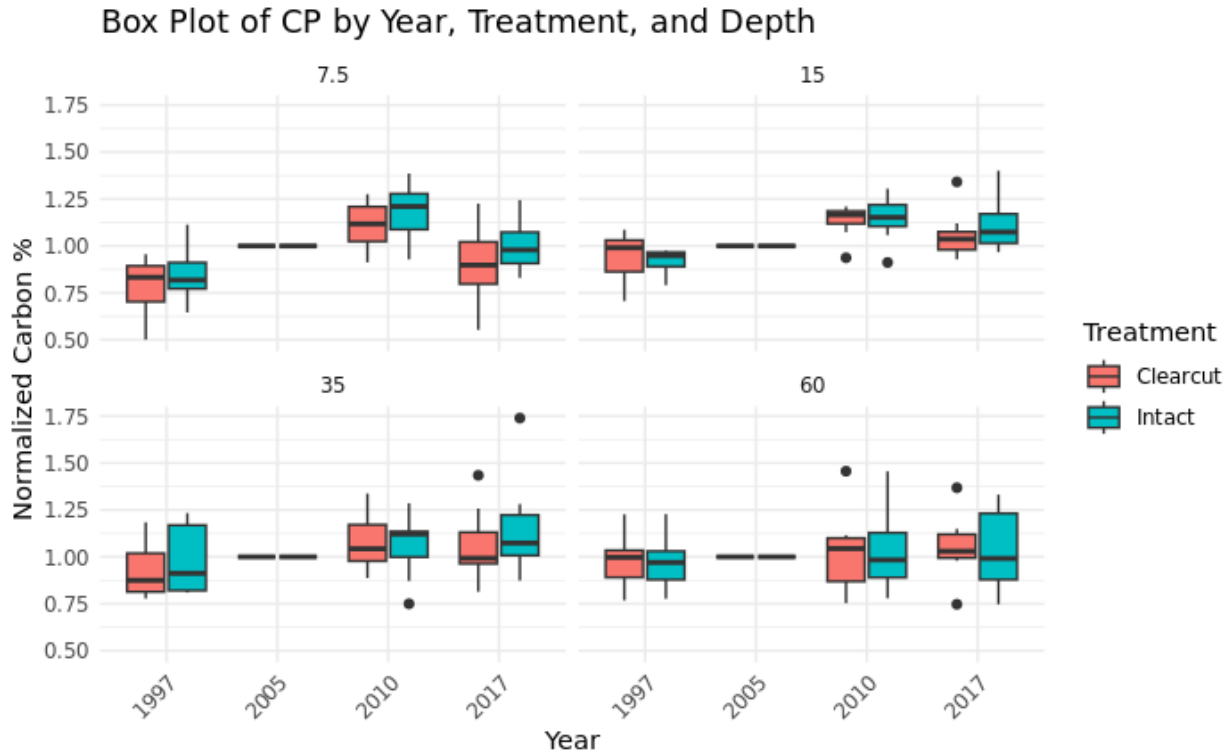


Figure 10. Boxplot of N (normalized by the concentration in 2005) in clearcut plots and intact plots by depth.

