The Effects of Whole Tree Harvest On Soil Carbon and Nitrogen after 15 years

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This thesis was completed as a part of a larger research project at HBEF in collaboration with Steven Hamburg, Chris Johnson, and Tom Huntington.

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ABSTRACT

This study examines the effects of whole tree harvesting on soil carbon and nitrogen 15 years following harvest. Two specific questions were addressed: what is the duration and extent of C and N loss following harvest; how do C and N cycles in the forest floor and mineral soil behave after disturbance? Hubbard Brook Experimental Forest Watershed 5 (HBEF W5) was whole tree harvested (WTH) in 1983-84 and a quantitative pit approach was used to collect data in 1983 (pre-harvest), 1986, 1991 and 1998. The forest floor mass in 1998 was 97 Mg ha^{-1}, total C was 31 Mg ha^{-1} and total N was 1.5 Mg ha^{-1}. The mineral soil mass in 1998 was 3100 Mg ha^{-1}, total C was 110 Mg ha^{-1} and total N was 5.1 Mg ha^{-1}. The data suggests that after 15 years C and N pools of the forest floor and mineral soil are comparable to pre-harvest levels. However the effects on the individual organic horizons and mineral depth strata vary, with a significant decrease between 1983 and 1998 in the C pool for the combined Oi + Oe horizon and strong decreasing trends for the C and N pools of the 20+ depth strata and for Oie mass. The effects of harvest after fifteen years also differ by elevation group with the highest and lowest elevations losing nutrients, and the mid elevations retaining nutrients.

INTRODUCTION

The effects of forest management practices on soil fertility have been a focus of study since the 1950's when several early studies found that forest floor depth declined for a decade or more after clearcutting (Sartz and Huttinger 1950, Trimble and Lull 1956 as cited by Covington 1981). Since that time there have been innumerable investigations of macro and micro soil nutrient changes in response to disturbance. The increase in whole tree harvesting (WTH), which is the most intensive form of harvesting, has prompted additional studies. These cover topics from nutrient dynamics (Edwards and Ross-Todd 1983, Freedman et al. 1986, Hendricksen et al. 1989, Hornbec and Kropelin 1982, Johnson et al. 1982) to studies of compaction (Dickerson 1976, Mace 1970) and seedling regeneration (Mou et al. 1993). Most earlier investigations exploring C or N pool dynamics in response to forest management have either focussed on short term changes (Dominski 1971, Mroz et al. 1985), or relied on a chronosequence approach (Covington 1981, Federer 1984). In an investigation of forest management and soil carbon, Johnson (1992) found only two papers out of thirteen which discussed forests cut longer than 3 years ago which were not chronosequences (Reich 1983, Aztet et al. 1989). In contrast, the effects of forest management practices on the northern hardwood forest have been a topic of study at Hubbard Brook Experimental Forest in New Hampshire for over 35 years. Hubbard Brook and other long term ecological research sites are invaluable for the investigation of forest management. Data is collected from these sites prior to experimental manipulation. There is a baseline for comparison and the site consistency allows more detailed analysis than is possible in a multi-site chronosequence.

Chronosequence studies investigating forest floor nutrient change after clear cutting have indicated a loss in forest floor organic matter of 50% within 15 years (Covington 1981) and 40% within 10-15 years (Federer 1984). Federer (1984) also reports an N content decrease of 30%. Bormann and Likens (1979) have estimated for N that stream water export and plant nutrient uptake account for less than 50% of the estimated loss. Suggestions to account for the rest of the estimated N loss include soil mixing during harvest (Ryan et al. 1992), translocation to mineral soil (Mellilo 1981), immobilization in slash (Covington, 1981) and volatilization by chemical or biological denitrification processes (Borman and Likens 1979). In addition the chronosequences may have overestimated the N loss. Eight years after WTH of Hubbard Brook Experimental Forest watershed-5 (HBEF W-5), the forest floor C pool size had decreased (insignificantly) by 25% (Johnson et al. 1995), while forest floor N pool size decreased insignificantly by 17% (Johnson 1995).

Nitrogen is a vital component to plant growth and is often a limiting nutrient. Because the natural flux of nitrogen is small, perturbations of the cycle that change N availability may have large effects. To evaluate future N availability it is important to know what proportion, out of the total N lost to the forest floor, is retained in a different soil compartment, and what proportion is lost to the watershed. If chronosequences overestimated N loss, then stream water loss and plant uptake may account for the majority of N flux after WTH. 7 years after WTH at HBEF W-5 it was apparent that the forest floor organic matter pool had not reached a minimum (Johnson et al. 1995). Now, at the 15-year study of HBEF W-5, loss of the forest floor should be stabilizing according to the chronosequence studies. If total N for the forest floor has not decreased from earlier years then the question becomes why the chronosequences overestimated loss. This study was designed to provide a single site investigation of C and N dynamics over the long term in order to provide a check of the chronosequence studies and allow a greater depth of investigations into nutrient processes.

The effects of forest management on carbon cycling have recently reached global importance. Current interest in climate change has led to international negotiations on carbon emissions necessitating the development of accurate global and regional carbon budgets. Whether a terrestrial ecosystem serves as a sink or source for carbon is related to land use change and forest management practices. The effect of land use on the global carbon cycle may be of comparable magnitude to the effect fossil fuel emissions (Post et al 1990) and thus has been the focus of numerous recent studies mostly in the tropics (Detwiler 1986, Lugo et al. 1986, Schlesinger 1986). The northeastern part of the United States, however, is also under scrutiny because it has been suggested as a carbon sink that is yet unaccounted for in global carbon budgets. Regrowth of forest lands is a sink for C (Marland 1988, Vitousek 1991), and the amount of forested land in the United States has increased almost fourfold from 1920 to the late 1970's (Clawson 1979).

