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## Challenges of measuring forest floor organic matter dynamics: Repeated measures from a chronosequence

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### Abstract

Accurate estimates of the retention of carbon in forest soils following forest disturbances are essential to predictions of global carbon cycling. The belief that 50% of soil carbon is lost in the first 20 years after clearcutting is largely based on a chronosequence study of forest floors in New Hampshire northern hardwoods (Covington, 1981). We resampled forest floors in 13 stands in a similar chronosequence after an interval of 15 years. The three youngest stands, which were predicted to lose organic matter over this time, did not exhibit the 40–50% losses predicted by the original chronosequence. The oldest stands had about twice as much organic mass in the forest floor as those cut recently, but this pattern could be explained equally well by historical changes in the nature of forest harvest as by the age of the stands. For example, mechanized logging probably causes more mechanical disturbance to the forest floor than horse logging, burying more organic matter into the mineral soil. Markets for forest products and the intensity of harvest removals have also changed over time, possibly contributing to lower organic matter in the forest floor in young stands. In any chronosequence study, effects of change in the nature of the treatment over time can easily be misinterpreted as change with time since treatment. Repeated sampling of the chronosequence provides controls for some of these effects. In the case of forest floor organic matter, however, high spatial variation makes it difficult to distinguish whether the observed variation is more likely due to changes in treatment over time or to differences in time since treatment. Because of the large amounts of carbon involved, small changes in rates of soil organic matter storage may be quite important in global climate change, but they will remain difficult to detect, even with very intensive sampling.

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### 1. Introduction

In some forest types, organic matter accumulates in one or more thick organic-rich horizons at the surface of the soil. This mor-type forest floor (Green et al., 1993) is important to energy budgets and nutrient

cycling, detrital food chains, and soil development. Because the forest floor is more easily studied than the mineral soil, patterns observed there have been assumed to apply to the soil as a whole. In particular, the belief that soil organic matter declines precipitously after logging can be traced to Covington's (Covington, 1981) study of forest floors in northern hardwood stands in New Hampshire. In that study, a series of stands of different ages was used to describe the pattern of forest floor mass and organic matter

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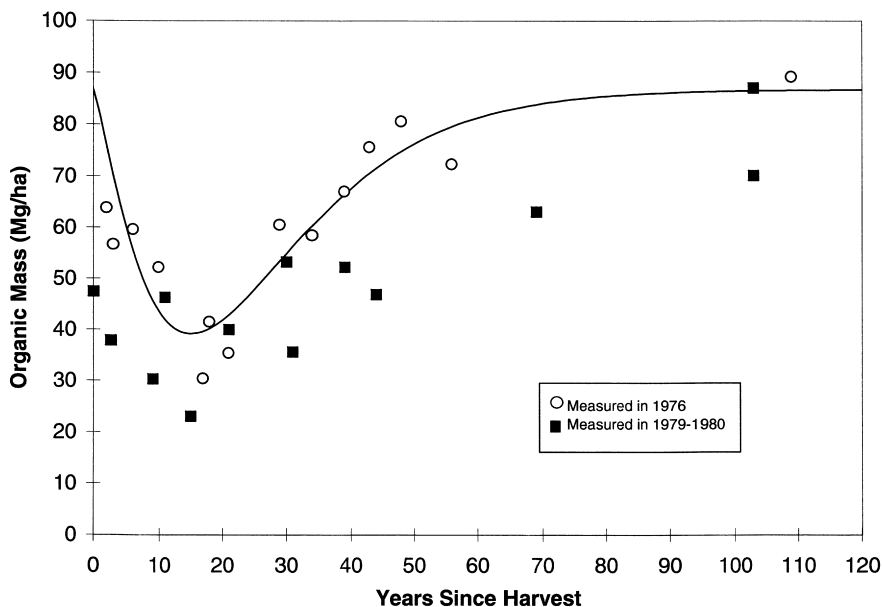


Fig. 1. Forest floor organic matter as a function of stand age. The curve is that fit by Covington to samples from stands measured in 1976 (Covington, 1981): organic matter content (Mg/ha) =  $-5.25X^{1.24} \exp(-0.0649X^{1.063}) + 86.75$ , where  $X$  = time since logging (years). Stands measured in 1979–1980 are those reported by Federer (1984); these samples were reanalyzed in this study.

content during succession following logging (Fig. 1). Covington's curve predicts a loss of 50% of forest floor organic matter in the first 20 years after the disturbance. Federer (1984) tested Covington's curve with the addition of 13 more stands in the region. His forest floors did not show as sharp a minimum as Covington's, but the oldest stands had the most organic matter in forest floors and those between 10 and 30 years old had the least (Fig. 1). Covington (1981) attributed the rapid loss of organic matter in young stands to increased decomposition rates and reduced inputs of litter.