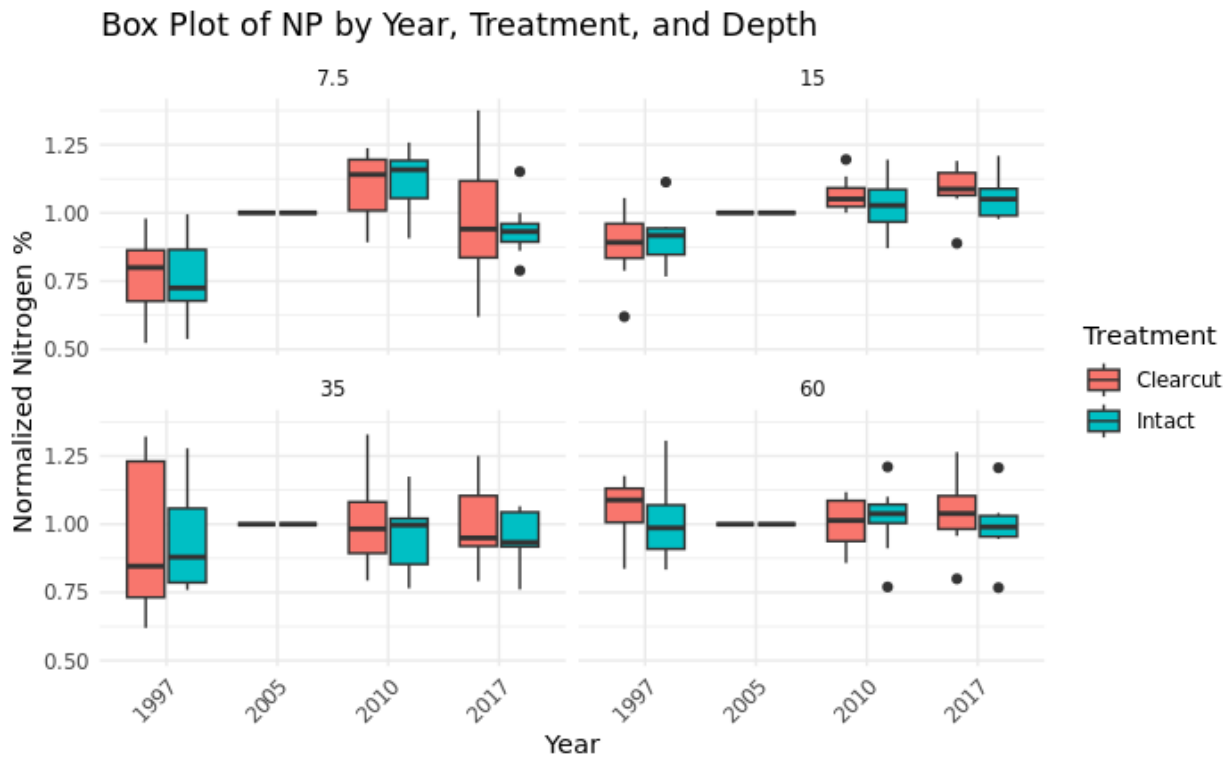


Table 1. Number of soil samples collected in each year from 1962 to 2017.

<i>Year</i>	<i>Depth</i>	<i>Block</i>	<i>Spacing</i>	<i>N</i>	<i>Note</i>
1962	4	4	4	62	Missing I-10-35 to 60cm and II-10-35 to 60cm*
1968	2	4	2	15	Missing II-8-0 to 7.5cm
1977	4	4	2	32	Intact plots only
1982	4	4	2	31	Intact plots only; one outlier (I-8-15 to 35cm) was removed due to approaching analysis limit of the equipment for N
1990	4	4	2	32	Intact plots only
1997	4	4	4	64	
2005	4	4	4	64	
2008	3	4	2	24	Clearcut plots only
2010	4	4	4	64	
2017	4	4	4	62	Missing IV-8-35 to 60cm and IV-10-35 to 60cm

*Samples are coded using a Block-Spacing-Depth format.

Table 2. T-test or Mann-Whitney U test results for comparison between CV after and before the normalization at each depth with an alternative hypothesis that CV before normalization is greater than after.

<i>Variable</i>	<i>Depth</i>	<i>Test</i>	<i>P-value</i>
<i>C</i>	0 – 60 cm	t-test	<0.0001
<i>C</i>	0 – 7.5 cm	Mann-Whitney U test	0.0078
<i>C</i>	7.5 – 15 cm	t-test	<0.0001
<i>C</i>	15 – 35 cm	Mann-Whitney U test	0.1304
<i>C</i>	35 – 60 cm	t-test	0.3438
<i>N</i>	0 – 60 cm	Mann-Whitney U test	<0.0001
<i>N</i>	0 – 7.5 cm	t-test	0.0034
<i>N</i>	7.5 – 15 cm	t-test	<0.0001
<i>N</i>	15 – 35 cm	Mann-Whitney U test	0.2891
<i>N</i>	35 – 60 cm	t-test	0.0268
<i>CN</i>	0 – 60 cm	Mann-Whitney U test	0.9973
<i>CN</i>	0 – 7.5 cm	t-test	0.9922
<i>CN</i>	7.5 – 15 cm	t-test	0.9749
<i>CN</i>	15 – 35 cm	t-test	0.9151
<i>CN</i>	35 – 60 cm	Mann-Whitney U test	0.7109