The methods and assumptions underlying models of carbon flux are also under scrutiny. The data and theory on which the models are based is still uncomfortably incomplete. Carbon sequestered in the mineral soil accounts for 50% of a forest's C pool (Turner et al. 1995), however there is little solid information on the effects of harvest practices on the C pool of the mineral soil. It is unclear whether C lost from the forest floor is mostly emitted to the atmosphere, lost through leaching, or sequestered into the mineral soil. Whether the mineral soil loses C after clear cutting is also unclear. One of two recent carbon models assumed a 20 % decrease in the post harvest soil carbon pool, but the 'soil pool' consisted of soil, litter & woody debris (Moore et al. 1981). A model by Turner et al. (1995) assumed no net change in mineral soil carbon but a large loss of forest floor carbon. These differing assumptions affect the accuracy of model projections. Knowing how much of the C lost from the forest floor is sequestered in mineral soil compartments and how much is emitted for varied soil types after different types of harvests will help us analyze the role of forests and forest management in carbon budgeting.

As part of a long-term study of forest management effects on the northern hardwood forest, this study of Watershed 5(W5) of the Hubbard Brook Experimental Forest (HBEF) in central New Hampshire was designed to assess changing C and N distribution among soil compartments and total C and N loss over 15 years re-growth following WTH. In earlier iterations of the study physical mixing has played an equal or greater role in C and N concentration and pool sizes than accelerated decomposition and leaching losses (Johnson et al. 1995).

Whether the impact of physical mixing declines relative to decomposition after 15 years has important implications for forest recovery. The amount of time it takes for natural recovery processes to mask the effects of mixing and soil compaction can inform silvicultural practices. Whether the effects of clear-cutting on forest floor nutrients are as severe as chronosequence studies suggest, and what the fate is of nutrients that are lost from the forest floor, informs both regional carbon budgeting and the growing understanding of nutrient flux.

METHODS

Site description

Watershed 5 (W5) of Hubbard Brook Experimental Forest (HBEF) in the southern White Mountains of New Hampshire, is a 22.5 ha catchment from 510-750 m in elevation with an average 15^{o} slope and a southeast aspect. W5 has an average soil depth to the C horizon of 0.6m (Huntington et al. 1988). Soils are generally acidic and well drained, with low base saturation and cation exchange capacity (Johnson et al. 1991). W5 soils are Haplorthods and Fragiorthods of the Tunbridge, Lyman, Berkshire, Skerry, and Becket series (Huntington et al. 1988, Johnson et al. 1991), developed on stony glacial till between zero and several meters thick (Johnson et al. 1981) underlain by Littleton gneiss and Kinsman quartz monzonite bedrock.

The pre-harvest forest was dominated at low and mid elevations by beech (Fagus grandifolia Ehrh.), yellow birch (Betula alleghaniensis Britt.), and sugar maple (Acer saccharum Marsh.). Upper elevations and exposed slopes were dominated by red spruce (Picea rubens Sarg.), balsam fir (Abies balsamea(L.)Mill.), and white birch (Betula papyrifera Marsh.). Pin cherry (Prunus Pensylvanica L.) dominated the early successional post-harvest forest, but by the 15 year sampling, dominance had mostly returned to its pre-harvest composition with a sparse population of canopy pin cherries.

Before WTH, the last extensive logging ended in 1918 (Bormann and Likens 1979). Prior to the WTH, W5 was also impacted by the hurricane in 1938 and subsequent salvage logging through 1941. W5 was classified as "21-60% blow down" with the greatest damage at lower elevations (Peart et al. 1992).

In the fall and winter of 1983-1984 all trees greater than 5cm diameter at breast height (dbh) were whole tree harvested with feller bunchers or chainsaws. Trees from 85% of the watershed were removed using rubber tired skidders by fall of 1984. 12% of the watershed was cleared of trees during the summer of 1985, and 3% was never cleared (Johnson 1995). Harvest resulted in the removal of 180 Mg ha^{-1} of aboveground biomass (Siccama et al. 1994). An estimated 65% of the watershed showed signs of mechanical disturbance, and the forest floor was removed from 25% of the watershed surface (Ryan et al. 1992).

Sampling Method

Prior to treatment, the watershed was surveyed into 360 25 by 25 meter plots. Sixty sampling locations were chosen using a stratified random design to select 10 sites within each of 6 elevation bands as described in Huntington et al. (1988). Near each site, 3 additional sampling sites were chosen with similar microtopography along the contour between 3 and 6m apart. One of the 4 sites for each location was randomly chosen for excavation during each sampling period. Samples were collected prior to whole tree harvesting (July 1983), 3 years (July 1986), 8 years (Summer 1991), and 15 years (Summer 1998) after harvest.

Each site was sampled using a quantitative pit approach described in Huntington et al. (1988). The forest floor was collected in two strata: the combined Oi and Oe horizons (referred to hereafter as the Oie), and the Oa horizon. Mineral soil depth strata were designated as 0-10cm, 10-20cm, and 20cm to either the top of the C horizon or bedrock (referred to hereafter as the 20+ strata). Laboratory procedures are also described in Huntington et al. (1988). There were a few minor inconsistencies which shouldn't affect results but should be noted: organic horizons were sieved through a 5 mm screen in 1991 (Johnson 1995), and 1998, and a 6 mm screen in 1986 and 1983 (Huntington and Ryan 1990); all weights were reported on an oven dry basis at 105^{o} C, however in 1886 organic samples were dried at 60^{o} and reported at 105^{o} (Huntington et al. 1988) while other papers did not report this procedure; C and N concentrations were determined using an EA 1108 in 1991 (Johnson 95) and a NA-1500 in 1983, 1986, and 1998; 60 pits were excavated in all sampling periods except 1983 when 59 pits were excavated; the pits for all 4 sampling periods were dug in the predetermined locations except that in 1986 a pit was inadvertently excavated in plot 204 instead of plot 203 in a location with substantially different microtopography.

The N and C contents of each pit by depth stratum were determined using methods described in Huntington et al. (1988). For 1998, values of 0.0 where pits did not contain a particular horizon were included in averages for concentrations, pool size estimates, and soil mass. Whether this practice was followed in the other sampling periods was not reported and must be clarified.

Significance between years was determined using a two sample T test assuming unequal variance. The two sided p values reported are of the data from Chris Johnson and Tom Huntington's files and may compare mean values that differ from the published means. All published and unpublished means are reported in Appendix A with the anomalies highlighted and noted under "Differences".

RESULTS

Totals

In 1998 the mean carbon pools of the Oie and Oa horizons were 8.2 Mg ha^{-1} and 24 Mg ha^{-1} respectively. For Oie there was a significant (p=.04)[1] reduction in C content from 1983 to 1998 (11 Mg ha^{-1} to 8.2 Mg ha^{-1}). Oie C content declined slightly in 1986 and never returned to original values**.** The C content of the Oa horizon fluctuated up and down between sampling periods (Table 1).