The effect of forest harvest on soil organic matter is important not only to local successional processes but to global carbon storage. Covington's predicted loss rate of 50% has been used in modeling carbon storage in managed forests (Cooper, 1983; Liski and Westman, 1997), estimating the effect on carbon budgets of converting old-growth to young forest (Harmon et al., 1990), and predicting the effects of land use change on global carbon flux (Houghton et al., 1983). Covington's curve has also been used to estimate nutrient release from the forest floor (Hornbeck et al., 1986), to validate a simulation model (Pastor and Post, 1986),

and to supply evidence of continuing carbon accumulation in mature stands (Lugo and Brown, 1986).

The evidence for forest floor loss over time following logging, however, has not been convincing. Some studies have compared cut and uncut stands, and found less massive forest floors in the cut stands (Mattson and Smith, 1993; Brais et al., 1995). The differences, however, could be due to mixing with the mineral soil during the logging operation (Mroz et al., 1985; Ryan et al., 1992). If carbon is lost from a forest floor but transferred to the mineral soil rather than the atmosphere, it has quite different implications for global atmospheric change as well as local soil properties. Other studies comparing the same stands before and after logging have found that forest floor organic mass increased (Hendrickson et al., 1989; Mattson and Swank, 1989; Johnson et al., 1991). One study did have results consistent with the prediction of Covington (1981): forest floor organic mass declined significantly from 3 to 8 years after a whole-tree harvest (Johnson et al., 1995). Studies comparing decomposition rates before and after logging have also had mixed results (Blair and Crossley, 1988; Mattson and Smith, 1993).

An alternative to the use of time since logging in attempting to explain the observed pattern of forest floor organic matter content in relation to stand age (Fig. 1) is to examine the method of logging. The stands that were 10–30 years old at the time they were sampled by Covington in 1976 were necessarily logged between 1946 and 1966. Before the late 1940s, logging in the White Mountains was accomplished with horses. Rubber-tired skidders replaced crawler tractors during the 1960s. Other changes in the amount of soil disturbance and removal of logging residue might relate to changes in ages of trees being cut, stumpage prices, and markets for wood chips and firewood (Whitney, 1994). It is a limitation of the chronosequence approach that time of treatment, with all its historical context, cannot be distinguished from time since treatment, which is the intended independent variable.

The primary objective of this study was to test the validity of the pattern of organic matter loss and accumulation predicted by Covington's chronosequence. In 1994–1995, we revisited the 13 stands that were sampled in 1979–1980 by Federer (1984). We measured the depths of the forest floors as well as the masses and percent organic matter, to determine whether changes in forest floor organic matter content were associated with changes in thickness, bulk density, or the percentage of organic matter per unit mass. According to Covington's curve (Fig. 1), the three youngest stands should have lost 37–52% of their forest floor organic matter by 1994–1995. Middle-aged stands were predicted to gain up to 46% organic matter over the same interval. The oldest stands should have achieved steady state, with organic matter essentially unchanged. Alternatively, if part of the pattern in Fig. 1 were caused by historical changes in logging practices, then forest floors should not be expected to match these predictions as they age. In either case, changes over time within stands should reveal the rates of forest floor recovery, as influenced by rates of decomposition and detrital inputs as succession proceeds.

## 2. Methods

### 2.1. Definition of forest floor

Our definition of 'forest floor' differs from that of the Soil Science Society of America Glossary (SSSA,

1997). The glossary makes the forest floor synonymous with the O horizon, which is defined as having more than 20% organic carbon (Soil Survey Staff, 1975), while we would include some or all of an A horizon. In this paper, we follow the practice of earlier work (Federer, 1982, 1984; Yanai et al., 1999) by including in the forest floor A horizon material relatively high in organic matter. This material is characterised by very dark color, with or without visible sand grains, generally has 20–40% organic matter, and may overlay an E horizon. Functionally, this material seems more like forest floor than like mineral soil. We encountered these A horizons in 55% of our forest floor samples. In the rest, the O generally lies over an E horizon.

