The Legacy of Subsistence Agriculture on New England's Successional Forest Soils:

A 25-year Direct Measurement Perspective

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My quantitative thanks go to the Brown 2006 HBEF summer crew: Kemen, Becca, Stephan, and Natalie for allowing me to intermittently become part of their family and experience the realities of soil pit methodology.

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To Professor Hazeltine, thank you for your validation during lecture, by asking my real world opinion and suggesting that business and the environment do not have to be exclusive. Everyone should experience the shear joy of all things geologic expounded by Professor Jan Tullis.

The Resumed Undergraduate Education program for providing the opportunity for a second chance; old dogs can learn new tricks.

To my wife, Deborah, for all the things that truly matter.

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Abstract

Soil science over the last quarter century has been heavily focused on the long-term effects of natural and anthropogenic disturbance to the forest ecosystems. With a presumed understanding of carbon cycling, recent study has moved beyond the basics with a special focus on nutrient and microbial dynamics. Although the original intent of these studies was to determine the lasting effects of deforestation, the possibility of forest recovery and to maximize forest management, they have become increasingly relevant to global climate change. This paper challenges the predictions of a 200-year soil carbon recovery period reported in a 1980 old-field chronosequence that was re-sampled in 1992 and 2005 as well as the paradigm that soil C recovery is occurring following abandonment of agricultural lands. This unprecedented 25-year direct measurement of the effects of agricultural legacies on the development of re-growing forests suggests that the soils of 19th century subsistence hill farms of central New Hampshire are a source of carbon dioxide to the atmosphere at this point in time. I found evidence of a predisposition of the Ap horizon to increased respiration and that the assumed steady state references, vital to the chronosequence technique, are in flux. I show that these results correlate with increases in median annual temperature, and incidence of soil frost reported at Hubbard Brook Experimental Forest (HBEF) and that they suggest climate change may be providing positive feedback to the terrestrial carbon cycle. These results question the long-term mitigation potential of temperate successional forests growing on formerly cultivated lands.

Introduction

A major global environmental concern of the latter third of the 20th century was deforestation / logging and its impacts on environmental quality. Had clear-cutting and the removal of forest cover resulted in a degraded landscape? In the 1980's, carbon was understood to be key to understanding soils nutrients generally. The best data at the time suggested that the forest floor declined in mass by 50% within 20 years following forest harvesting, but recovery of the lost carbon would take a century of forest re-growth (Covington 1981). Although Covington's curve has yet to be duplicated in full, this paradigm has been used to describe response to forest harvest globally and to validate carbon and climate change simulation models (D.Yanni *et al.* 2003). This early work, inspired studies of the mechanical mixing of the upper horizons of the mineral soil that occurs during harvest. Further investigation of soil C began to show evidence that the roles of C and nutrients may be reversed. The soil's nutrients may retain or bind the soil C into the soil matrix (Schlesinger 1984; Trettin *et al.* 1999). These new insights may have lessened researcher concern over potentially declining soil C, implied their concurrence or simply distracted them from the original fundamental question of forest ecosystem recovery. Impending climate change has recently changed that focus.

Unfortunately, the methodology of the majority of these studies looking at forest soil carbon can be interpreted as qualitative. Site variability was addressed with a large quantity of easily obtained surface samples as opposed more comprehensive samples collected using soil pit / long core methodology. Mineral soil samples, largely relegated to collection using a push-corer, have proved inadequate in determining bulk density or intra-horizon variability data now considered critical to soil ecosystem study. The chronosequence technique, used in the studies just described, allowed researchers to evaluate the long-term ecosystem response to disturbance in a short period of time.

Trading space for time, meant studies need not involve a long period of research and multi-generations of researchers.

In the late 1970's, as a part of a new exploration in soil dynamics, Steven Hamburg, a doctorial candidate at Yale University, established a chronosequence to study the effects of 19th Century subsistence agriculture on the successional forest ecosystems of central New Hampshire (Hamburg 1984a). Selection of a study area within close proximity to Hubbard Brook Experimental Forest (HBEF) allowed use of the extensive long-term ecosystem data collected at that site. His study would also serve as comparison to the response of the comparatively short-term disturbance of forest harvesting studied in the aforementioned studies, with a study of primary forest clearing and a century long disturbance of the mineral soil: a 100-year disturbance as opposed to a year's disturbance by logging skidder. (Appendix A).

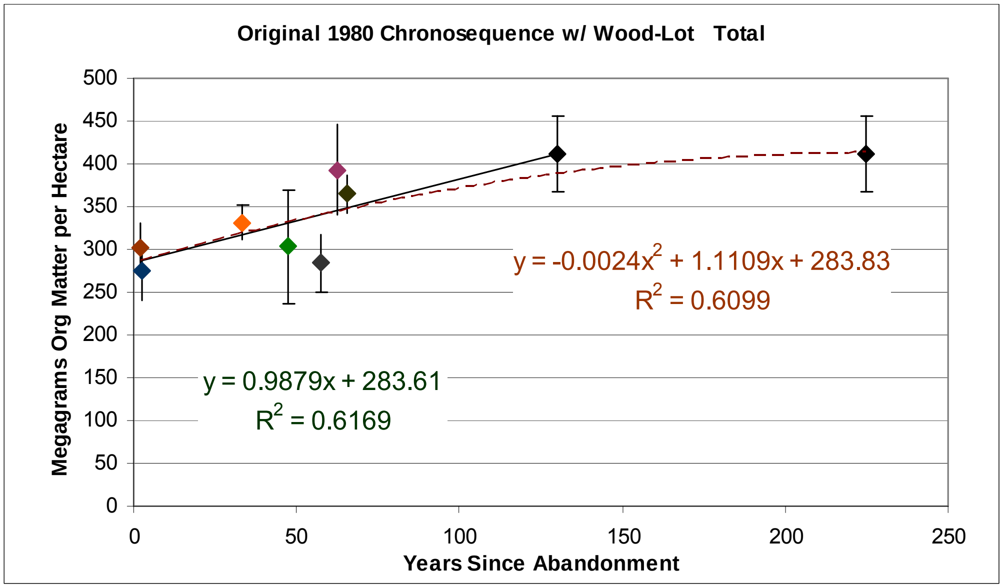

Figure 1: Total solum organic matter content changes over 150 years of forest re-growth following abandonment of agricultural lands, and a wood lot. Linear regression, (solid black line) and polynomial regression (red-segmented line) represent two potential models of long-term changes in soil C. (adapted from Hamburg 1984b)

Highlighting the finding of decreasing organic matter within the Ap horizon, he estimated that it would take approximately 200 years (Figure 1) for soil to return to levels present in the pre-settlement forest (Hamburg 1984b). This rate suggested a doubling of the Covington curves temporal span (Covington 1981; Schlesinger 1984).

Today this soil research can be used to address questions about the global carbon cycle and concern for increasing atmospheric carbon dioxide (CO_2) concentrations. The presence of a "Missing Sink" reminds all researchers of the uncertainty still present in our carbon budgeting. Northern temperate forests have been identified as a potential site for the missing carbon (C) sink (Billings 1938; Borman 1982; Hooker & Compton 2003; Johnson & Driscoll 1995). It is estimated that one third of forest carbon is located in the aboveground biomass; the majority resides in the mineral soil.

The objective of this research is to re-examine the predictions of the original old-field chronosequence study that estimated rates of carbon re-accumulation on abandoned agricultural land by re-sampling five of the original eight sites, 12 and 25 years after the original measurements. These re-measurements provide insight into the validity of the original chronosequence based research. In addition, it allows us to examine the effects of conifer dominance at some sites, grass cover at others, and steady state conditions of woodlots to be critically examined.

The questions answered in this thesis were:

- Are the soils of the northeastern hardwood successional forests re-growing on abandoned agricultural lands acting as sinks or sources of atmospheric carbon?
- At what rate are the carbon stocks of abandoned agricultural soils changing?

Site Description

The original 1980 study as well as this study is confined to two km^2 in the northwestern corner of Campton, New Hampshire, in the south western foothills of the White Mountains, (Latitude 43°51' North Longitude 71°42' 30" West) 12 km north of Plymouth, New Hampshire and 10 km south of Hubbard Brook Experimental Forest (HBEF). This proximity to HBEF allows the use of an extensive database on climate and forest structure and function. The climate is cool temperate, humid-continental, with short cool summers and cold winters. At an elevation of 450 m, the mean temperature in July is 19° C and -9° C in January. Annual precipitation averages approximately 140 cm, of which 25 to 35% falls as snow. Each winter a 1.5 m deep snow pack is persistent (Santore *et al.* 1995).

The study area is underlain by Concord Granite and is covered by a mantle of felsic; base-poor glacial till deposited approximately 14,000 years ago. Soils that have developed in this till are acidic, with a pH of less than 4.5. They are well-drained Haplorthods of the Skerry and Becket series with an average depth of 60 cm (Hamburg 1984b; Johnson & Driscoll 1995)

Although the composition of the vegetation of the Bald Mountain Community is classified as northern hardwood, it contains a mix of both hardwoods and softwoods. The dominant species include red maple (*Acer rubrum L.*), trembling aspen (*Populus tremuloides Michx.*), grey birch (*Betula populifolia Marsh*) sugar maple (*Acer saccharum Marsh*) red spruce (*Picea rubens Sarg.*) balsam fir (*Abies balsamea Mill.*) and white pine (*Pinus strobus L.*)

The 1980 study focused on seven sites on four abandoned farms. (Appendix C) The sites were selected based on the following criteria.

- Becket or Skerry soil series
- An elevation of 450 to 550 meters
- Minimal slope and/or southern exposure
- Uniform land-use and physiographic characteristics forming a discrete land-use unit
- Little or no surface micro topography and few surface rocks
- Evidence of extensive cultivation, i.e. homogenous plow layer (15 - 20 cm thick), stonewalls or piles and small fist sized rocks on the down slope side of the field of interest.
- Little evidence of use for post abandonment pasturage. i.e. no barbed wire, few multi-stemmed (wolf) trees and no major discontinuities in tree ages.

These criteria ensured similarity among sites effectively implementing the space for time substitution inherent in the chronosequence approach. Sites were selected to represent a range of forest ages, time since agricultural abandonment. Consistency, among site histories was confirmed using aerial photographs, (1942, 1955, 1978) archival records (town tax records, land deeds, agricultural census schedules) and interviews with past and present residents (Hamburg 1984a). A more detailed description of each of the 2005 sample sites as well as recent observations is available in Appendix D.

Table 1: Site Characteristics of the Eight Abandoned Fields of the Original Chronosequence Study

Highlighted sites have been compromised and will not e used in this study. (Adapted from Hamburg 1984b)

Site	Open Field # 9	Open Field # 4	Forested Site # 3	Forested Site # 5	Forested Site # 8	Forested Site # 6	Forested Site # 2	Woodlot Site # 7
Area (ha)	0.3	0.2	0.5	1.0	0.8	0.8	0.5	0.2
1980 Age (yrs)	2	2 - 3	31 -36	45 - 50	55 - 60	60 - 65	63 - 68	200+
1992 Age (yrs)	1	1	43 - 48	57 - 62	C	72 - 77	C	212+
2005 Age (yrs)	1	1	56 - 61	70 - 75	C	85 - 90	C	225+
Elevation (m)	470	520	520	490	550	520	520	520
Soil Drainage	Well	Well	Well	Well	Well	Moderately Well	Well	Well
Soil Series	Becket	Becket	Becket	Becket	Becket	Skerry	Becket / Skerry	Becket
Aspect	SE	N	NW	E - NE	SE	E - SE	E	NW
Slope (°)	10	2	11	6	20	10	10	9
Forest Composition (Basal Area m²/ha)			SM 5 RM 4 WP 10 F 1 S 2 WA 1 O 1	A 10 RM 6 SH 3 WA 3 F 1 WP 2 O 1	RM 18 S 6 SM 1 A 5 PB 1 O 1	RM 13 F 9 S 6 A 4 O 3	S 20 F 7 GB 7 RM 2 PB 2 O 1	S 9 F 2 SM 2 B 6 H 5 StM 4 WA 3

Abbreviations used **A** = Populus tremuloides Michx. , **B** = Fagus grandfolia Ehrh.,
BC = Prunus serotina Ehrh. , **C** = Compromised Site, **CC** = Prunus virginiana L.,
F = Abies balsamea Mill., **GB** = Betula populifolia Marsh, **H** = Tsuga canadensis Carr.,
PB = Betula papyrifera Marsh, **RM** = Acer rubrum L., **S** = Picea rubens Sarg.,
SM = Acer saccharum Marsh, **StM** = Acer pensylvanicum L., **WA** = Fraxinus americana L.,
WP = Pinus strobus L., **YB** = Betula lutea Michx., and **O** = other

The chronosequence technique is designed to represent one site through time, in the 1980 case, 70 years. Specifically, this chronosequence was designed to represent a typical subsistence farmed agricultural site that has been abandoned and natural re-forestation allowed to occur. Additional data was provided from re-sampling three of the forested sites, two mowed fields and one multi-aged woodlot, representing a 200-plus age forest, two additional times in 1992 and in 2005.