The mean carbon pools for the mineral depth strata in 1998 were 32 Mg ha^{-1}, 25 Mg ha^{-1} and 56 Mg ha^{-1} for the 0-10, 10-20 and 20-C strata respectively.

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[1] All p values specified are two sided from two sample t-tests assuming unequal variances. These are based on the data available for this study, the means of which do not necessarily reflect published values. The differences are catalogued in appendix 1, and are mentioned in the text when they are large enough to effect interpretation.

Values for the 0-10 and 10-20 strata were comparable between 1983 and 1998, but the 20+ strata showed a declining trend (p=.07).

Mean N content for the Oie and Oa were 410 kg ha^{-1} and 1120 kg ha^{-1} in 1998. This represents an insignificant reduction in the size of the Oie pool from 1983 to 1998 (p=0.30) and also an insignificant increase from intermediate values. In contrast, total C declined between each sampling period. For the Oa, differences between published values and available data for 1983 were large. The high published value for 1986 may reflect the addition of pit 203 which was dug in the wrong place.

The mean N pools of the mineral strata for the 0-10 and 10-20 showed no measurable differences between 1983 and 1998 (Table 1). The 10-20 horizon showed an insignificant increase in 1986 before returning to values comparable to 1983. The mean N pool for the 20+ strata in 1998 showed a decreasing trend of 30% from 1983 to 1998 (p=0.07).

The coefficients of variability (CV) for carbon pool sizes of the organic horizons were greatest in 1986. For the mineral horizons the CV for the carbon pools were comparable over the years, with the highest values in 1991(0-10) and 1998 (10-20, 20+). The CV for total N was substantially higher in 1986 than any other year, more than doubling 1983 values. By 1998 the CV for N had returned to values comparable to 1983 (Table 1).

Concentrations

The C concentration for the Oie in 1998 decreased from 1983 values (7% p=0.03) but increased significantly from 1986 (13% change, p=0.003). There was no significant change between 1991 and 1998 (p=0.36). 1998 Oie N concentration is 22 g kg^{-1} which was identical to 1991 values, increased from 1983 (p=0.09), and significantly increased (p=0.00) from 1986 when there was a significant decrease relative to the 1983 value.

C concentration for the Oa was 220 g kg^{-1} in 1998, which is identical to the published value in 1986, and higher than the 1991 value (180 g kg^{-1}], but still lower than the 1983 value. The Oa N concentration in 1986 was significantly lower than the 1983 value (33% p=0.00). The 1991 values were comparable to 1986 values (p=0.30). 1998 values showed an insignificant increase from 1991 derived values (p=0.12), but were still significantly lower than 1983 (p=0.02 derived values). Excluding pit 203 from 1986 data had only minor effects on Oa concentration, reducing the mean value from 218g kg^{-1} to 213 g kg^{-1}. Oie concentrations were insignificantly higher in 1998 than in 1983 (p=0.09)

C and N concentrations in 1998 for the mineral horizons had not changed greatly from 1983 (Table 2). The differences between the published means and the mean values in the data used for 1983,1986, and 1991 are too great to allow for significant comparison at this time (Appendix A).

1998 had no outliers (defined as values greater than 20% from the nearest value) for the total solum C and N pool sizes or when broken down into organic and mineral totals. 1983 and 1991 both had an outlier in the upper values. Oa C concentration for 1986 also had one upper outlier belonging to pit 204 but Oie C concentration for 1986 did not show an outlier.

Soil Mass

Soil mass of the Oa went up insignificantly in 1998 from 1983 (p=0.07) if the available data was used. However when the published mean from 1983 was used there was no observed difference. Soil mass for Oa in 1998 went down 30% from 1986 published values (significance could not be determined). Soil mass of all other horizons were not significantly different between 1998 and 1983.

C:N Ratios

The C:N ratios in 1998 for the Oie and Oa were 20.1 and 20.3. These were both significant decreases from 1983 values (p=0.00 and p=0.04). From 1983 C:N ratios went up insignificantly in 1986 and declined significantly in 1991 (Johnson 1995), stabilizing at the lower levels (Table 3). C:N ratios in 1998 for the mineral soils were comparable to 1983 ratios. The C:N ratio showed a highly significant (p<0.01) increase between the 0-10 strata and the 20+ strata for all study periods except 1991 (p=0.14). For 1998 there was a significant increase in C:N ratio between 0-10 and 10-20 strata (p=0.03) and an increasing trend between 10-20 and 20+ (p=0.12). CV values for 1998 were within the range of the earlier years but on the high end for the Oa and 20+ (Table 3).

Elevation

Relative to pre-harvest values, total soil mass in 1998 was reduced in the highest and lowest elevation groups (Table 4). Nutrients contents closely matched mass, with the total N and total C reduced for the upper two and lowest two elevation classes, but increased or stable for the middle two elevation classes. The elevation groups which lost nutrients were also the groups with the highest initial nutrient contents. The greatest nutrient loss (40%) was in the lowest elevation group. The elevation datum from 1986 and 1991 in relation to 1983 do not follow the same pattern as the data from 1998.

Paired Sampling

For total solum mass the correlation between 1998 and 1991 was greater than the correlation for the 1998-1983 or 1998-1986 pairs. Without forcing the line through zero, the line equation for the 1998-1991 pair was $y=3004x + 215$, with an R^2 value of 0.1. Exclusion of the 20+ strata from the mass total increased the correlation between 1998 and 1983 but decreased the correlation for the 1998-1986 and 1998-1991 pairs. Pits without an Oa horizon numbered14 in 1986, 20 in 1991, 14 in 1998, and two in 1983.

DISCUSSION

Forest Floor

After 15 years of recovery from whole tree harvest the forest floor is still undergoing transition While for the total forest floor there was no significant difference in N or C content between 1983 and 1998, nutrient concentration decreased for the organic horizons. In addition the Oie and Oa horizons have not shown a uniform pattern over the years. The Oie shows a declining trend in both nutrient contents, whereas the Oa has fluctuated widely between the four sampling periods[2], resulting in an increase in content in 1998 from 1983[3]. Some of these differences may illustrate relative importance of the processes effecting the Oie and Oa horizons, however some is clearly due to the analytical issues affecting the data.