### 2.2. Study sites and sampling methods

Thirteen stands of northern hardwoods in the White Mountain National Forest, New Hampshire, USA, ranging in latitude from 43°56' to 44°13'N and in longitude from 71°14' to 71°44'W, were selected for study by Federer (1984) (Table 1). Tree species included beech (*Fagus grandifolia* Ehrh.), yellow birch (*Betula alleghaniensis* Britt.), paper birch (*B. papyrifera* Marsh.), sugar maple (*Acer saccharum* Marsh.), pin cherry (*Prunus pensylvanica* L.f.), red maple (*A. rubrum* L.), ash (*Fraxinus americana* L.), aspen (*Populus tremuloides* Michx.), and striped maple (*A. pennsylvanicum* L.) (Taylor, 1996; Fig. 2). Soils were coarse-loamy, mixed, frigid, Typic Haplorthods. Elevations ranged from 310 to 550 m. All stands were sampled at an interval of 15 years.

Six stands were located in the Bartlett Experimental Forest. Forest floor thicknesses in these stands had been measured in 1951 and 1959 (Federer, 1982). Forest floor organic matter was first measured in 1979 (Federer, 1984). At that time, forest floor samples were collected from 10 systematically located points along each of six 100 m transects in each stand; in one stand smaller than 1 ha, transects could be only 33 m long. At each sampling point, a 10×10 cm block of forest floor was collected to the depth of the E or B horizon. Horizon boundaries were identified and thicknesses were measured before separating the blocks into Oi, Oe, Oa, and A horizons. The 10 sample points from each line were composited by horizon to give  $n=6$  samples per stand and horizon.

Table 1  
Sites visited in this study

Site	Time of Cutting	Location	Elevation (ft)	Latitude	Longitude	Treatment
H6	Winter 1983–84	Bartlett, compartment 23	1200	44°08'N	71°17'W	Clearcut, mechanical
M6	Winter 1979–80	Sabbaday Falls, “Fool Killer #1”	1700	43°59'N	71°25'W	Clearcut, mechanical
M5	Winter 1976–77	Jackson, “Ellis River #2”	1500	44°12'N	71°14'W	Clearcut, followed by TSI thinning
C3	November 1970	Hubbard Brook, W-101	1600	43°56'N	71°44'W	Clearcut
H5	1967	Bartlett, compartment 28	1200	44°03'N	71°17'W	Clearcut Strips were scarified, limed and fertilized, but these strips were not sampled in 1979 or 1994
T20	1958	Sawyer River Road	1700	44°03'N	71°24'W	Heavily cut; some, but not all, cull trees were girdled
M4	About 1949–50	West of Jackson, beyond FR 325	1500	44°09'N	71°14'W	Clearcut, intensity unknown. Recent clearcuts approach it on the south (about 1975 and 1988)
T30	1948	Iron Mountain Road, towards FR 325	1800	44°08'N	71°14'W	Intensity of cut unknown
H1	1939	Bartlett, compartment 16, 1.4 acres	1100	44°08'N	71°16'W	Clearcut after 1938 hurricane, removing all stems >2” diam
H4	1933–35	Bartlett, compartment 22	1200	44°03'N	71°17'W	Commercial clearcut Thinning in 1959 (45% of basal area removed) affected about half of the plot sampled by Federer in 1979; we omitted this area in 1984
M3	1910	Jackson, Ellis River	1500	44°12'N	71°14'W	Presumed to be cut around 1910
H2	About 1875	Bartlett, compartment 16	1100	44°08'N	71°16'W	Clearcut for fuelwood and used as pasture. Thinned (20–30% removed) in 1936
H3	About 1875	Bartlett, compartment 16	1000	44°08'N	71°16'W	Clearcut for fuelwood and used as pasture