Methods

1980 Sample Collection Methodology

The following methodology is adapted from (Hamburg 1982) and (Hamburg 1984) as well as a review of the original data notebooks and personal communication with Professor Hamburg.

The 1980 forest floor samples of the forested sites were collected from 15 randomly selected locations within each site. Alternate locations were selected if the original was encumbered by a tree, log or rock. A 16 cm by 16 cm (.0256 m^2) cutting template was spiked to the forest floor and its perimeter was traced with a keyhole saw. The produced block of forest floor was inverted onto a tarp and separated into Oi and Oe/Oa horizons. Both horizons were oven dried at 80°C and processed with a Wiley Mill fitted with a #20 screen. This process produced one sub-sample for each of the 15 blocks.

All of the 1980 sites mineral soil samples originated from three randomly selected pits excavated at each site. To reduce site erosional influences, a stratified design was employed such that pit locations occurred in each row and column of a 3 by 3 grid overlain on the site with one axis parallel to slope. Trees within one meter of the pit location or surface rocks within the pit location prompted relocation. A one-meter square (m^2) frame, spiked to the forest floor, defined the cross-section of the pit as well as provided a reference plane for subsequent horizon depth measurements. An evenly divided 5 by 5 grid was overlain on the X and Y-axes of the frame. This grid provided systematic Z depth to top and bottom of horizon measurements. The Ap/B horizon delineation was clearly differentiated by color. Although the B/C transition was more difficult to discern, color, structure and rooting depth were used as clues in its definition.

Forest floor within the $1m^2$ frame was removed and discarded to expose the top of the Ap horizon. Subsequent depth measurements and excavation of each horizons mineral soil provided a total volume calculation of both the Ap and B-horizons. Plumb pit walls and a square 1m² cross-section ensured accuracy. Each horizons coarse fraction, rocks and stones >2mm, were subtracted from the total calculated volume. Immovable rock volume was estimated with the aid of a 5cm by 5cm grid. Rocks protruding into the soil pit were removed, weighed and had the applicable volume subtracted from the calculated total. All roots within the soil pit were removed flush with the pit walls, shaken to remove attached soil and discarded. After removal, each horizons mineral soil was segregated and passed through a 13 mm hardware cloth sieve. From this material, a 10 kg sub-sample was air-dried, passed through a 2mm sieve and then through a riffle box which produced four 100g sub-samples.

Bulk density for all of the pits mineral soil was calculated with the use of a "Tim Wood" 62 cm^3 coring device pressed into the four walls of the soil pit within each horizon. A much simpler, 335 cm^3 device was also used on selected site pit walls for confirmation of the volumetrically smaller device and where a larger volume or less soil compaction was required. The simplified device consisted of a soup can with both ends removed, driven into the pit walls with a wooden block and hammer. Core samples were air dried and sieved through a 2mm screen to correct for coarse fraction, which was assumed to represent the entire soil volume removed. This quantitative methodology produced the volume of each horizon as well as the percentage of that volume attributable to fine mineral soil.

The open-field sites lack a forest floor, as such; none of the sod or living biomass above the mineral soil was collected. Instead, it was clipped flush with top of the Ap horizon and discarded. In an attempt to capture decaying organic matter, the uppermost 3 centimeters of the Ap horizon was removed and processed for analysis separate from the majority of the horizon. This processing also produced four 100g sub-samples. Although the >2 mm coarse fraction and the majority of roots were removed before analysis, bulk density was not calculated for these samples. All other methods remained the same.

As mentioned in the site description, the soil pits excavated in the wood lot did not suggest any signs of agricultural disturbance and as such, contained the expected E horizon in place of the Ap horizon. These mineral soil horizons were found to be intermittently layered with several different sub-horizons likely caused by tip-ups from wind thrown trees and other unaccountable disturbances. This inconsistency makes a direct horizon comparison impossible. Total O horizon and 0 - 20 cm and 20 plus cm mineral soil carbon content is the only data used in the 1980 or this study to suggest the soil carbon stability of this type of site.

The original 1980 analysis of the forest floor and fine fraction mineral soils relied on a macro-Kjeldahl procedure (Wilde *et al.* 1972) for nitrogen content and loss-on-ignition (LOI) at 500+/- 20°C to determine percent organic matter. Organic matter is approximately 50% carbon by weight. However, this conversion factor varies by solum horizon and makes a direct conversion and comparison unreliable.

1992 Sample Collection Methodology

The 1992 sample set was collected by S. Hamburg and others. The following methodology is adapted from a review of the original field data collection sheets as well as personal communication with Professor Hamburg.

Two sites were removed from the original chronosequence due to disturbances just prior to and following the 1980 sampling. Site 2 was compromised with the construction of an access road and utility easement. The trees on Site 8 were subjected to girdling for timber stand improvement aimed at increasing sugar maple for use as a sugar bush.

The 1992 soil pit methodology was unchanged from 1980 except for the cross-section of the pit, the calculation of bulk density and the number of sub-samples collected. Pit cross-section was reduced to one-half a meter square from the previous one meter square. Previous intra-pit variability and a desire for labor savings suggested this reduction in frame size. Additionally, Forest floor, Oi and Oe/horizons, were gathered from within the pit frame and after processing, provided a 50-gram sub-sample of each. To provide a cross-reference to the 1980 study, random 16-centimeter square (cm^2) forest floor samples were also collected in 1992. The 1980 studies pit wall cores where found less accurate in the stone and rock filled glacial till soils found at the study sites so bulk density was calculated from the actual soil removed from the pit. Mineral soil sampling similarly produced a single sub-sample of the Ap and B horizons by sub-sampling with a hand trowel from each shovelfuls going into a weighing bucket. This sub-sampling approach produced a 20 - 50 kg sub-sample that was air dried and pushed through a 2 mm sieve to determine bulk density and coarse fraction of the entire horizon contents. Extra material from the 20 - 50 kg sub-sample was archived for backup purposes.

2003 Sample Collection Methodology

Further evolution of the soil pit methodology occurred following the 1992 sampling. Experience in the field suggested the horizon identification could be considered subjective to collector perception and the identification of buried inter-layered horizons was creating inconsistencies in data collection. Subsequent sampling has been processed simply by depth: Oi, Oe/a, O-10cm, 10-20cm, 20-30cm, 30-50cm, 50cm +. Although the 2003 samples were collected by the Hamburg lab in pursuit of a different question that used the depth criteria, they mirrored the methodology used in 1992 and 2005.

2005 Sample Collection Methodology

The 2005 site data was collected by S. Hamburg and others involved with the Hamburg Lab summer program managed by Matt Vadeboncoeur. The following methodology is adapted from personal communications with both individuals and review of field data collection sheets and the results of an analysis of the collected data. The 2005 sampling retained all the aspects of the 1992 and 2003 collection technique but returned to a horizon-based methodology because of relevance to the previous data sets. The additional random cross-reference forest floor blocks were omitted.

All of the samples used in this analysis were furnished to the author in several different states. The following are the procedures used to ensure comparability across sites and collection dates.

1980 Sample Analysis Methodology

The original 1980 samples were archived, though some samples have been lost due to breakage of the glass containers in which they are stored. The samples were air dried in 1980 and should be stable with respect to total C and N. Approximately 10g sub-samples were obtained from each of the forest floor and all four of the original 100g samples by rotating the jar three times to mix the stratified contents and plunging a 15 cm diameter stainless steel scoop to the bottom of the jar and withdrawing two heaping amounts. These 10g sub-samples were oven dried at 80°C for 72 hours, pulverized in a shaker mill, returned to their vials and oven dried at 80°C for an additional 72 hours. Ten to 20 micrograms (μg) of the pulverized sub-sample was placed in 9mm tin boats to be analyzed in the CE Instruments model NC2100 elemental analyzer (CE Instruments, Wigan, UK).

As the 1980-collection methodology notes, each forested site produced 15 Oi and 15 Oe/Oa horizon samples and each of the three soil pits produced four Ap and four B mineral soil samples each. Open field sites generated four 0 - 3 cm Ap samples to substitute for the lack of forest floor. Of the total 30 forest floor or 4 upper Ap and 24 mineral soil samples for each site, all of the available forest floor samples, at least 1 of each soil pits B horizon and at least 2 of the 4 of each soil pits Ap horizon were analyzed. Triple replicates were run on a random selection of 10% of all sub-samples. Because of the variation in loss-on-ignition to C ratios, no direct comparison of the results of the original analysis and the re-analysis were attempted. The C content of all soil samples was 23% to 64% of the organic matter reported in 1980.

1992 Sample Analysis Methodology

Preparation of the 1992 samples, which had not previously been analyzed, was similar to the 1980 samples. Field sample collection produced 1 sub-sample for each horizon of each of the 3 soil pits as well as 15 Oi and 15 Oe/Oa random site cross-reference samples for each site. All 36 forest floor and six mineral soil samples from each site were analyzed. Three replicates were run on 10% of these sub-samples.

2003 Analysis

The 2003 samples of Site 7, the wood lot, were not available for reanalysis. The results of that study were used in this study to support changes to the site.

2005 Sample Analysis Methodology

The 2005 samples were processed and analyzed shortly after collection using the same procedures already outlined. However, the existing 0 - 3 cm of Ap Horizon sub-samples had been processed through a 6mm screen instead of the standard 2mm screen. Re-sub-sampling from the air-dried field sample was used to correct this inconsistency before analysis. The sample collection methodology produced one sub-sample for each horizon of each of the three soil pits, in total, 12 sub-samples for each site. To ensure that there were no analytical differences among the sampling periods, a random selection of all sub-samples and all of the Ap horizon samples were re-analyzed. Results of the reanalysis of the 2005 sub-samples were within 7% of the previous analysis.

Table 2: Difference between 2005 and 2006 analysis of 2005 sample set

Difference %C	Mean	Low	High
Oa	0.39	-4.90	4.64
0-3	2.76	0.80	4.66
Ap	-0.23	-1.91	5.09
B	0.15	-0.12	0.42

To insure consistency within the three sample years, all sub-samples were oven dried at 80°C for 72 hours prior to analysis. Mineral soil samples were not dried at the standard 105°C. To correct for this oversight, a random selection of mineral soil was dried after analysis at the prescribed 105°C to determine moisture mass. The mean loss was 1.8% in the Ap horizon samples and 1.3% in the B horizon samples. This extra mass during analysis overstated the carbon content of the mineral soil samples by 0.001% on average.

In total, each of the three collection years sub-samples were randomly placed in 10 runs of 78 sub-samples and standards run over the course of seven separate days. All runs used four known concentration standards and references to quantify analyzer calibration and drift. Minimum detectable C was 0.02% on a per-mass basis. A reference sample was analyzed with every ten unknowns: forest floor samples utilized Peach Leaves (47.3%C), Acetanilide (71.1%C), Pine needles (50.6%C) and

Cyclohexane (51.79%C). The maximum deviation from known C concentration, in the range of the forest floor samples was 3%. Mineral soil samples used Mag1 marine sediment (2.3%C), Acetanilide, Montana Soil SRM2711 (1.7%C) and Cyclohexane. The maximum deviation from known C concentration, in the range of the mineral soil samples was 9%.