Carbon

Mixing of organic and mineral horizons through mechanical disturbance was a major cause of the C concentration decline post harvest for both the Oie and the Oa (Huntington and Ryan 1990). By 1998 leaf litter deposition and decomposition had begun to increase C concentrations, but the effects of mixing were still significant 15 years after WTH. Oie C concentration in 1998 showed a significant increase from 1986 but remained significantly lower than 1983 values. Oa C concentration also decreased in 1986 and had not returned to pre-harvest values by 1998. For both N & C the concentration in the Oie increased before the Oa, and recovered more fully. The Oie was most immediately responsive to forest compositional changes, and, like the uppermost horizon, did not show the effects of mixing long after harvest. The Oa, which is the longer term reservoir of organic material, should take longer to recover.

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[2] The increase in nutrient content and mass of the Oa in 1986 may be accounted for by inclusion of pit 204 in the mean, and/or in part by decomposition of slash remaining after WTH.

[3] Significance between 1983 and 1998 for the Oa could not be determined because of difficulties with the available 1983 data.

The continued decline in C content indicates that decomposition rates and nutrient uptake by plants were still greater than the rate of input to the forest floor. Oie C content in 1998 was 20% lower than 1983 levels. The decreasing trend of about 20% for Oie mass correlates well with the decrease in C. In contrast, Oa C content and Oa soil mass increased by around 20% in 1998 from 1983**.** Some of the increase in the Oa could be from decomposition of the slash that was added after WTH. Siccama et al. (1994) estimated the slash remaining on site after WTH on W-5 was 9-14 Mg ha-1, much of which would have decomposed after 15 years.

Nitrogen

The pattern for N, which is quite different from the C pattern, may be indicative of both forest compositional changes and differential effects of mixing disturbance on leaching rates.

The input of high nutrient litter from early successional pin-cherry (Marks 1974, Mou et al. 1993) should cause N concentration to increase and C:N ratios to decrease. Indeed Oie N concentration increased above 1983 levels in 1991 and 1998 and C:N ratios significantly decreased. In contrast Oa N concentration remained low in 1991 and 1998. The effects of mixing on the Oa N concentration, as with C concentration, were still apparent. The C:N ratio for the Oa, as for the Oie, is lower in later years than in 1983. The effect of pin cherry on both Oie and Oa is apparent through the C:N ratio.

Although the transition from pin-cherry dominance to a young hardwood forest was visually apparent in 1998, it was not yet significantly reflected in the soil as C:N ratios did not increase between 1991 and 1998.

For the Oie and the Oa, N content, unlike concentration, did not decrease significantly from 1983 levels at any point in the study. Changes in the total N pool for the forest floor of W5 do not support the dominant view of high N loss post clear-cut (Bormann and Likens 1979). It appears from W5 data that the measured nutrient loss in stream water and exported logs and chips and estimated nutrient uptake by plants may account for the total loss from the watershed due to WTH. The 'unaccounted loss' of N discussed in Bormann and Likens (1979) may not exist.

Johnson, in his 8-year report of W5 N changes (1995), suggested that the redistribution of mineral soil during logging might cause N to be retained in the forest floor[4] although the driving mechanisms were not discussed. Johnson suggested that the differences in N loss reported by Covington, Federer, and at W5 could be because Covington excluded extremely disturbed sites, whereas Federer included all but the most disturbed sites, and the W5 study included all disturbance levels.

Johnson's (1995) theory of differential leaching due to physical disturbance doesn't explain the relationship between C:N ratios and pool sizes. C:N ratios for both Oa and Oie were consistently lower than 1983 values in 1991 and 1998 whereas pool sizes fluctuated. If the primary cause of the ratio change between 1983 and 1991 were differential leaching, the ratio shouldn't have remained constant when, in 1998, the Oa nutrient pool increased, and the Oie nutrient pool continue to decline. The 60% increase between 1991 and 1998 in Oa C and N pools while maintaining a constantly low C:N ratio suggests pin cherry succession is playing a major role in the Oa nutrient balance.

Concentrations and C:N ratio were clearly affected by the species composition change, and it is likely that the increased demand for N by pin cherry and blackberry caused the N to be preferentially retained in the system. Johnson discusses pin cherry in his analysis of C:N ratios for Oie but doesn't apply it to N pools. Unless pin cherry is correlated to soil disturbance, analysis of plots by disturbance class could help to determine the relative importance, for N retention, of physical disturbance and compositional changes.

There may be other effects due to disturbance levels which may have skewed Covington's estimates. Martin (1988) suggests an increase in disturbance over time as harvesting technology has changed, and Ryan et al. (1992) suggests the pattern of disturbance may have changed in a systematic way.

Full investigation of the trends have to include 1986 data. Once issues for 1986 Oa are resolved, the data could help to determine relative importance of succession and mixing in nitrogen retention, among other questions. The reported increase of around 50% for Oa C and N pools in 1986 (Huntington and Ryan 1990) is difficult to explain. Some of this increase may be due to addition of slash after WTH, however much of the slash would not yet have decomposed 3 years post harvest. The effect on C and N pool sizes of the mix up related to pit

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[4] Findings by Hendricksen et al. (1989) and Ryan et al. (1992) support this hypothesis.

203 and 204 and any other outliers must be investigated. If removing pit 203 drastically affects pool sizes interpretations will have to be altered.

Mineral Soil

The mineral soil has shown no significant changes in C&N pool sizes or soil mass over the past 15 years[5]. There is however a decreasing trend in N and C pool sizes for the 20+ layer (30% p=0.07 between 1983 and 1998). This trend is not due to differences in pit depth as there were 7 pits with no 20+ layer in both 1983 and 1998. Because of the low concentration of nutrients in the 20+ layer the role of analytical error is greater than for the other horizons and should be thoroughly investigated. Nonetheless a reduction in the nutrient content of the 20+ horizon without significant changes in the upper mineral strata could be partly explained if decomposition of root biomass were stabilizing nutrient levels of the upper strata. A study by Vogt et al. (1986) suggests that root turnover adds 18-58% more nitrogen to soil than litter fall. McCaugherty 1980 estimates root litter input is 1.3 times leaf litter. At W5, root biomass is 41.6 Mg ha^{-1}, which corresponds to a C pool of 21.6 Mg ha^{-1} (Johnson et al. 1995). Johnson et al. (1995) concluded that while C released from roots may represent a significant fraction of rough and fine roots may have stabilized mineral soil carbon of the total soil C pool, it is not large enough to be detected in this study. The strong decreasing trend in 20+ may provide an interesting addition to the discussion. It is possible that the mineral soil is losing carbon to the atmosphere and the loss is compensated in the upper strata, but not the 20+, by C input from severed roots.