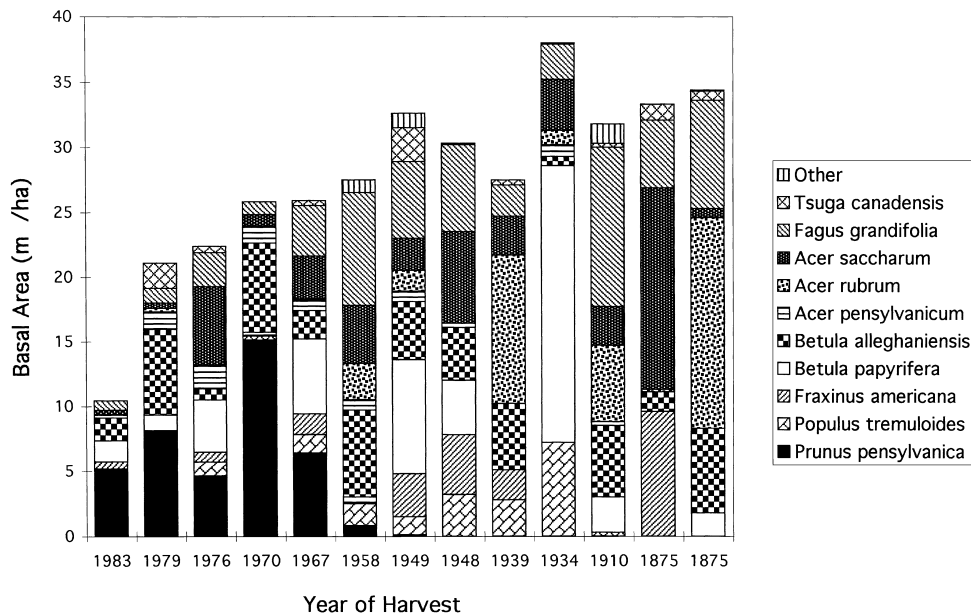


Fig. 2. Basal area, by species, of trees >2 cm in diameter in the 13 stands of the chronosequence.

The six stands in the Bartlett Experimental Forest were revisited in 1994. Some changes were made in the methods between 1979 and 1994 to improve consistency with the other stands and to facilitate future resampling. Specifically, in 1994 only five transects were sampled in each stand instead of six, and the transects were 50 m long instead of 100 m (except in the stand requiring 33 m transects). The transects to be omitted and the direction in which to shorten them were randomly selected.

Seven additional stands were sampled first in 1980 and again in 1995. In 1980, forest floor samples were not divided into horizons. In 1995, samples were divided into O and A horizons, to permit comparisons with other sites. The O horizon was not subdivided. In 1980, two stands were sampled without measuring horizon thicknesses; at all other occasions, thicknesses were measured before dividing the samples into horizons.

### 2.3. Laboratory analyses

Samples were air dried, sieved, and subsampled for air-dry moisture content. Different sieves were used in 1979 and 1980, so we sieved samples from the Bartlett

sites to 2 mm and samples from the other sites to 6 mm, to be consistent with the previous collections. Organic matter was determined by loss on ignition at 500°C (Wilde et al., 1978). Samples collected in 1979–1980 were analyzed for oven-dry weight and organic matter content when they were first collected (Federer, 1984); samples were then stored air dry for 15 years. These samples were analyzed again along with the samples collected in 1994–1995; as a result, our values for organic matter in the archived samples differ slightly from those reported by Federer (1984).

### 2.4. Statistical analyses

Tests of statistical significance, such as *t*-tests and regressions, were computed on log-transformed variables, to meet the requirements of normal distributions in populations or residuals. Two-sample *t*-tests were used to compare differences within stands over time, because in most cases, individual transect lines could not be paired. Significant differences were evaluated using  $\alpha=0.05$ . Means of untransformed variables are also reported, because these describe the average properties in a plot or a landscape.

### 3. Results

The organic matter content of the forest floor did not change according to the pattern predicted by Covington (1981). The three youngest stands were in the age range for which declines were predicted (Fig. 3); two of these stands had more organic mass in the forest floor than they had 15 years earlier. The observed values were significantly greater than predicted for all three stands, whether taken collectively ( $p=0.02$  for the three stands) or individually ( $p=0.02-0.03$ , based on five sample transects in each stand). The observed changes in organic mass of forest floors in the 13 stands were not significantly related to stand age, either in linear or polynomial regression. The average change over the 15-year interval was  $<1\%$  and not significant. Variation within stands was high, such that few of the changes were significant within stands (Fig. 4).