Table 3: Reference and Standard Statistics for this study's carbon analysis

Std or Ref	Knwn Conc %	Mean %	Low %	High %	Std Dev
Pch	47.30	46.43	45.79	47.42	0.49
Acet	71.09	69.83	55.31	74.58	4.28
Pin	50.60	51.43	50.90	51.94	0.30
Cycl	51.79	50.03	44.16	53.37	2.67
Mag	2.30	2.35	2.25	2.62	0.09
Mt	1.70	1.83	1.71	1.92	0.07

Results

Open-field Site Data

The open-field sites were key to the establishment of the original 1980 chronosequence and were assumed to have a steady pool of carbon since cessation of planting in row crops. The analysis of these open-field sites, which have been mowed for most of the past 50 years, (Sites 4 and 9) provide insight into the validity of the assumption of a stable C pool since abandonment.

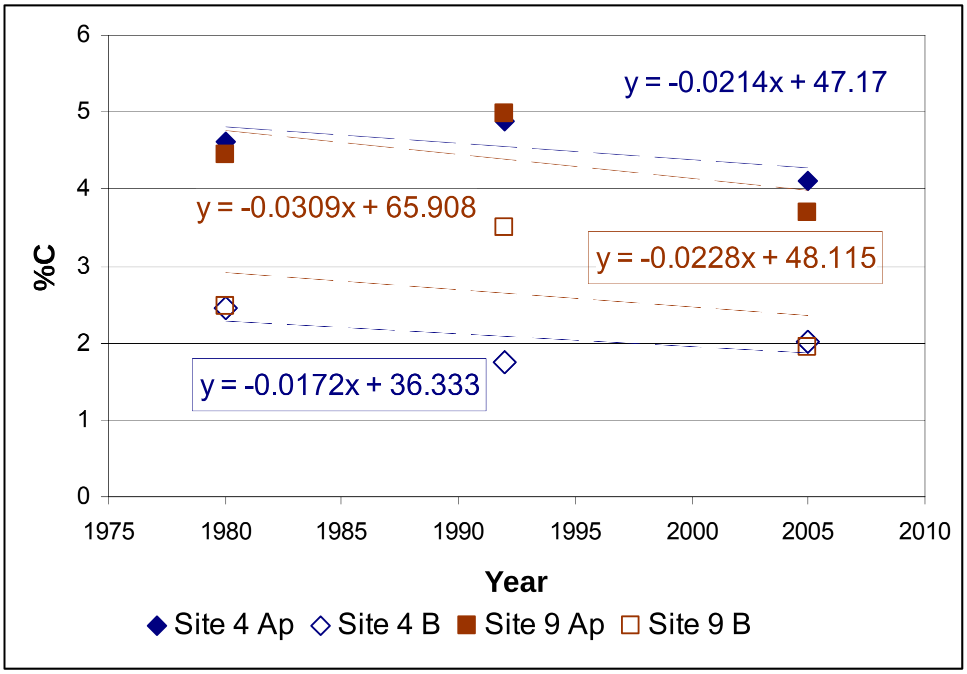

Figure 2: Percent C of the open-field sites 4 and 9 Ap and B horizons.

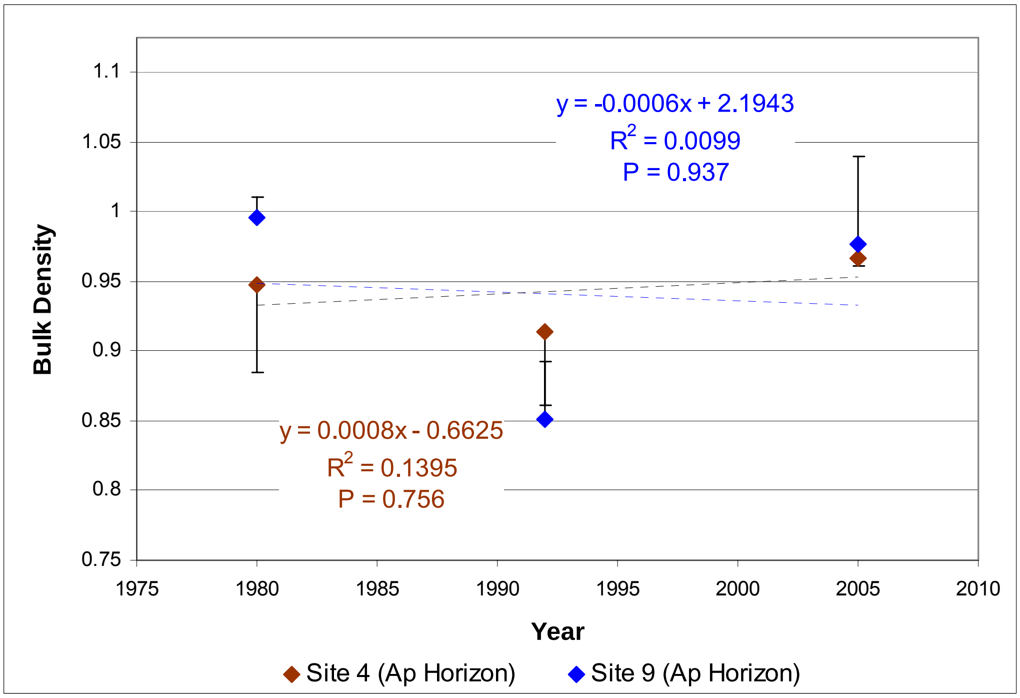

Figure 3: Bulk densities of open-field sites 4 and 9 Ap horizon. Error bars are the standard deviation from the mean, only plus or minus are used for clarity.

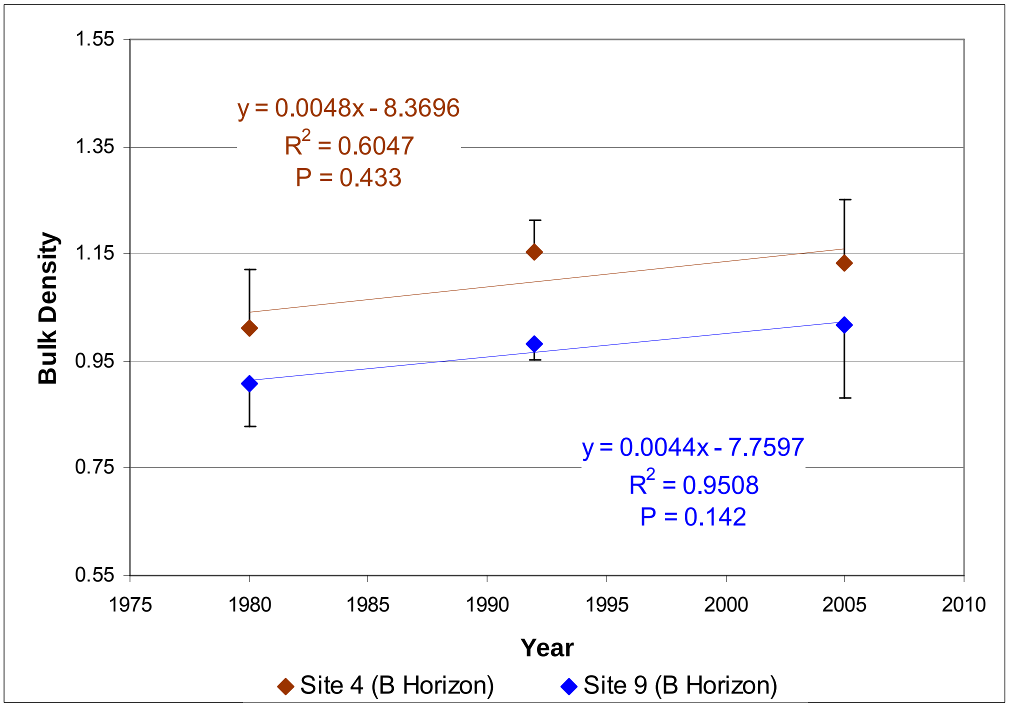

Figure 4: Bulk densities of open-field sites 4 and 9 B horizon. Error bars are the standard deviation from the mean. Only plus or minus are used for graph clarity.

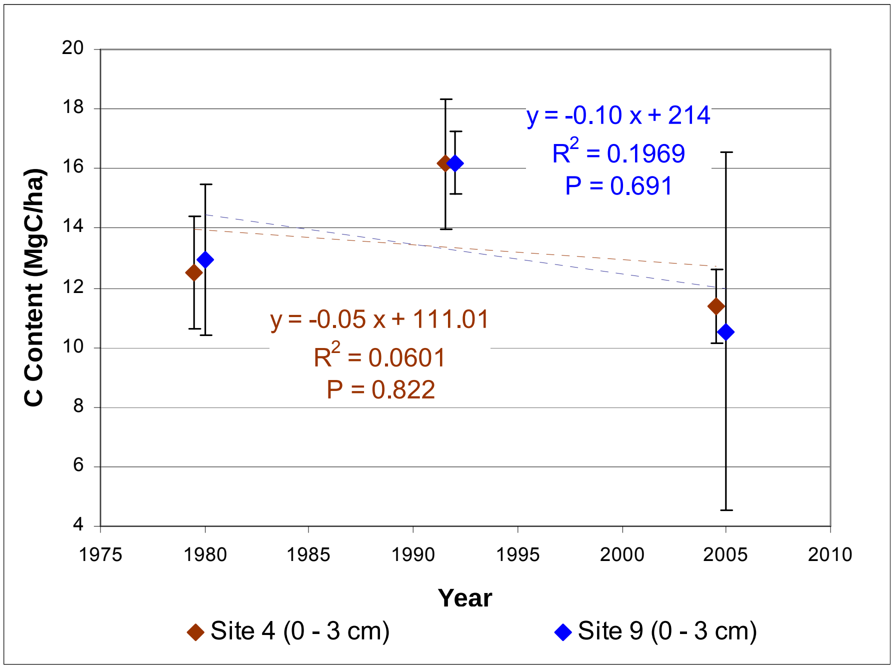

Figure 5: Carbon content of the upper 3 cm of Ap horizon of the open-field sites 4 & 9 in the bald mountain community. Error bars are the standard deviation from the mean.

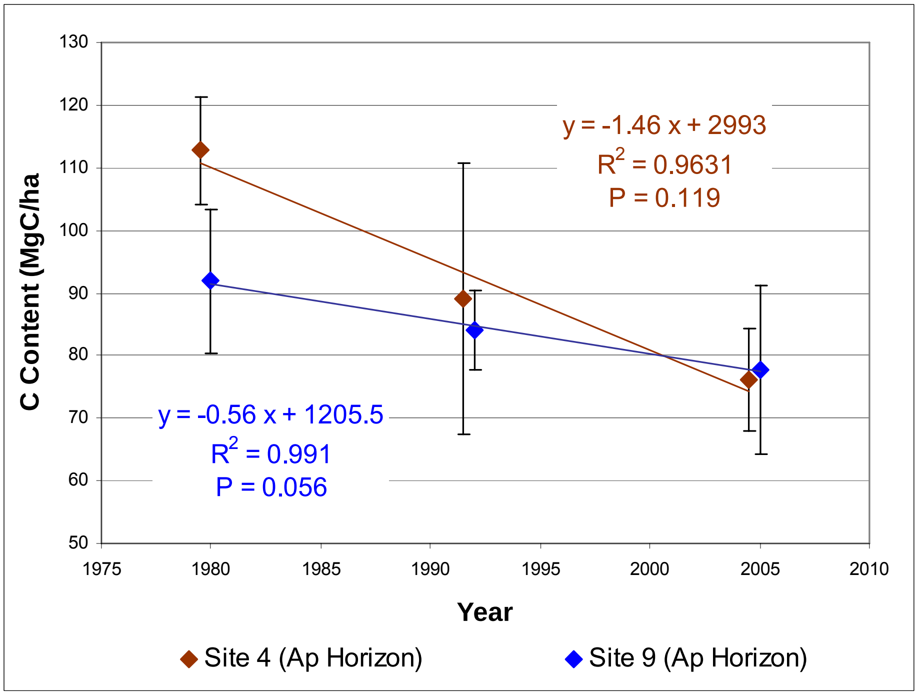

Figure 6: Carbon content of the entire Ap horizon of the open field sites 4 & 9. Error bars are the standard deviation from the mean.