Table 3. Segmented regressions of normalized C, normalized N, and original CN by depths. P-value was determined through the Davies test for a non-zero difference-in-slope of a segmented regression (Davies, 2002).

<i>Variable</i>	<i>Depth</i>	<i>Breakpoint Year</i>	<i>Slope 1</i>	<i>Slope 2</i>	<i>P-value</i>
<i>NormC</i>	0 – 7.5 cm	1970 ± 4	-0.0233	0.0151	0.0899
<i>NormC</i>	7.5 – 15 cm	1990 ± 6	-0.0015	0.0132	0.0132
<i>NormC</i>	15 – 35 cm	2003 ± 8	0.0008	0.0138	0.2193
<i>NormC</i>	35 – 60 cm	1982 ± 11	-0.0113	-0.0038	0.2183
<i>NormN</i>	0 – 7.5 cm	1974 ± 3	-0.0377	0.0111	<0.0001
<i>NormN</i>	7.5 – 15 cm	1985 ± 2	-0.0163	0.0130	<0.0001
<i>NormN</i>	15 – 35 cm	1979 ± 4	-0.0166	0.0053	0.0040
<i>NormN</i>	35 – 60 cm	1985 ± 2	-0.0205	0.0006	<0.0001
<i>CN</i>	0 – 7.5 cm	1987 ± 2	0.5340	-0.1967	<0.0001
<i>CN</i>	7.5 – 15 cm	1983 ± 3	0.4548	-0.1563	<0.0001
<i>CN</i>	15 – 35 cm	1985 ± 6	0.1959	-0.0618	0.0288
<i>CN</i>	35 – 60 cm	1990 ± 6	0.2068	-0.1544	0.0311

Table 4. T-test or Mann-Whitney U test results for normalized C between clearcut plots and intact plots at each depth and in each year. 2005 was removed because all data values were normalized to 1.

<i>Year</i>	<i>Depth</i>	<i>Test</i>	<i>P-value</i>
1997	0 – 7.5 cm	t-test	0.4328
1997	7.5 – 15 cm	t-test	0.6383
1997	15 – 35 cm	Mann-Whitney U test	0.7209
1997	35 – 60 cm	t-test	0.9011
2010	0 – 7.5 cm	t-test	0.2916
2010	7.5 – 15 cm	Mann-Whitney U test	1
2010	15 – 35 cm	t-test	0.8382
2010	35 – 60 cm	t-test	0.9267
2017	0 – 7.5 cm	t-test	0.2671
2017	7.5 – 15 cm	t-test	0.4416
2017	15 – 35 cm	t-test	0.4858
2017	35 – 60 cm	t-test	0.8868

Table 5. T-test or Mann-Whitney U test results for normalized N between clearcut plots and intact plots at each depth and in each year. 2005 was removed because all data values were normalized to 1.

<i>Year</i>	<i>Depth</i>	<i>Test</i>	<i>P-value</i>
1997	0 – 7.5 cm	t-test	0.9110
1997	7.5 – 15 cm	t-test	0.6726
1997	15 – 35 cm	t-test	0.9847
1997	35 – 60 cm	Mann-Whitney U test	0.5283
2010	0 – 7.5 cm	t-test	0.7892
2010	7.5 – 15 cm	t-test	0.3872
2010	15 – 35 cm	t-test	0.5760
2010	35 – 60 cm	t-test	0.7934
2017	0 – 7.5 cm	t-test	0.7555
2017	7.5 – 15 cm	t-test	0.5402
2017	15 – 35 cm	t-test	0.4691
2017	35 – 60 cm	t-test	0.5116