Although there was no pattern in the change in organic mass with time, there was a pattern in the organic mass as a function of time since logging. As in

the earlier chronosequences (Fig. 1), the oldest stands had the most organic matter in the forest floor, and young or middle-aged stands had the least (Fig. 4). This pattern can be described as a function of time since logging or as a function of time of logging (which is related to logging method). Regression analysis of the 40 stand-level measurements (14 stands measured by Covington in 1976, 13 measured by Federer in 1979–1980, and the same 13 stands remeasured in this study in 1994–1995) showed that the year of harvest explained just as much variation as the time since logging ( $r^2$  of 0.46 or 0.47,  $p<0.001$ ). The magnitude of the difference between the oldest and youngest stands in our study was about a factor of 2.

Organic matter distribution with depth was measured in six of our stands, in which four horizons (Oi, Oe, Oa, and A) were collected in both 1979 and 1994. In the other seven stands, horizons were not distinguished in the original (1980) sampling, but we distinguished the O and A horizons in 1995 (Fig. 5). Where horizons can be compared over time, the

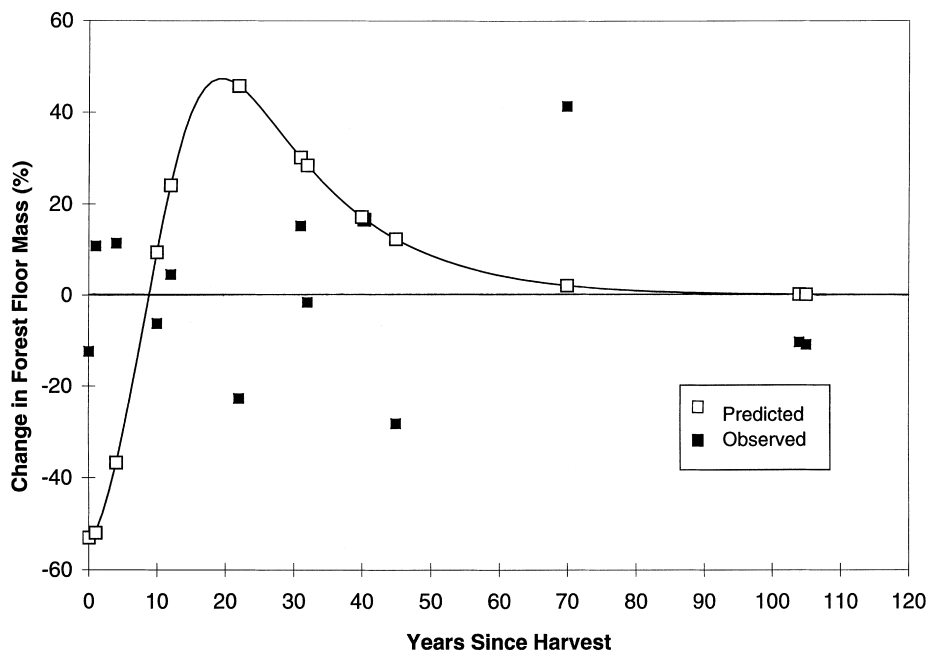


Fig. 3. Predicted and observed changes in forest floor organic matter over a 15-year interval as a function of stand age. The predicted change is projected following Covington's equation (see Fig. 1). The observed change is based on log-transformed organic mass. The age shown is that at the first sampling date.