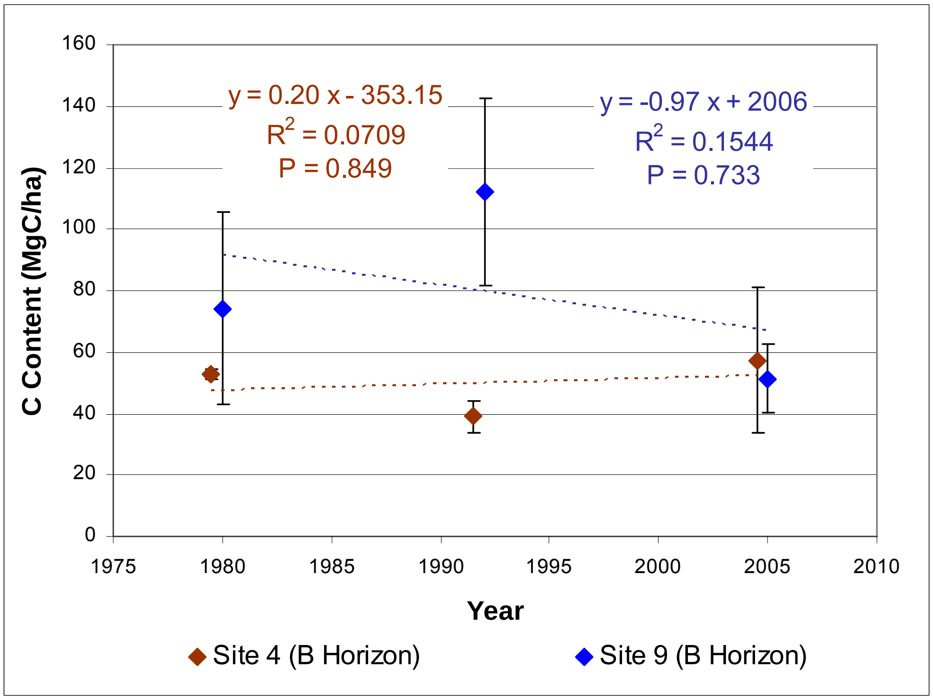

Figure 7: Carbon content of the B horizon of the open-field sites 4 & 9. Error bars are the standard deviation from the mean.

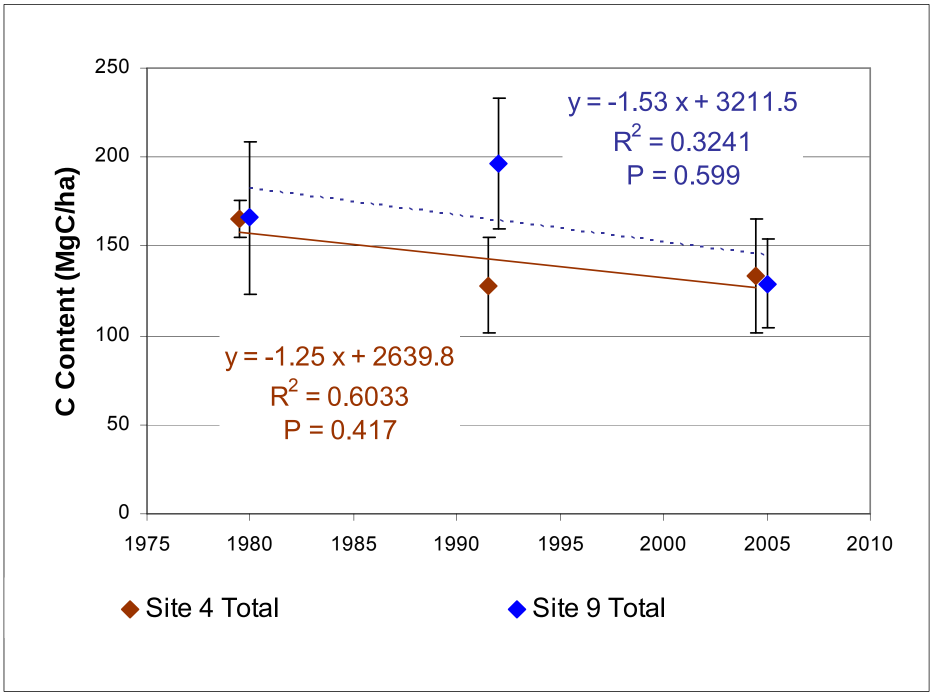

Figure 8: Carbon content of the total mineral soil of the open field sites 4 & 9 Error bars are the standard deviation from the mean.

The percentage C of the open-field sites Ap and B horizons (Figure 2) all show slight declining trends, average 0.0231%/yr, while bulk density results (Figures 3 & 4) are relatively flat and non-significant in the Ap horizon (site 4, 0.0008 g/cm^3/yr and site 9, 0.0006 g/cm^3/yr) and significantly increasing in the B horizon (0.0048 g/cm^3/yr and 0.0044 g/cm^3/yr, respectively). The weakly significant results of the uppermost 3 cm of the Ap horizon from both open field sites are presented in Figure 5 above. Site 4 is in red and site 9 is in blue. Site 4 indicates a decrease of 0.06 MgC/ha/yr ($p = 0.822$; $r^2 = 0.06$), site 9 a decrease of 0.1MgC/ha/yr ($p = 0.691$; $r^2 = 0.20$). For the entire Ap horizon (Figure 6), open-field site 4, shows a significant decrease in soil carbon of 1.46 MgC/ha/yr ($p = 0.119$; $r^2 = 0.96$). While open-field site 9 had a significant decrease of 0.56 MgC/ha/yr ($p = 0.056$; $r^2 = 0.99$). Results for the carbon content of the B horizon are less clear (Figure 7) with a non-significant increase of 0.20 MgC/ha/yr ($p = 0.849$; $r^2 = 0.07$) and non-significant decrease of 0.97 MgC/ha/yr ($p = 0.733$; $r^2 = 0.15$) at site 9.Total mineral soil carbon (Figure 8) at both of the open-field sites has decreased. At site 4, significantly by 1.25 MgC/ha/yr ($p = 0.417$; $r^2 = 0.60$) and site 9 insignificantly by 1.53 MgC/ha/yr ($p = 0.599$; $r^2 = 0.32$).

Re-forested Site Data

The next series of figures show the results of the reforested sites of the 1980 chronosequence.

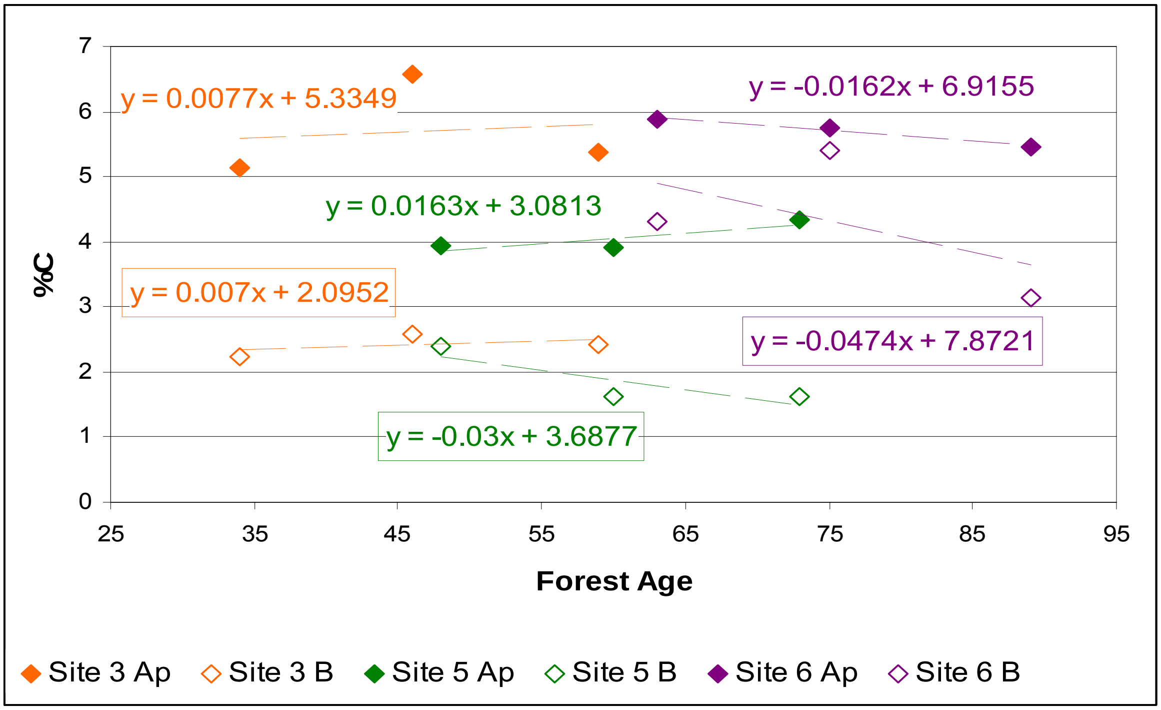

Figure 9: Percent C of the re-forested sites 3, 5 and 6 Ap and B horizons.

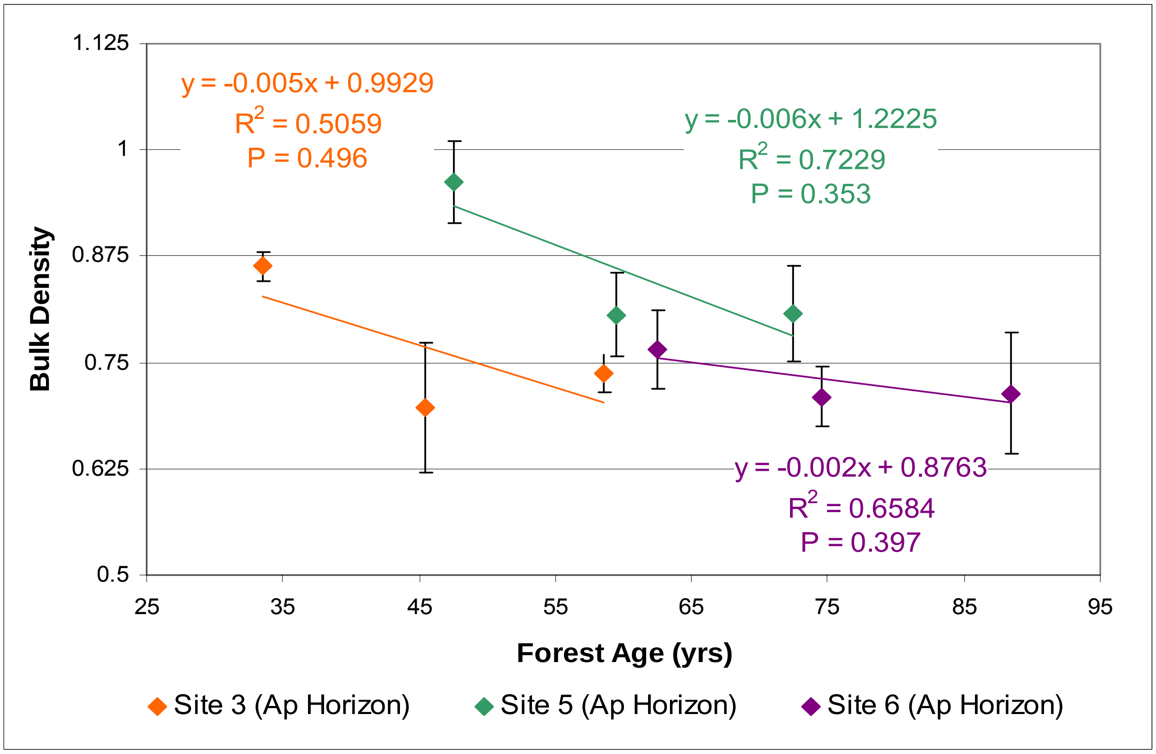

Figure 10: Bulk densities of reforested sites 3, 5 and 6 Ap horizon. Error bars are the standard deviation from the mean.