The lack of significant changes in the nutrient pools of the mineral soil may be primarily because the magnitude of the C and N pools is far greater than loss through leaching or out-gassing and thus loss is proportionally minor. The reduced C:N ratio of the lower mineral strata observed in 1991 (Johnston 1995) was not observed in 1998, which had ratios comparable to 1983. C:N ratios are a more sensitive indicator of soil chemistry than pool sizes and the preferential loss of carbon suggested by Johnson (1995) may have occurred into 1991 with recovery by 1998, however these differences may simply indicate the variability of W5 soils.

In contrast with the hypothesis of preferential loss of carbon are the findings that in all study periods the C:N ratio for the mineral soil increases significantly between the 0-10 and 20+ depth strata. This suggests that N is regularly more labile then C in the mineral soil. If N is more labile in the mineral soil that would further support the hypothesis that N in the forest floor was retained through biological processes and not because of physical mixing. It would be useful to look at the C:N ratios over time in relation to trends in C and N concentrations and also carefully look at C:N ratios of 1986 before drawing conclusions about the mechanisms involved.

Elevation

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[5] Johnson (1995) reported a significant decrease in the carbon pools of the 10-20 and 20+ depth strata 8 years after WTH but this is based on the exclusion of zero values from 1983 and

Eight years after WTH Johnson (1995) found that the largest losses to nutrient pools were in the 'high hardwood' zone which he suggested was due primarily to the higher slope in that area. How closely the high hardwood zone correlates to elevation group is unclear, however Johnson's high hardwood zone is generally at mid elevations. In 1998 however, nutrient pools decreased at the lowest and highest elevations, only remaining constant or increasing for the mid-elevation between 610-690m. In 1986 pool sizes relative to pre-harvest values appeared to increase in 1986 at higher elevation and changed little at lower elevations (Huntington & Ryan 1990). Clearly there is significant variation in trends between years.

Some of the decrease in soil mass and nutrients observed in later years may be due to slope, and some to changing forest type. Huntington et al (1988) found that N concentration was positively correlated with elevation, while soil mass was negatively correlated. In 1998 soil mass and nutrients display the same pattern of change. There are many potential contributing factors to the variety observed in the elevation data. Elevation groups may differ in rates of primary productivity, decomposition and erosion. The differences in nutrient composition for early and late succession forest cover may vary by elevation. Disturbance levels are greater in areas with a high slope. In addition the high natural variability will have a greater effect on the smaller sample size of the elevation groups vs. the combined totals. It would be valuable to look at the correlation over the years between many of these factors especially disturbance levels by elevation.

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inclusion of zero values in 1991 mean..

Suggestions for Further Analysis

There are many further analyses to be done with this data but first the inconsistencies in the data, which are listed in appendix A, must be resolved. To this end it is very important to the usefulness of this study to create a compilation of all the data, and a consensus on the publishable quantities. It is especially important that all decisions regarding data processing (especially inclusion or exclusion of outliers and the number of points included for all strata) be clearly noted.

The original design of the study was paired, however the greatly increased variability between 1983 and 1986 led researchers to abandon paired analysis. Variability for most parameters declined in 1991 and 1998, reopening the possibility of deriving useful information from paired analysis. Without forcing the line through zero it was difficult to determine whether the correlation for soil mass between the later years and 1983 was greater than between 1986 and 1983. The closest correlation was between 1991 and 1998. This is most likely because the soil for both years was disturbed but had some time to recover. Some of the disturbance impacts still remained in 1998 which explains why the correlation between 1998 and pre-harvest in 1983 was not as strong as the correlation between 1991 and 1998. Pre harvest, only two sites did not have an Oa horizon. Post harvest, the number of sites missing an Oa ranged from 14 to 20. Identifying rejection criteria for extremely disturbed sites is likely to improve the paired comparison. In addition, stratification by level of disturbance could provide valuable information toward separating physical disturbance and associated effects from the harvesting. This would contribute to a growing understanding of appropriate forestry practices.

CONCLUSIONS

Fifteen years after WTH, nutrient pools and soil mass for the forest floor were comparable to pre-harvest values. The general pattern for the forest floor is one of visible disturbance 3 years after harvest (1986), which returns to near pre-harvest levels by 1991 and remains stable or increases in 1998, 15 years post harvest. Nutrient dynamics of the forest floor fifteen years after WTH were dominated by input and decomposition of high N leaf litter. Some effects of the harvest, however, may still be visible for the individual horizons. Nutrient concentrations for the Oa may still have been lower than pre-harvest values due to physical mixing, and Oie mass and nutrient content had not yet stabilized.

The impact of clear-cutting on forest floor nutrient totals is clearly not as great as suggested by the chronosequence studies even though plots with high levels of disturbance were included in the study. Physical disturbance may actually play a role in retaining N. Nutrient availability for plants, however, is a function of the concentration of nutrients near fine roots as well as the total nutrient content, and the effect of mixing during WTH is still apparent in the Oa fifteen years post harvest. That nutrient levels decreased at the highest and lowest elevation groups, but not for the middle elevations indicates that the effect of WTH may be dependent on factors like slope and forest cover. The level of nutrient loss after harvest has also been found to differ depending on the soil quality, with nutrient rich soils having greater loss (Mroz et al. 1985). Appropriate forest management decisions clearly require some understanding of the topography and soils of the area involved.