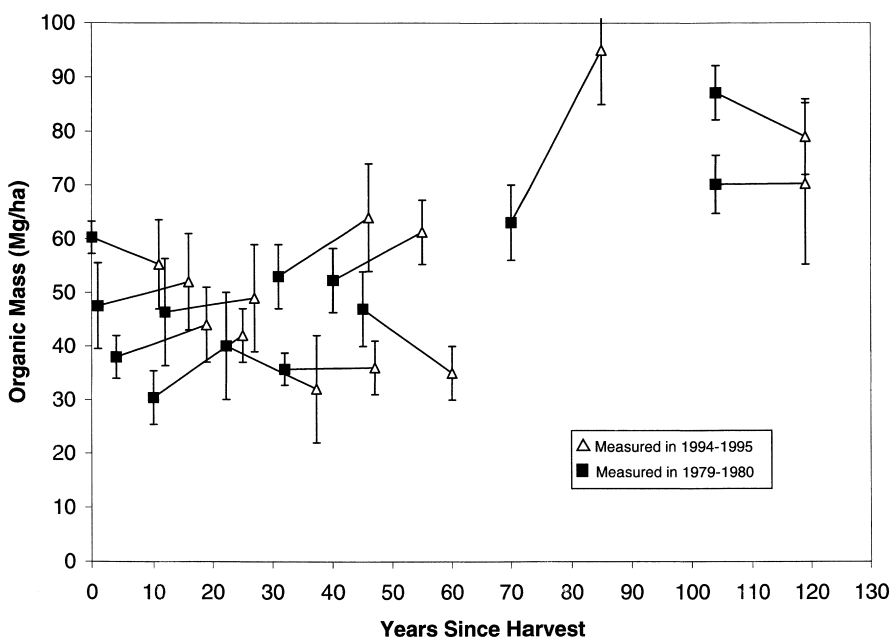


Fig. 4. Forest floor organic matter as a function of stand age, sampled over a 15-year interval. Error bars show standard error of the mean for each stand.

changes in horizons are similar to the change in the forest floor as a whole. There was not a horizon that predominated in explaining forest floor gains or losses.

In all stands in which O and A horizons were distinguished, the O horizons averaged >40% organic matter, and the A averaged <40% organic matter (Fig. 6), confirming that the separations we made in

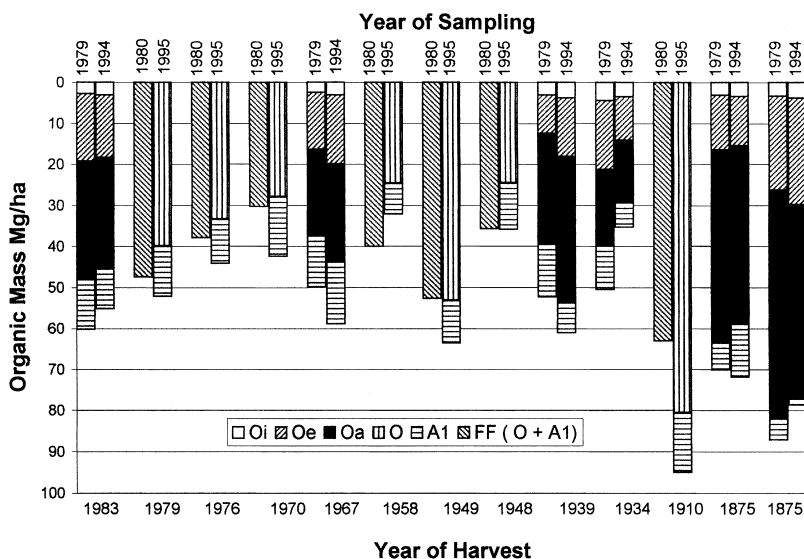


Fig. 5. Forest floor organic matter by horizon in 13 stands, arranged by date of harvest, at two sampling dates. The totals were significantly different at the two sampling dates at  $p < 0.05$  for the stands cut in 1958 and 1910.

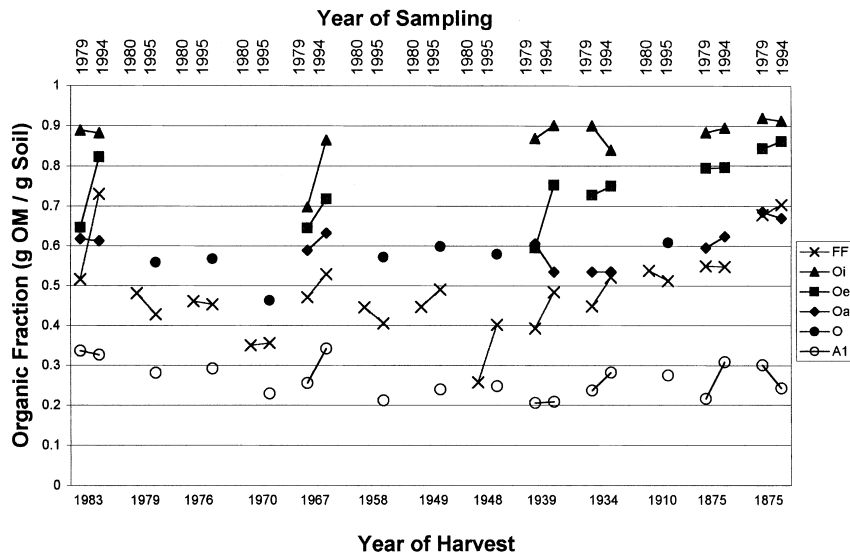


Fig. 6. Organic matter fraction in horizons of the forest floor in 13 stands, arranged by date of harvest, at two sampling dates.