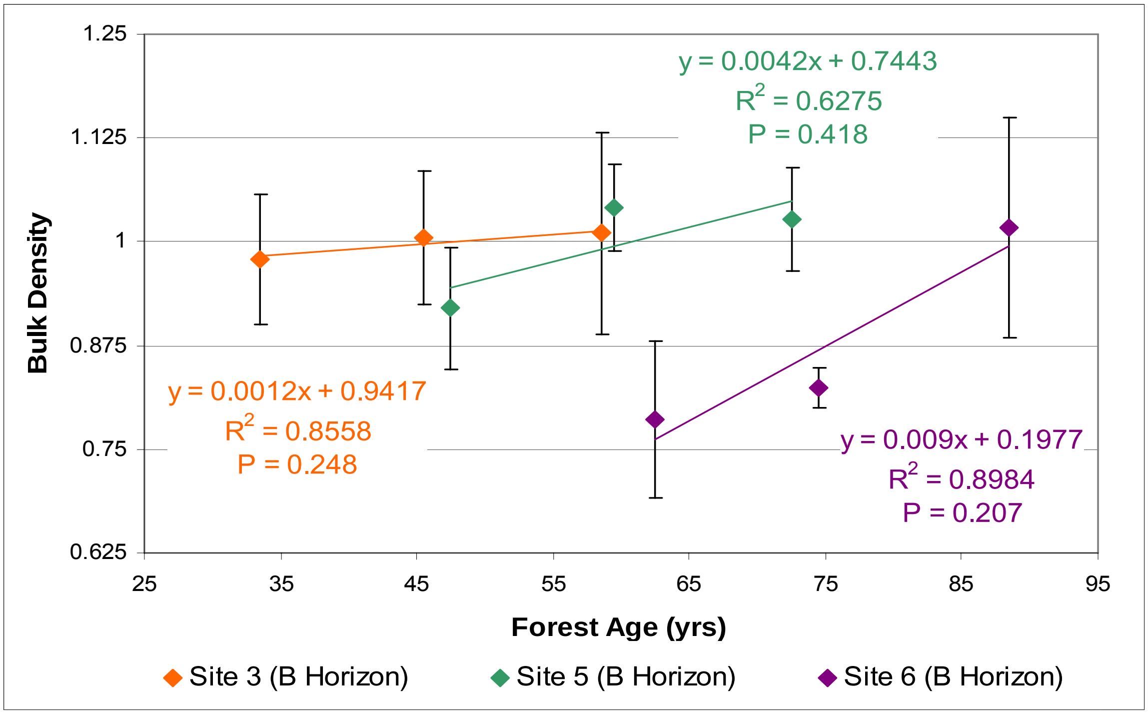

Figure 11: Bulk densities of reforested sites 3, 5 and 6 B horizons. Error bars are the standard deviation from the mean.

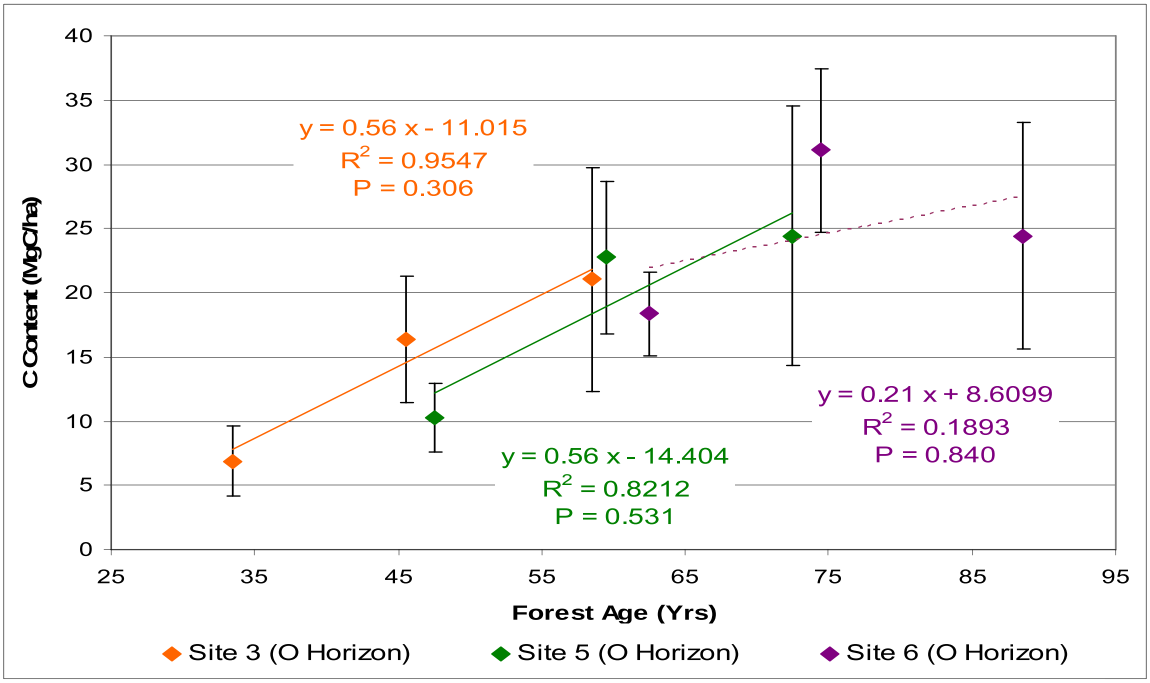

Figure 12: Carbon content of the O horizon of the re-forested sites 3, 5 & 6. Error bars are the standard deviation from the mean.

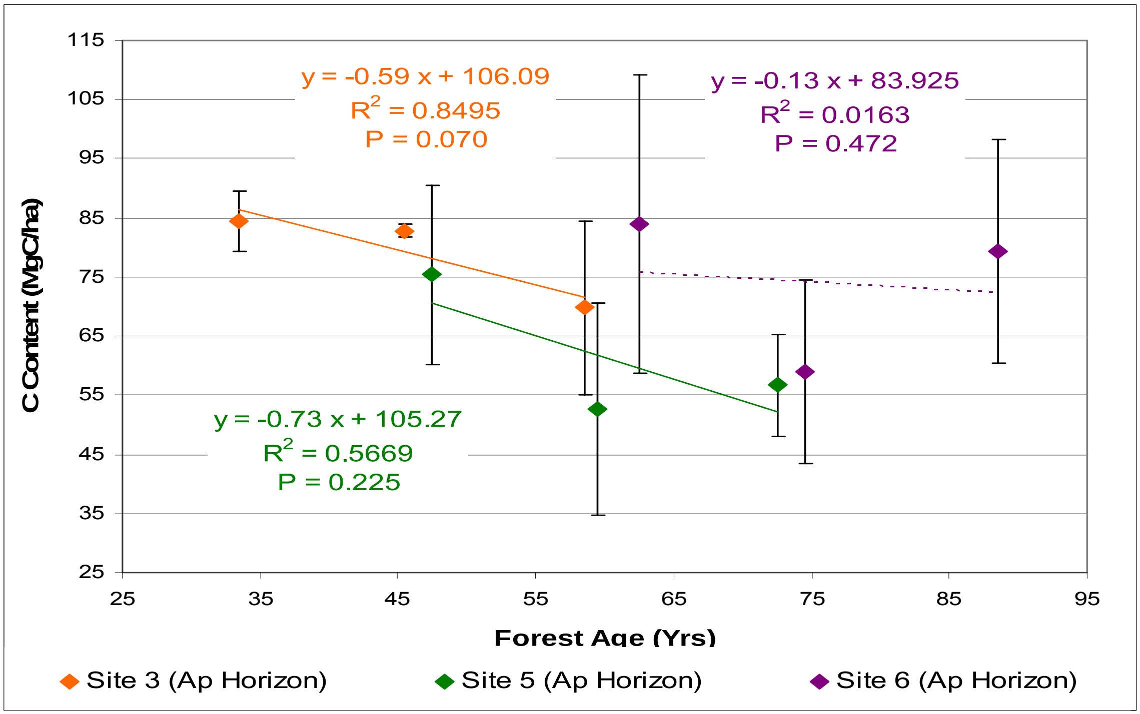

Figure 13: Carbon content of the Ap horizon of the forested sites 3, 5 & 6. Error bars are the standard deviation from the mean.

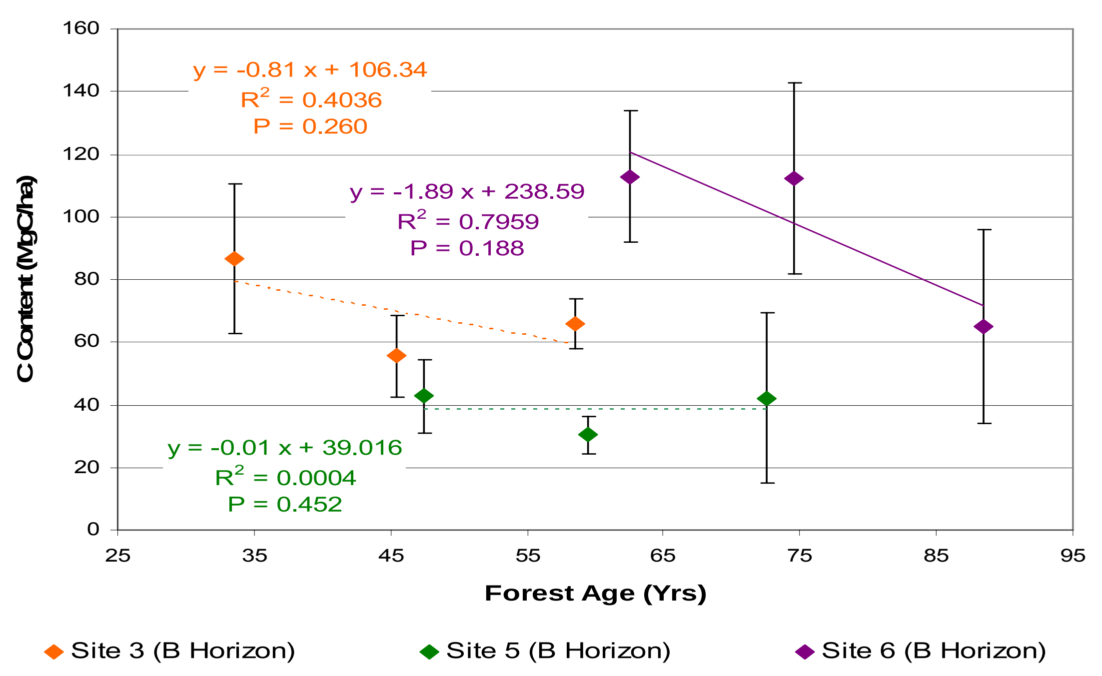

Figure 14: Carbon content of the B horizon of the forested sites 3, 5 & 6. Error bars are the standard deviation from the mean.