No significant effect was apparent in the mineral soils at fifteen years, or at any earlier period. This suggests that carbon budget models would be correct in assuming no change in the forest floor pool post-harvest. This assumption must be used with caution however. Because the C pool in the mineral soil is so large, even changes due to forest management that were below the detection limit of this study could have a substantial effect on the regional carbon budget. CO2 flux at the soil surface for Hubbard Brook based on soil respiration data was estimated to increase from 4.7 to 5.7 Mg C ha^{-1} yr^{-1} 8-10 years after clear-cutting. (Johnson et al 1995). In addition it is not possible to determine whether the estimated C release from roots was sequestered in the soil or lost through respiration. (Johnson et al 1995). The strong decreasing trend in C content of the 20+ amounts to a loss of over 15 Mg ha^{-1} over fifteen years. Because of the potentially large effect on C budgets of small changes in the mineral soil, continued focus on C dynamics at Hubbard Brook and other long term ecological research sites is necessary.

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Table 1.

Soil mass and C and N soil pools by depth strata for all 4 sampling periods.

	1983 (pre-harvest)		1986 pub (3 years)		1991(8 years)		1998 (15 years)		
Total C	**Mg ha^{-1}**	**CV**	**Mg ha^{-1}**	**CV**	**Mg ha^{-1}**	**CV**	**Mg ha^{-1}**	**CV**	P
Oie	10 (1.0)	66	8.9 (1.6)	140	8.5 (1.2)	106	8.2 (0.6)	53*	.04
Oa	**20 (1.5)**	94	31 (8.5)	210	14 (2.2)	126	24 (3.4)	113	***
O-10	32 (1.2)	30	34 (1.5)	34	32 (1.5)	37	32 (1.4)	33	0.74
10-20	27 (1.6)	35	31 (1.9)	48	23 (1.4)	46*j	25 (1.6)	49	0.61
20+	73 (6.8)	58	75 (6.6)	68	63 (5.9)	73*j	56 (5.8)	84	0.07
FF	**30**		39(9.3)		22	*j	32	88	
MS	130		140(8.6)		117		120	51	
Total	150		180		140		150	39	0.32
Total N	**Kg ha^{-1}**	**CV**	**Kg ha^{-1}**	**CV**	**Kg ha^{-1}**	**CV**	**Kg ha^{-1}**	**CV**	P
Oie	460 (38)	60	390 (77)	150	390 (47)	92	410 (29)	53	0.30
Oa	**870** (66)	94	1300 (300)	300	700 (116)	129	1100 (138)	97	***
0-10	1600 (65)	32	1600 (73)	73	1600 (69)	34	1600 (68)	34	0.95
10-20	1200 (70)	46	1300 (90)	90	1100 (64)	45	1100 (75)	51	0.73
20+	3100 (295)	73	3100 (280)	280	2900 (264)	70	2400(243)	83	0.07
FF	**1300**		1600 (340)		1100 (145)		1500	77	
MS	5900		6000 (390)		5600 (340)		5100	48	
Total	**6900**		7600		6700 (370)		6700	36	0.48
Soil Mass	**Mg ha^{-1}**	**CV**	**Mg ha^{-1}**	**CV**	**Mg ha^{-1}**	**CV**	**Mg ha^{-1}**	**CV**	P
Oie	22 (1.7)	58	23 (4)	130	19 (2.4)	97	18 (1.1)	48	0.07
Oa	**66 (7.2)**	83/97*h	114 (20)	140	57 (5.6)	132	79 (9.2)	90	***
0-10	490 (23)	36*h	560 (27)	38	479 (20)	32	520 (22)	33	0.30
10-20	520 (35)	51	620 (30)	28	514 (32)	48	550 (29)	41	0.51
20+	2200 (180)	63	2100 (190)	70	2300 (210)	69	2000 (210)	83	0.56
FF	**88**		135 (22)		76		97		
MS	3200		3300 (210		3300		3100		
Total	**3300**		3400		3400		3200		0.68

P = level of significance of a two-sided, two-sample t-test with unequal variance comparing the 1983 and 1998 means

* indicates a significant difference at the 0.05 level between 1983 and 1998.
* j indicates a significant difference at the 0.05 level between 1983 and 1998 published in Johnson 1995
*h indicates a significant difference at the 0.05 level between 1983 and 1986 published in Huntington et al 1988

Table 2.

C and N concentration by depth strata for all 4 sampling periods.

	1983 (pre-harvest)		1986 (3 yrs)		1991(8years)		1998 (15 years)		
C Conc	**g kg^{-1}**		**g kg^{-1}**		**g kg^{-1}**		**g kg^{-1}**		**P value**
Oie	460 (9)	13*h	380 (14)	27	450 (15)	26	430 (9)	15*	0.03
Oa	290 (14)	32*h	220 (14)	43	**180** (19	32	220 (18)	64	***
O-10	72 (4)	46	68 (4)	43	72 (5)	49	69 (4)	50	0.59
10-20	**50** (4)	43	56 (4)	49	49 (4)	61	50 (3)	49	0.86
20+	**32** (3)	52	39 (3)	58	25 (2)	45	29 (3)	67	0.40
Conc N	**g kg^{-1}**		**g kg^{-1}**		**g kg^{-1}**		**g kg^{-1}**		**P value**
Oie	21 (1)	14*h	16 (0.4)	29	22 (1)	23	22 (1)	17	0.09
Oa	13 (1)	28*h	10 (1)	36	**9** (1)	22	11 (1)	62	***
0-10	3.6 (0.3)	53	3.1 (0.2)	49	3.6 (0.2)	44	3.3 (0.2)	51	0.42
10-20	**2.3** (0.2)	53	2.4 (0.2)	55	2.4 (0.2)	61	2.2 (0.2)	52	0.92
20+	**1.4** (0.1)	63	1.6 (0.1)	55	1.2 (0.1)	39	1.2 (0.1)	64	0.36

* indicates a significant difference at the 0.05 level between 1983 and 1998.
* j indicates a significant difference at the 0.05 level between 1983 and 1998 published in Johnson 1995
*h indicates a significant difference at the 0.05 level between 1983 and 1986 published in Huntington et al 1988

Table 3.

C:N ratios by depth strata for all 4 sampling periods.