the field correspond, on average, to the definition of organic and mineral horizons (Federer, 1982). The stand averages represent five or six composite samples, each representing 10 soil blocks, which reduces the effect of random error. The individual soil blocks were not always separated at the 40% boundary; in fact, five of the 101 composite samples designated as Oa had <40% organic matter, and 11 nominal A horizon samples had >40% organic matter. We refer to the percentage organic matter by weight as the 'organic fraction' in this paper.

Changes in the organic fraction in any horizon over the 15-year interval were generally small. One exception was the youngest stand, which was harvested in 1883, between our sampling dates. Decaying woody debris from the harvest and an accumulation of *Rubus* canes contributed material high in organic fraction; decomposing wood was most notable in the Oe.

It is difficult to determine whether changes in organic fraction represent changes in the ecosystem over time, such as transfers of organic matter from one horizon to another or changes in rates of input or decay, or merely changes in the collection methods. Because the organic fraction declines with depth from the Oi to the Oe to the Oa (Fig. 6), it is possible to collect samples with higher organic fraction by erroneously placing the horizon boundaries at a higher

point in the profile. Comparing the change in organic fraction with the change in organic matter content provides a check on this source of sampling error. Forest floors with reduced organic mass (those in stands logged in 1883, 1858, 1848, 1834, and 1875, Fig. 5) had higher organic fraction in four of six cases (Fig. 6), suggesting that some observed losses may be an artifact of bias in sampling. On the other hand, increased organic mass was associated with reduced organic fraction in only three of seven cases, suggesting that differences in the delineation of horizons was not solely responsible for the cases of increased organic matter in the forest floor. Increased organic fraction in combination with increased organic matter over time is consistent with a slow rebuilding of O horizons after mixing with mineral soil at the time of logging. Bulk density generally decreased (Yanai et al., 1999), consistent with the increased organic fraction (Federer, 1983).

#### 4. Discussion

The chronosequence approach uses sites of different ages as a basis for describing patterns attributable to individual sites as they age. This approach provides a means to study processes that take many decades to develop, such as forest succession following distur-



bance. In northern hardwood stands in the central White Mountains of New Hampshire, forest floor organic matter is significantly lower in young stands than in old stands, and this difference has been attributed to a loss of organic matter following logging disturbance (Covington, 1981).

The chronosequence approach is subject to several sources of error, because sites can differ for reasons unrelated to the time since disturbance. A chronosequence study of 23 hardwood stands in Nova Scotia found inter- and intrastand variation in forest floors to be greater than that related to stand age (Wallace and Freedman, 1986). In our chronosequence, stands with similar ages differed considerably in forest floor organic matter content (Fig. 4). Site factors that affect forest floors include local climate, influenced by slope, aspect, and elevation; species composition and stand structure; soil type, including soil organisms; the history of insect outbreaks causing defoliation; and weather events affecting woody litter input.

A more insidious source of error in chronosequence studies is the correlation between age of the site and the time (and method) of treatment. Properties of sites may vary with age because of changes in the nature of the treatment: sites should not then be expected to follow a trajectory over time that is predicted by the pattern of properties that vary with stand age. In our study, resampling a chronosequence after 15 years provided an opportunity to distinguish between time of treatment and time since treatment as causes of the observed pattern in forest floor organic matter. Changes in stands over time did not agree with the pattern in the original chronosequence (Fig. 3). Young stands had less forest floor than old stands (Fig. 4), but this pattern was equally well explained by the year of harvest, which is related to the method of logging, as by the age of the stands.

These two possible causes for the pattern in forest floor organic mass with stand age involve quite different processes. In the case of time since logging disturbance, factors that may contribute to changes in forest floor organic matter in the sites studied include: inputs of woody debris at the time of logging; differences in rates of leaf litter decomposition with species succession (Hughes and Fahey, 1994); and the timing of woody litterfall with self-thinning.