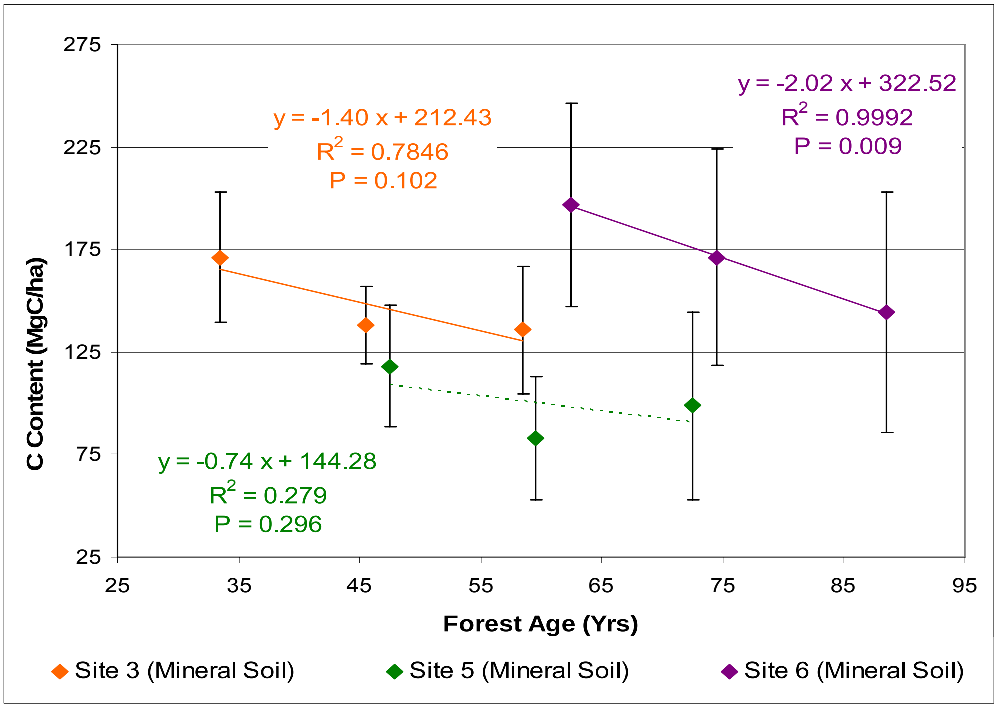

Figure 15: Carbon content of the Mineral Soil of the forested sites 3, 5 & 6. Error bars are the standard deviation from the mean.

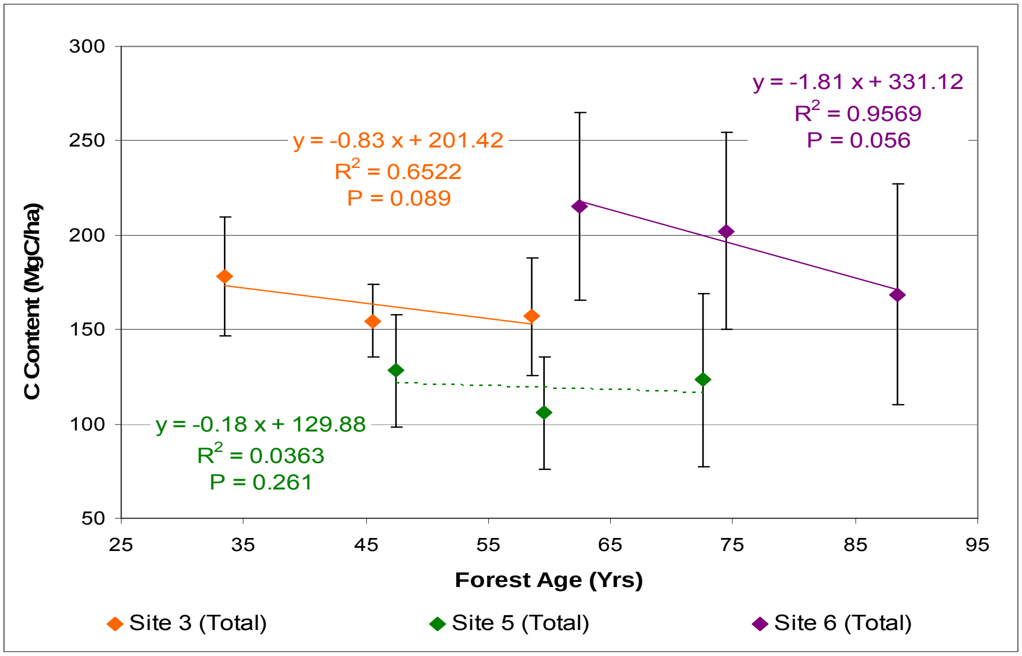

Figure 16: Total solum column carbon content of the forested sites 3, 5 & 6. Error bars are the standard deviation from the mean.

The percentage C of the re-forested sites Ap and B horizons are variable, with a maximum increase of 0.016 %/yr for the Ap horizon of Site 5, and the largest decrease of 0.047 %/yr of the B horizon of Site 6 (Figure 9). Bulk density changes (Figures 10 & 11) show a significant ($p < 0.496$; $r^2 > 0.51$) decrease in the Ap horizon averaging 0.004 g/cm^3/yr and significant ($p < 0.418$; $r^2 > 0.63$) increases in the B horizon averaging 0.005 g/cm^3/yr. The three re-forested sites produced the expected increase in carbon in the organic horizon (Figure 12) with site 3, the youngest site showing a significant increase of 0.56 MgC/ha/yr ($p = 0.306$; $r^2 = 0.95$) and site 5, showing a similar increase ($p = 0.531$; $r^2 = 0.82$). Site 6, the oldest site showed a non-significant increase of 0.21 MgC/ha/yr ($p = 0.840$; $r^2 = 0.18$). The Ap horizon of the forested sites show a decline in C with increasing forest age consistent with the pattern predicted in 1984 using the 1980 data. (Figure 13) Site 3 and 5 show a significant decrease of 0.59 MgC/ha/yr ($p = 0.070$; $r^2 = 0.85$) and 0.73 MgC/ha/yr ($p = 0.225$; $r^2 = 0.57$) respectively. Site 6 shows a non-significant decrease of 0.13 MgC/ha/yr ($p = 0.472$; $r^2 = 0.02$). B horizon results are contrary (Figure 14) to the original 1980 studies results of a slight increase. Site 3 and 5 show a non-significant decrease of 0.81 MgC/ha/yr ($p = 0.260$; $r^2 = 0.40$) and 0.01 MgC/ha/yr ($p = 0.452$; $r^2 < 0.01$) although site 6, shows a significant decrease of 1.89 MgC/ha/yr ($p = 0.188$; $r^2 = 0.80$). Total mineral soil trends (Figure 15) all suggest declines in carbon content. Site 3 shows a significant 0.74 MgC/ha/yr ($p = 0.296$; $r^2 = 0.28$) decline, Site 5, a non-significant 1.40 MgC/ha/yr ($p = 0.102$; $r^2 = 0.80$) decline, and site 6, a significant 2.02 MgC/ha/yr ($p = 0.009$; $r^2 = 0.99$) decline. Total solum trends in soil C of the forested sites (Figure 16) all suggest declines in carbon content over the 25-year study period. Site 3, a significant .83 MgC/ha/yr ($p = 0.261$; $r^2 = 0.65$) decline, Site 5, a non-significant 0.18 MgC/ha/yr ($p = 0.089$; $r^2 = 0.65$) decline, and site 6, a significant 1.81 MgC/ha/yr ($p = 0.056$; $r^2 = 0.95$) decline.

Wood Lot Data

The wood lot, Site 7, was a key reference site for the original 1980 chronosequence and was assumed to have a steady pool of carbon since forest changes were minimal. The analysis of the wood lot data, although not statistically significant (2 sample sets vs. 3), provides insight into the validity of the assumption of a stable C pool in undisturbed forest stands.

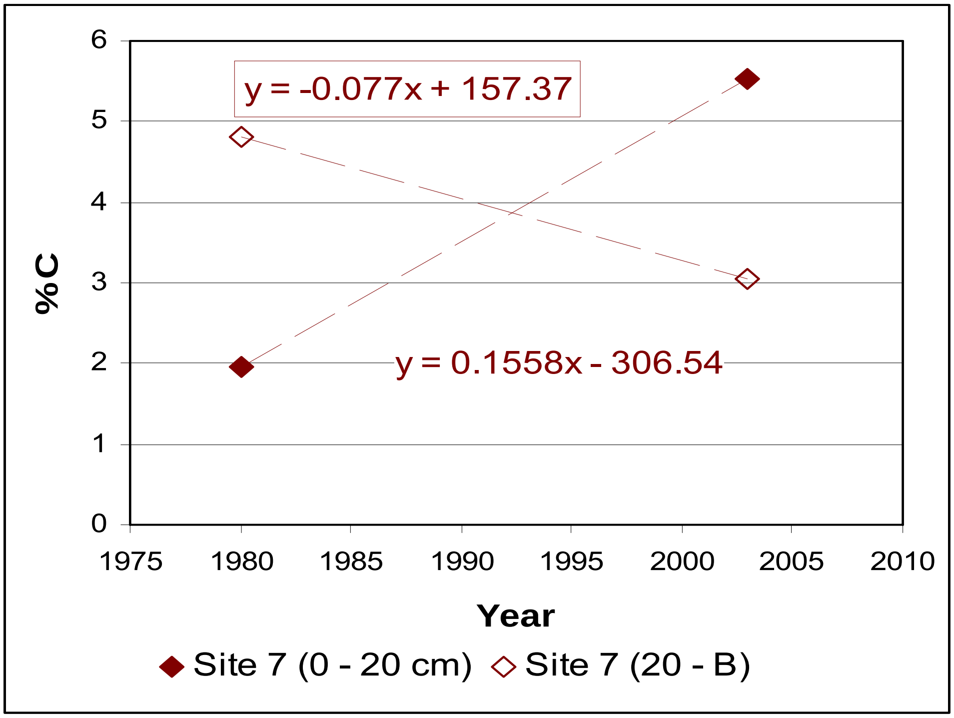

Figure 17: Percent C of the Wood Lot, site 7, upper (0 - 20 cm) and lower (20 cm - B) mineral soil.

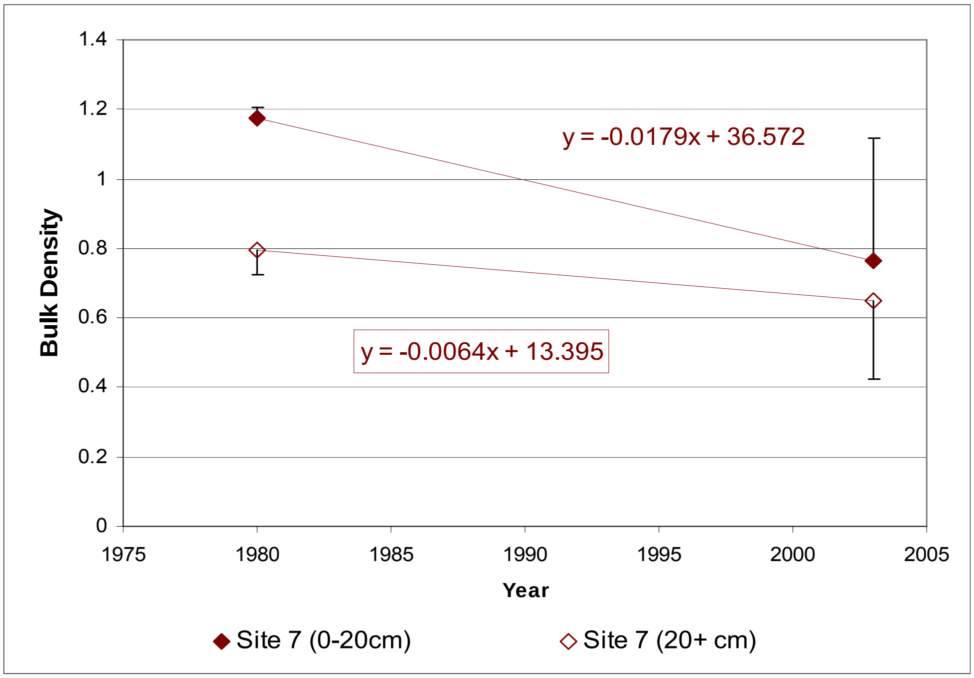

Figure 18: Bulk densities of the wood lot, site 7, upper (0 - 20 cm) and lower (20 cm - B) mineral soil. Error bars are the standard deviation from the mean, only plus or minus are used for graph clarity.