C:N ratios	83 (pre-harvest)	86pub (3 yrs)	91(8years)	98 (15 years)	P value
	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	
Oie	23 (0.3)	24 (0.5)	21 (0.6)	20 (0.3)*	0.00
Oa	22 (0.4)	22 (0.4)	20 (0.7)	20 (0.5)*	0.04
O-10	20 (0.3)	22 (0.4)	20 (0.5)	21 (0.4)	0.29
10-20	23 (0.5)	24 (0.5)	21 (0.5)	22 (0.4)	0.62
20+	23 (0.4)	25 (0.6)	21 (0.6)	23 (0.4)	0.98

* indicates a significant difference at the 0.05 level between 1983 and 1998.

Table 4.

Soil mass and C and N soil pools by elevation for 1998.

Elevation meters	Plot range	n	N content Kg ha-1	C content Mg ha-1	Soil Mass Mg ha-1
			Forest Floor		
510-560	**308 - 360**	8	996	18	53
560-610	**244 - 307**	10	2120	40	132
610-660	**197-243**	8	1395	31	88
660-690	**138-195**	9	1498	30	112
690-730	**65-137**	12	900	19	58
730-750	**1-64**	10	2068	49	139
			Mineral Soil		
510-560	**308 - 360**	8	3697	81	2534
560-610	**244 - 307**	10	5028	116	4120
610-660	**197-243**	8	5458	122	3109
660-690	**138-195**	10	5573	120	3037
690-730	**65-137**	12	5920	131	3105
730-750	**1-64**	11	4404	102	2238
			Total Solum		
510-560	**308 - 360**	7	4692	99	2587
560-610	**244 - 307**	10	7148	156	4252
610-660	**197-243**	8	6853	153	3197
660-690	**138-195**	9	7071	150	3149
690-730	**65-137**	12	6820	149	3163
730-750	**1-64**	10	6472	151	2377

Appendix A

There are a number of disagreements between the data I had available to me for my thesis and the published numbers. For my large scale analysis of trends I used the published information, unless there were clear reasons to do otherwise. All P values, by necessity, related the available data for previous years and the 1998 data. All published numbers and the values from the data I received are tabulated in appendix pages A1-A3. This appendix is meant to begin the process of developing both a comprehensive and final set of publishable numbers, and a compilation of all the original values in the event of further analysis in the future.

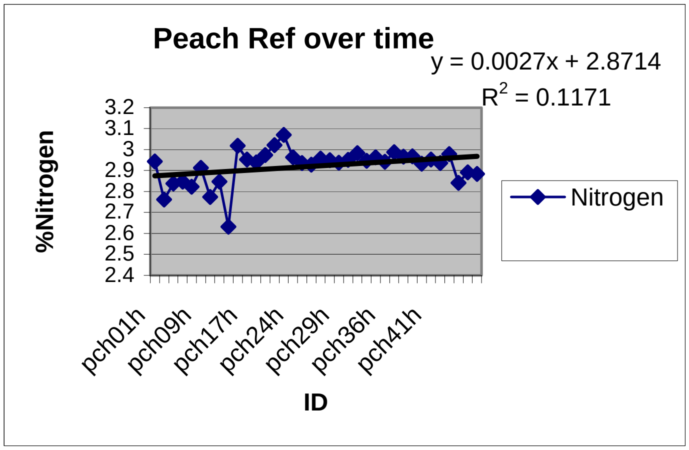
In addition to differences between the data and published values, there are some small differences between published numbers by Huntington et al 1988 (H88), Huntington and Ryan 1990 (H90), and Johnson 1995 (CJ95) for 1983 which are also tabulated. Some of these may be from further analysis and cleaning up the data in later years, and some may be rounding errors or disagreements over inclusion of 0.0 values. Either way these differences must be accounted for and agreement reached on a value for publication.

A decision clearly has to be made regarding the inclusion of pit 204 from the 1986 data. This pit was mistakenly dug instead of 203, and was in a swale, violating the original paired concept which aimed at a minimum to maintain a similar microtopography count.

Appendix B

1998 Data

The 1998 data is not 100% clean. Before a CV for the reference samples is published a correction has to be made for the references processed up to reference 23 as these were not dried in the dessicator prior to sampling and for peach there is more variation and a lower mean for these samples than the dried samples. This is especially apparent in % N as is clear in the graph below.



In addition some samples had high C:N ratios relative to the others. These may be due to high wood content in the sample, but should be confirmed. These are: Oie 74, 22 Oa, 81 Oa, 203 Oa, 203 0-10.

The following were not included in analysis and may be missing from the physical set of samples: 15 Oie, 149 Oie, 328 Oie, 344 20+.

Because a significant change is observed in the 20+ it is additionally important to be absolutely certain of correct values. The low C and N concentrations in the 20+ strata make error more possible. Reaching certainty regarding the 20+ mean may involve checking references between years, and running more replicates in the 20+ category.

REFERENCES

Aztet, T., Powers, R.F.,McNabb,D.H., Amaranthus, M.P.,Gross,E.R., 1989. Chapter 10. Maintaining long-term forest productivity in southwest Oregon and Northern California. Pp. 185-201 IN: D.A. Perry, Meurisse,R, Thomas,B., Miller,R., Boyle,J., Means,J, Perry,D.R., Powers,R.F. (eds.) Maintaining long-term productivity of Pacific Northwest Forest Ecosystems. Timber Press. Inc. Portland, OR.

Bormann, F.H. and Likens, G.E., 1979. Pattern and Process in a Forested Ecosystem. Springer, New York, 253pp.

Clawson, M. 1979. Forests in the Long Sweep of American History. Science. Vol 204:1168-1174.

Covington, W.W., 1981. Changes in Forest Floor Organic Matter and Nutrient Content Following Clear Cutting in Northern Hardwoods. Ecology 62(1):41-48.

Detwiler, R.P., 1986. Land use change and the global carbon cycle: The role of tropical soils. Biogeochemistry 2:67-93.

Dickerson, B.P. 1976. Soil Compaction after Tree Length Skidding in Northern Mississippi Soil Sci. Soc. Am 40:965-966.

Dominsky, A.S. 1971. Nitrogen transformations in a northern hardwood podzol on cotover and forested sites. PhD thesis, Yale University, New Haven, Conn.

Edwards, N.T. and Ross-Todd, B.M., 1983. Soil carbon dynamics in a mixed deciduous forest following clear cutting with and without residue removal. Soil. Sci. Soc. Am. J., 47: 1014-1021.