In contrast, the primary factors associated with the logging method used at the time of treatment are the

degree of soil disturbance and the intensity of harvest. Tractor logging presumably caused more mechanical disturbance to forest floors than did horse logging; rubber-tired skidders may have been intermediate in their effect. Mechanical mixing of forest floor material into the mineral soil, rather than decomposition, has been identified as a factor in explaining the initial loss of organic matter due to logging (Mroz et al., 1985; Ryan et al., 1992). In our study, we did not collect the buried organic horizons we encountered, nor did we sample the mineral soil below the A horizon, so we cannot quantify the importance of soil mixing as a function of time of harvest.

Changes in logging technology, combined with changes in markets for wood products, affect the intensity of harvest. The amount of standing timber and logging slash left in the forest affects organic matter input to the forest floor. In the oldest stands, logged with horses, only selected boles would have been removed, leaving the maximum organic mass on site. Whole-tree harvest leaves a minimum of residues, and bole-only harvest can have a similar effect if the trees are limbed at the landing rather than in the woods. Living trees continue to contribute litter to the forest floor, as do snags in various stages of decay; changes in litter inputs following logging may be more important to forest floor mass than changes in decomposition rates (Wallace and Freedman, 1986).

Finally, both the degree of soil disturbance and the intensity of harvest affect the species composition of regrowth. In northern hardwoods, pin cherry originates from buried seed (Bormann and Likens, 1979), which is displaced when the forest floor is scalped. In contrast, birch seeds germinate best on exposed mineral soil. Beech and sugar maple are shade tolerant, and regenerate better than pin cherry or birch under a residual canopy. The nature of the harvest operation affects the survival of advance regeneration, which is likely dominated by shade-tolerant species. An extreme case of species effects was reported in Upper Michigan, where clearcutting resulted in the replacement of eastern hemlock by northern hardwoods, accompanied by 35% reductions in forest floor organic mass (Hix and Barnes, 1984). Variation in species composition in our chronosequence (Fig. 2) may contribute to the differences in the amount and rate of accumulation of forest floor organic matter among stands.

Although much of the variation between stands is unexplained, the difference in forest floor organic matter between young stands, harvested recently, and old stands, harvested a century ago, is statistically significant and ecologically substantial. In our study, the difference was a factor of 2 over 120 years (based on log-transformed masses). Linear regression on the untransformed masses gives a slope of 0.33 Mg/ha per year, remarkably similar to that for 23 northern hardwood stands in Nova Scotia (0.36 Mg/ha/h) (Wallace and Freedman, 1986). In contrast, 41 northern hardwood stands in the Lake States had an increase of only 0.04 Mg/ha per year in the forest floor of stands between 50 and 100 years old (Grigal and Ohmann, 1992). Again, because some of the differences between young and old stands may be due to differences in the logging treatment, we cannot predict whether the young stands will gain organic matter at the rate suggested by these regressions.

We attempted to measure actual rates of change in forest floor organic matter over a 15 year period. Unfortunately, the high spatial variation in forest floor organic matter makes it impossible to detect small rates of change using reasonable sampling schemes. Only two of our 13 stands showed a statistically significant change over our 15 year study. For the median stand we sampled, a difference smaller than 54% in organic matter content would not be detectable using a *t*-test at  $\alpha=0.05$ . Variation in organic matter in mineral soil horizons may be somewhat less than in the forest floor (Johnson et al., 1991), but mineral soil horizons are more difficult to sample quantitatively. Because of the challenges of measurement, theoretical models of soil organic matter dynamics following forest disturbance or other changes in land use are likely to remain untested. Although we could reject the predicted loss rate of 50% (Covington, 1981), we cannot determine with confidence whether forest floors in this study are gaining or losing carbon at more modest rates. Previous research assumed that a steady state in this and other ecosystem pools would be achieved in mature or old stands (Bormann and Likens, 1979), but continuous changes in climate, carbon dioxide concentrations, and other anthropogenic stresses make this assumption unwarranted. Quite small rates of change in soil organic matter could be very important to the global carbon budget when extrapolated to large areas, especially if they are

more common than major disturbances such as forest harvest.

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