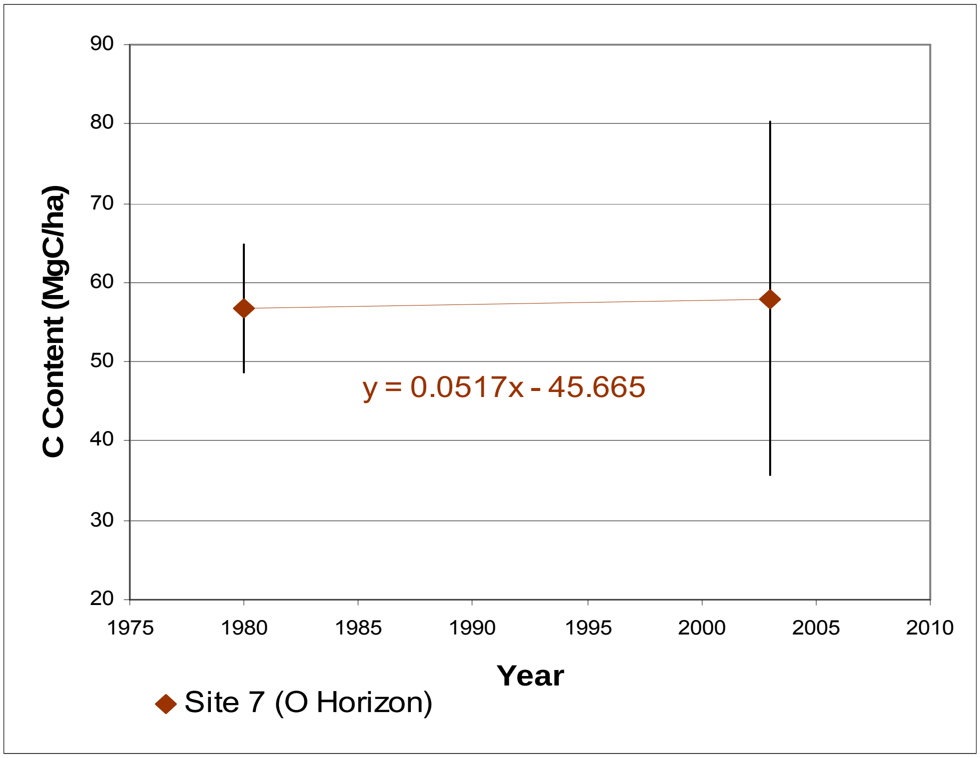

Figure 19: Carbon content of the O horizon of the wood lot, site 7. Error bars are the standard deviation from the mean.

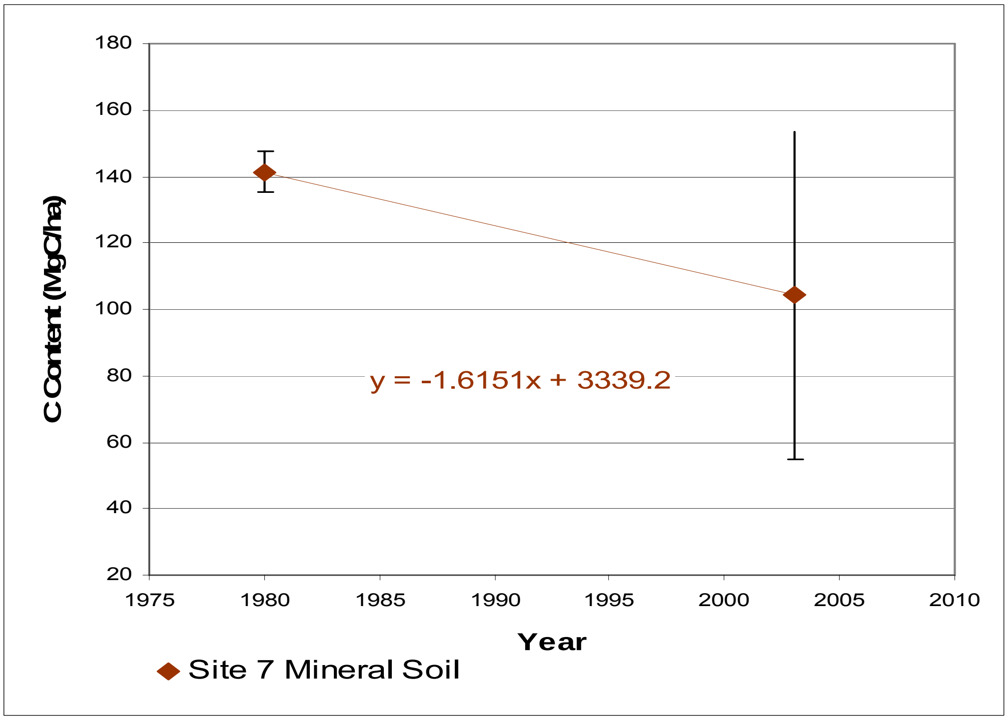

Figure 20: Carbon content of the total mineral soil of the wood lot, site 7. Error bars are the standard deviation from the mean.

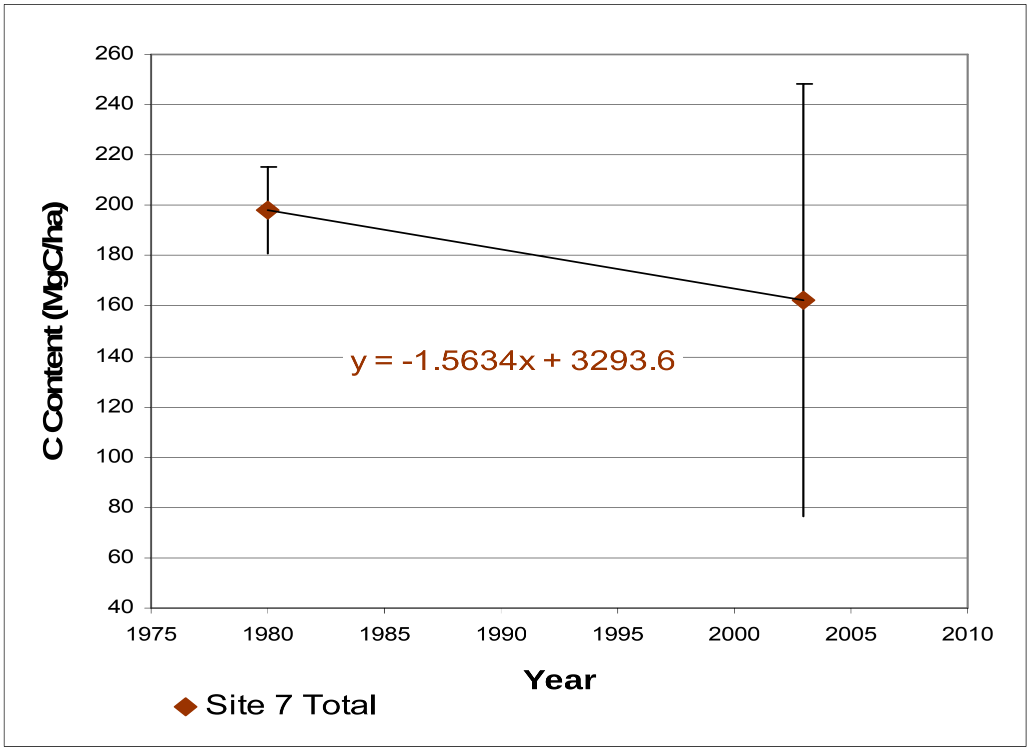

Figure 21: Carbon content of the total soil column of the wood lot, site 7. Error bars are the standard deviation from the mean.

The C percentage of the wood lot upper and lower mineral soil (Figure 17) are changing in opposite directions. The upper 20 cm is increasing at 0.156 %/yr while the lower mineral soil is decreasing by 0.077 %/yr. The bulk density results for upper and lower mineral soil (Figure 18) are decreasing at 0.018 $g/cm^3/yr$ and 0.0064 $g/cm^3/yr$ respectively. Although the forest floor of site 7 increased in C content slightly at 0.0517MgC/ha/yr the total mineral soil lost C at 1.62 MgC/ha/yr. The increasing C of the O horizon offset the decreasing mineral soil and produced a total decrease for the soil column of 1.56 MgC/ha/yr.

Discussion

Data Summary

The most obvious departure from the 1980 chronosequence predictions of a "steady state" are the declines in C content of the mineral soil suggested by the data of the open field sites. Site 4 data suggest a 1.3 MgC/ha/yr decrease in carbon content within the mineral soil while site 9 indicated a slightly larger decrease of 1.5 MgC/ha/yr over the last 25 years. While the total loses were very similar it occurred at different depths, Site 4 in the Ap, and Site 9 in the B horizon. In 1980, both sites had approximately 166 MgC/ha in the soil and by 2005 had <134 MgC/ha, a >5% decrease.

Momentarily ignoring the well documented increases in C associated with the forest floor found in this and other studies, the three reforested sites, 3, 5, and 6, decreased an average of 1.4 MgC/ha/yr in the mineral soil. 1980 mineral soil C content ranged from the oldest reforested site 6, with 197 MgC/ha to the middle aged reforested site 5, at 118 MgC/ha. This mix in chronologic sequence may suggest a longer agricultural use and further reduction in soil C of Site 5. The 2005 data suggests that these reforested sites declined in mineral soil carbon content to between 144 and 72 MgC/ha respectively.

Conversely, carbon content of the forest floor from the three reforested sites is increasing on average, by almost 0.5 MgC/ha/yr. In theory, C accumulation should be roughly linear with forest age but the data represented in Figure 12 does suggest that Site 5 is almost 10 years behind Site 3 in forest floor C accumulation. Site 6 data suggests that it also lags behind Site 3 by 10 years but its trend exceeds the average C accumulation rate in the first 12 years and then abruptly declines to almost half those gains during the following 12 years.

The data obtained in 1980 and then again in 2003 from the wood lot, Site 7, suggests a forest floor that has remained quite stable in carbon content at 57MgC/ha while the mineral soil has decreased from 141MgC/ha to 104MgC/ha over a 23 year span; 1.6 MgC/ha/yr

Five observations of the entire C content data set trends include:

- The soil carbon in the open field Sites 4 and 9 are not at "steady state"
- Site 5 mineral soil carbon content is consistently lower than either open-field site throughout the 25-year period.
- The three reforested sites do not show a C content consistent with forest age; the youngest does not have the lowest amount of carbon.
- The soil C of reforested Site 6 and to a lesser extent Site 3 exceeded that of the wood lot, in both mineral soil and total solum C.
- The rate of mineral soil carbon decrease is proportional to the 1980 carbon pool.

Site	1980 C (MgC/ha)	Decline (MgC/ha/yr)
4	159	1.25
9	161	1.53
3	171	1.40
5	119	0.74
6	195	2.02
7	141	1.62

- The soil carbon in the wood lot, Site 7, is not at "steady state".

The total solum carbon of all of the sites is declining in mineral soil C and thus will not recover to the levels measured in the wood lot in 1980. The data suggests that soil at all of the sites has been a net emitter of CO_2 to the atmosphere. The mineral soil at the open field sites and the re-forested sites averaged a decline or off-gassing of 1.4 MgC/ha/yr or roughly the equivalent of the carbon gains seen in the above-ground biomass of re-growing southern New England forests between 10 and 90 years old (1.53 MgC/ha/yr) (Hooker & Compton 2003) . This soil carbon loss is partially offset by an increase in the forest floor carbon content of 0.5 MgC/ha/yr.

Chronosequence viability

(Trettin *et al.* 1999) challenges the use of "undisturbed" control or reference sites in short-term studies. His further contention is these inadequate temporal scales have provided the bulk of information about the structure and function of forested ecosystems. In the closest to this studies temporal span, his study suggests that over 21 years, soil C pools to a depth of 60 cm were either stable or declining in an undisturbed upland hardwood stand located in Oak Ridge, Tennessee. Additional support for steady state site dynamics include several long-term studies reviewed by (Johnson 1991) that suggest that soil change can occur on the scale of decades or seasons under certain conditions.

Proprietor's records, census data and interviews all indicate that each site, excluding the wood-lot, employed long crop rotations of five to seven years in hay, preceded by one or two years in cereal crops with some spending one year in potatoes (Hamburg 1982b). In thinking about ecosystem recovery following agricultural abandonment, including the above ground biomass, it is reasonable to establish a chronosequence of forested sites with a starting point represented by non-forested sites and a less disturbed mature forested site as a representative end-point. However, when studying soils, the assumptions are less robust. Although each of the sites has spent some time in hay, at the time of the original study the only definitive condition that can be used to calculate change over time, is that the open field sites have been non-forested for 160 to 200 years and the wood lot has always been forested.