Federer, C.A. 1984. Organic matter and nitrogen content of the forest floor in even-aged northern hardwoods. Can.J. For. Res. 14: 763-767.

Freedman, B., Duinker, P.N. and Morash, R., 1986. Biomass and nutrients in Nova Scotian forests and implications of intensive harvesting for future site productivity. For. Ecol. Manage., 15: 103-127.

Hendricksen, O.Q., Chatarpaul, L., Burgess, D. 1989. Nutrient cycling following whole-tree and conventional harvest in northern mixed forest. Can. J. For. Res. 19: 725-735.

Hornbeck, J.W. and Kropelin, W., 1982. Nutrient removal and leaching from a while-tree harvest of northern hardwoods. J. Environ. Qual., 11:309-316.

Huntington, T.G., Ryan, D.F., 1990. Whole tree harvesting effects on soil nitrogen and carbon. For. Ecol. Management., 31: 193-204.

Huntington, T.G., Ryan, D.F., Hamburg, S.P., 1988. Estimating Soil Nitrogen and Carbon Pools in a Northern Hardwood Forest Ecosystem. Soil Sci. Soc. Am. J. 52:1162-1167.

Johnson, C.E., Johnson, A.H., Huntington, T.G. 1992. Sample size requirements for the determination of changes in soil nutrient pools. Soil Science 150, No. 3: 637-644.

Johnson, C.E., 1995. Soil nitrogen status 8 years after whole-tree clear-cutting. Can. J. For. Res. 25: 1346-1355.

Johnson, C.E., Johnson, J.H., Siccama, T.G., 1991. Whole-Tree Clear-Cutting Effects on Exchangeable Cations and Soil Acidity. Soil Sci. Soc. Am. J. 55:502-508.

Johnson, D.W., West D.C., Todd, D.E., and Mann, L.K., 1982. Effects of saw log vs. whole-tree harvesting on the nitrogen, phosphorous, potassium, and calcium budgets of an upland mixed oak forest. Soil Sci, Soc. Am. J., 486: 1304-1309.

Johnson, D.W., 1992. Effects of Forest Management on Soil Carbon Storage. Water, Air, and Soil Pollution 64:83-120.

Jonson, N.M.,Driscol,C.T.,Eaton,J.S.,Likens,G.E.,McDowell,W.H. 1981. ‘Acid rain’, dissolved aluminum and chemical weathering at the Hubbard Brook Experimental Forest, New Hampshire. Geochim. Sosmochim. Acta 45: 1421-1437.

Lugo, A.E., Sanchez, A.J., Brown, S., 1986. Land use and organic carbon content of some sub-tropical soils. Plant Soil 96: 185-196.

Mace, A.C., 1970. Soil Compaction due to tree length and full tree skidding with rubber-tired skidders. Minn. For. Res. Note 214, 4p.

Marks,P.L. 1974. The role of Pin Cherry In the Maintenance of Stability in Northern Hardwood Ecosystems Ecol. Monographs 44: 73-88.

Marland, G. 1988. The prospect for solving the CO2 problem through global reforestation. Tech. Rep. 39. U.S. Dep. Energy, Office of Energy Res., Washington, DC.

McClaugherty, C.A., J.D. Aber, and J.M. Melillo. 1980. Analysis of fine root dynamics in forest ecosystems. Bull Ecol Soc 61(2)113.

Melillo, J.M., 1981. Nitrogen cycling in deciduous forests. IN Terrestrial nitrogen cycles. Edited by Clark, F.E., Rosswall,T. Swedish National Science Research Council, Stockholm. Biol. Bull. 33. Pp. 427-442.

Moore, B., Boone, R.D., Hobbie, J.E., Houghton, R.A., Melillo, J.M, Peterson, B.J., Shaver, G.R., Vorosmarty, C.J., Woodwell, G.M., 1981. A simple model for analysis of the role of terrestrial ecosystems in the global carbon cycle. Pages 365-385 in B. Bolin, (ed.) Carbon cycle modeling. John Wiley & Sons, New York, NY, USA.

Mou, P., Fahey, T.J., Hughes J.W., 1993. Effects of Soil Disturbance on Vegetation Recovery and Nutrient Accumulation Following Whole-tree Harvest of a Northern Hardwood Ecosystem. Journal of Applied Ecology 30:661-675.

Mroz, G.D., Jurgensen, M. F., Frederick, D. J., 1985. Soil Nutrient Changes Following Whole Tree Harvesting on Three Northern Hardwood Sites. Soil Sci. Soc. Am. J., 49:1552-1557.

Peart, Cogbill, & Palmiotto., 1992. Bull. Torrey Bot. Club 119:29-38.

Post, W.M., Peng, T-H., Emanuel, W.R., King, A.W., Dale, V.H., DeAngelis, D.L., 1990. The global carbon cycle. American Scientist 78:310-326.

Raich, J.W., 1983. Effects of forest conversion on the carbon budget of a tropical soil. Biotropica 15: 177-184.

Ryan, D.F., Huntington, T.G.,Martin, C.W., 1992. Redistribution of Soil Nitrogen, Carbon and Organic matter by mechanical disturbance during whole-tree harvesting in northern hardwoods. For. Ecol. and Management, 49: 87-99.

Sartz, R.S., Huttinger, W.D., 1950. Some factors effecting humus development in the Northeast. Journal of Forestry 48: 341-344.

Siccama, T.G., Hamburg, S.P.,Arthur, M.A., Yanai, R.D., Bormann,F.H.,Likens,G.E., 1994 Corrections to Allometric Equations and Plant Tissue Chemistry for Hubbard Brook Experimental Forest. Ecology 75(1):246-248.

Trimble, G.R., Lull,H.W., 1956. The role of forest humus in watershed management in New England. Research Paper 85, United States Forest Service, Washington DC, USA.

Turner, D. P., Koerper, G.J., 1995. A Carbon Budget for Forests of the Conterminous United States. Ecological Applications. 5(2):421-436

Vitousek, P.M. 1991. Can planted forests counteract increasing atmospheric carbon dioxide? J. Environ. Qual. 20:348-354.

Vogt, K. A., Grier, C.C, Vogt, D.J, 1986. Production, turnover, and nutrient dynamics of above- and below- ground detritus of world forests. Advances in Ecological Research 15: 303-377.