Unquantifiable details of the land-use histories of the 1980 chronosequence include type of crops grown, individual farming practices, pasturing, and most importantly the time each site had been in use prior to abandonment, the point of re-accumulation of forest biomass. Regular plowing promotes C decomposition, effectively lowering the soils equilibrium level at the start of succession. Crop residue, mowed organic matter, and root mass, all add C inputs. Although these land-use subtleties were addressed as unquantifiable in the 1980 study, they are discernable in this direct measurement. Neither, the open field and wood lot sites assumed steady C pool, nor the forested sites C pool dependence on forest age, are supported by the results of this study. Each of the sites appears independent in C content and flux and when assembled into a chronosequence can provide spurious patterns of change with respect to soil C. Neither the open field sites nor the wood lot can be used as the starting or ending points for the reforested sites, as all of the sites are still changing in their carbon profiles.

Bulk Density

Although this study questions the validity of the 1980 chronosequence, the quantitative methodology of sample collection used in the original study makes it viable to use the data in prospective studies. Patterned after (Lyford 1964), the quantitative soil pits reduce intra-site soil C concentration variability between the three pits in the highly variable glacial-till soils of New England and increases the accuracy with which one can estimate carbon content of soils with low carbon percentages (typically in the range of .1 - 8 % by mass) found in mineral soils. Without the bulk density data presented earlier in this paper as part of the total calculation, the changes in concentration data suggest little change or even gains over time. When considered on a mass basis using paired bulk density samples the story changes radically (Figures 2, 9 & 16). Because push-soil-core methodologies dominate the literature, there is little information available to compare the observed trends in bulk density, and none with this studies temporal span (Davidson & Ackerman 1993). Although (Hooker & Compton 2003) found a significant decrease (0.7 to 0.4 Mg/m^3) in the bulk density of the Ap horizon (0 to 20 cm) of their 110 year, quantitative soil pit chronosequence in Situate, RI, they fail to suggest a cause. There is a suggestion that an increase in soil frost brought about by a decrease in snow cover could be effecting mineral soil bulk density (Groffman *et al.* 2006).

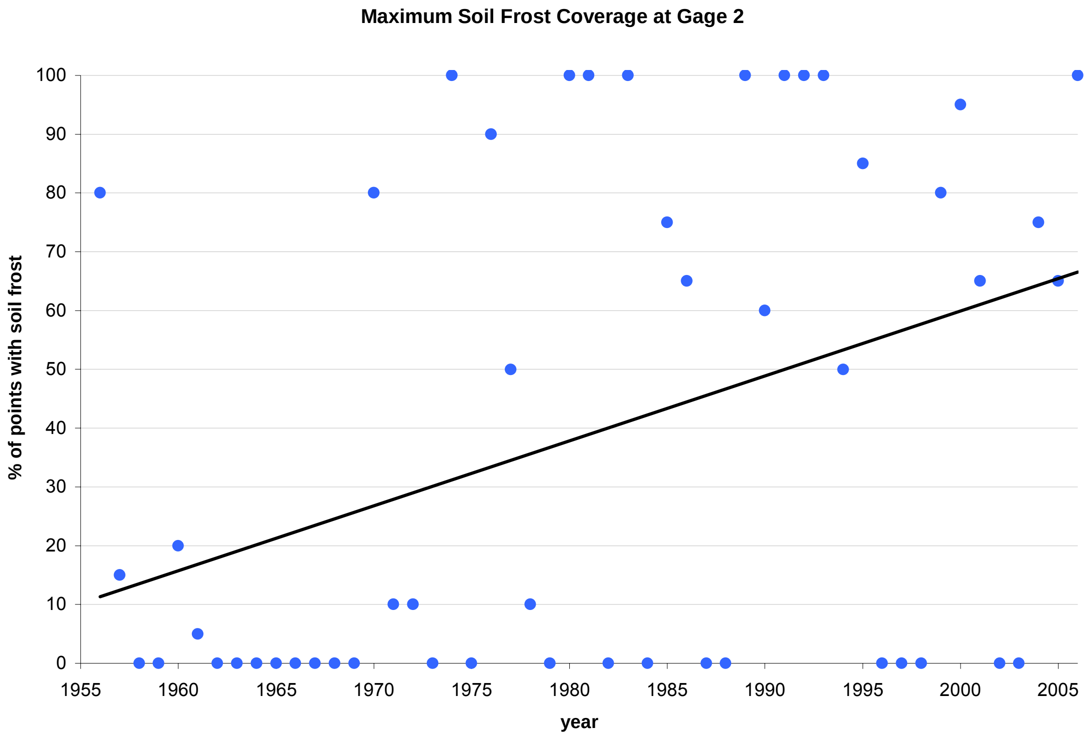

Figure 22: Graph of the incidents of ground frost at Gage 2, HBEF. Graph reproduced from (Groffman *et al.* 2006)

This author reasons, that the increased C levels present in the forest floor of this studies re-forested sites, and the plow introduced C of all of the sites (wood lot excluded), there could be increased moisture retention, (D.Yanni *et al.* 2003) which in turn would increase frost expansion. The solar exposure of the open field sites may mitigate this effect (D.Yanni *et al.* 2003). A reduction in bulk density may also be explained by an increase in root mass (physical displacement) as the forests mature as well as an increase in earth- worm populations (introduction of bore-holes). Earthworm presence has been recorded throughout the sites sampling history, but only quantified in the 2005 data. This change in bulk density, not quantitatively assessed in the soil science literature, may suggest a reason that this study's reported declines are so surprising. Bulk density is not accurately assessed with push-core sampling methodologies currently used in the majority of studies because they are based on coring to a specified depth as opposed to a horizon interface. A frost heaved soil profile is deeper and a specified core depth will yield more of the higher carbon surface soil. Regardless of the mechanism, this aerated soil may also increase heterotrophic respiration rates.

Soil Respiration

The literature provides little consensus on the causes for increased soil respiration. (Johnson 1995), as there is a general trend of increasing litter-fall, increased decomposition rates, decreasing forest floor and decreasing soil organic matter with increases in mean annual temperature. These general trends, excluding litter-fall (not quantified in this study), are reflected in the results from this study.

A 5-year eddy-covariance study (Goulden *et al.* 1996) at Harvard Forest, MA with hourly observations of the entire forest ecosystem, attributed small enhancements to respiration to unusually warm soil temperatures, deep snow acting as insulation and high winds, while declines in respiration were attributed to drought conditions. Although this site has elevated soil C levels when compared to the Bald Mountain community, they are thought to be attributable to twice the animal densities and extensive pasturing (Compton & Boone 2000; Goulden *et al.* 1996) that did not occur in Campton, NH. Although comparatively short-term, this information is inclusive of the entire system, takes place on agriculturally disturbed soils, not reliant on soil sampling methodologies and without the bias of reference sites. It should provide objective clues to possible causation of the declines in soil C trends found in this study. These reported controls of soil respiration were largely attributable to inter-annual variability of the local climate.

A summary of HBEF data for the 25-year span of this study suggests that precipitation has remained highly variable, but stable. Mean annual temperature however, is increasing at a rate of approximately 0.16° C per decade (Vadeboncoeur *et al.* 2006). A graph of the increases of four weather stations is represented in Figure 11. Gage 1 is closest in elevation to the Bald Mountain community.

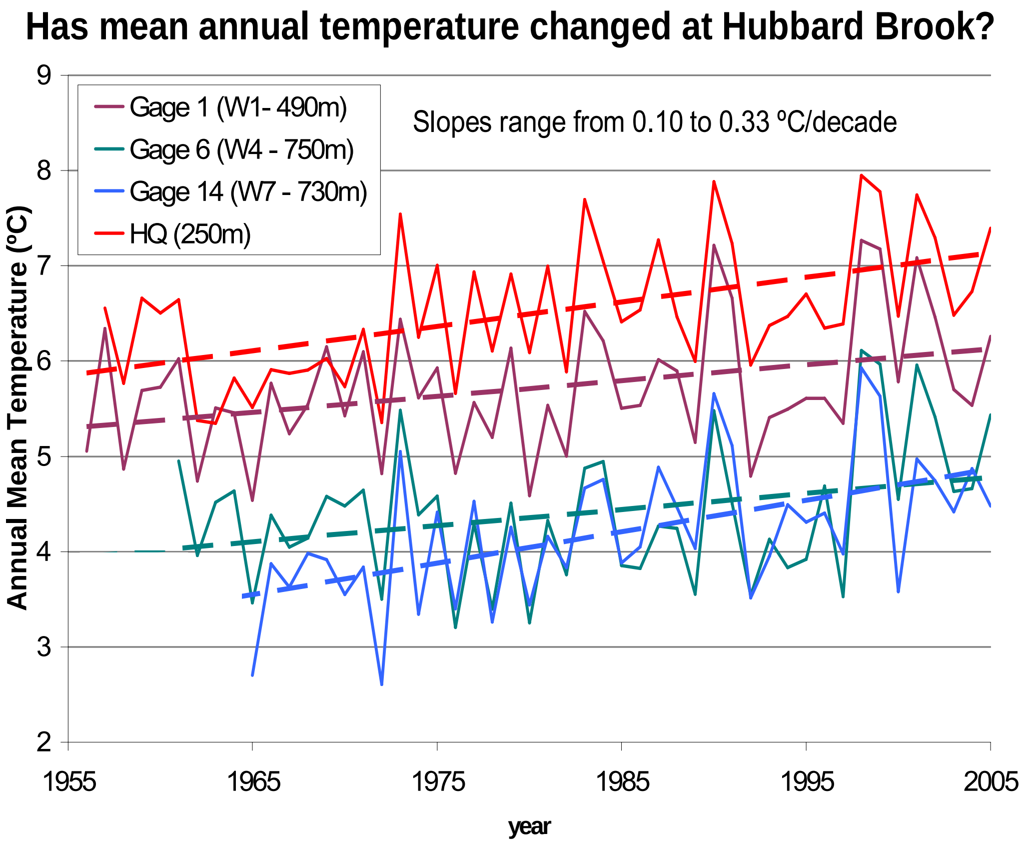

Figure 233: Mean Annual temperature increases of four HBEF data collection sites. Compilation of HBEF temperature data from Gage 1, 6, 14 and Head Quarters. Gage 1 elevation is comparable to the Bald Mountain hill community.

Conclusion

Is a 25-year direct measurement study, a significant indicator of successional forest soil trends? Compared to the centuries long cycle of the above ground biomass; soil cycles can function on decadal or seasonal basis (Johnson 1995). This study's 25-year span can be regarded as long enough to present meaningful trends and may support the idea of a dynamic soil ecosystem. At a minimum, the temporal span of this study questions the notion of using reference sites to represent steady state conditions and the predisposition of a mechanically disturbed soil condition to trend to a more stable state.

There is irony in my suggestion that the possible causes of the declines in mineral soil C reported in this study, may well be linked to climate change; the underlying motivation for this study. The suggested causes presented here are simple mechanical systems. If in fact, as suggested in the more recent literature, C is just one of many biogeochemical dynamics, the research of this found soil C decline is just beginning. (Shaver *et al.* 1992) argues that C cycling can be thought of an entirely dependent on Nitrogen and Phosphorus cycling rather than the reverse. The many classifications or fractions of carbon; light, heavy, fast, medium, slow, dissolved, all interact with each other and surrounding pools of nutrients to create the dynamic soil matrix that is studied. These dynamics are beyond the scope of this paper, but the results from this study may have bearing.

What this study's results highlight however is how dynamic and sensitive all of these components are to each other and to their environment. The reasons for using chronosequences are obvious, but it is unlikely that such an approach, with all of its assumptions and unquantifiable details can illuminate soil trends. Additionally, it may be presumptuous to assume that there exists a site in "steady state' or that the complete destruction of a forest system is easily recoverable. This study shows that the key to better understanding does not lie in the easily researched offices of record holders but in the waiting, tedium and real work of immersion in the medium we are trying to understand. Go dig a soil pit.

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