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# Long-term Effect of Silvicultural Thinnings on Soil Carbon and Nitrogen Pools

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**The effects of long-term silvicultural thinning on soil C and N content are not well known. We evaluated the impact of periodic thinnings on soil C and N pools in a 134-yr-old red pine (*Pinus resinosa* Ait.) forest in Minnesota, and a 104 yr-old northern hardwood forest in Wisconsin. The red pine stands had five thinning regimes (13.8, 18.4, 22.7, 27.6, 32.1 $m^2$ $ha^{-1}$ residual basal area [BA]), which were cut five or seven times over 46 yr. The northern hardwood stands had three residual basal area treatments (13.8, 17.2, 20.6 $m^2$ $ha^{-1}$) that were thinned five times over 50 yr. Our results showed that the heaviest-thinned (13.8 $m^2$ $ha^{-1}$) and uncut control red pine stands had higher C and N contents in the mineral A horizon, as compared to the other four thinning treatments. Multiple thinning did not affect C and N pool size in the forest floor and surface mineral soil (30-cm depth) in either red pine or hardwood stands. Within stand BA variability was positively correlated to C and N pools in the forest floor of the lightly-thinned (32.1 $m^2$ $ha^{-1}$) red pine treatment, but was negatively correlated to C and N pools in the A horizon. Our study and the literature indicate that stem-only removal for wildfire risk reduction and bio-energy production would have little impact on total soil C and N pools. However, more information is needed on the effects of whole-tree thinning regimes on soil C and nutrient contents.**

**Abbreviations:** BA, basal area.

Since soil is a major C pool in many forest ecosystems, soil organic matter (OM) loss from stand disturbance (e.g., logging, fire) can have a large impact on forest ecosystem function, and possibly affect long-term site productivity (Johnson et al., 1995; Grigal, 2000; Johnson and Curtis, 2001). Forest soils also have the potential to remove (sequester) large amounts of C from the atmosphere (Kimble et al., 2003), and are an important component in climate change models (Lavoie et al., 2005). Therefore, considerable interest has developed on the impact of forest management practices on soil C pools (e.g., Liski et al., 2001; Heath et al., 2003).

Extensive research of timber harvesting effects on soil properties has shown that traditional, clear-felling harvesting with heavy logging equipment can often have a negative, short-term impact on soil OM content, primarily though increased decomposition of residual forest floor and reduced litter inputs (e.g., Alban et al., 1994; Powers et al., 1998; Stone and Kabzems, 2002; Powers et al., 2005). However, long-term studies and forest models generally have shown that soil OM and C levels eventually recover to preharvest levels on most sites during the first rotation (e.g., Johnson and Curtis, 2001; Nave et al., 2010). Many studies have also assessed the impact of timber harvesting on soil N content, and usually found N losses in the forest floor, but little change in the mineral soil (e.g., Olsson et al., 1996; Jurgensen et al., 1997; Johnson and Curtis, 2001).

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In contrast, much less is known on the impact of silvicultural treatments on soil OM and C pools. Thinning is a common forestry practice used to increase the quality and quantity of merchantable timber, alter stand structure, improve soil water and nutrient availability, and reduce damage from disease and fire (e.g., Zeide, 2001; Ostaff et al., 2006; Powers et al,. 2010). While most studies have focused on the effects of cutting intensities and intervals between cuts on aboveground yield responses and economic return (e.g.,Liechty et al., 1986; MacDonald et al., 2004; Cao et al., 2008; Powers et al., 2011), less is known on belowground impacts of this practice. Thinning usually raises soil temperatures (e.g., Carlyle, 1995; Selig et al., 2008), which can increase OM decomposition in the forest floor and surface mineral soil (Thibodeau et al., 2000; Concilio et al., 2005; Slodicak et al., 2005), and change soil microbial community structure (Maassen et al., 2006). Mechanized stand thinning can also cause soil compaction (Mace, 1970; Landsberg et al., 2003; Makineci, 2005), affecting OM decomposition rates and C and N cycling (Li et al., 2004; von Wilpert and Schäffer, 2005).

Since thinning periodically removes significant amounts of stand biomass, it also can reduce soil OM and nutrient inputs from litterfall (Klemmedson et al., 1990; Novák and Slodičák, 2004; Blanco et al., 2006). However, the litter from thinned stands may have higher nutrient concentrations than litter from unthinned stands (Hökkä et al., 1996; Lopez-Serrano et al., 2005). Thinnings usually remove less biomass than final harvests, so they would be expected to have less impact on soil C and nutrient pools, and consequently, on subsequent stand growth. In a meta-analysis of 22 studies, Nave et al. (2010) found no significant difference between clearcut harvesting and thinning on C storage in the forest floor and mineral soil. However, a recent analysis by Powers et al. (2011) indicated that long-term, multiple thinning regimes in red pine and northern hardwood ecosystems decreased total above- and belowground C pools, as compared to unmanaged stands. Model calculations by Rolff and Ågren (1999) also indicated that two whole-tree thinnings during a rotation of Swedish Norway spruce stands [*Picea abies* (L.) Karst.] may have a greater impact on tree growth than a final whole-tree, clearcut harvest. Removing younger, smaller trees in thinning remove disproportionally greater amounts of nutrients than cutting older, larger trees at final harvest.

The results from short- and long-term thinning studies on soil C and N pools have been mixed. Thinning can increase (Selig et al., 2008), decrease (Wollum and Schubert, 1975; Vesterdal et al., 1995), or have little effect (Strong, 1997; Skovsgaard et al., 2006; Moghaddas and Stephens, 2007; Boerner et al., 2008; Nilsen and Strand, 2008) on C and/or N in the forest floor and surface mineral soil. However, these results are confounded by the number of thinnings conducted over the stand rotation (Rosenberg and Jacobson, 2004), whether the cut trees were left in the stand (Thibodeau et al., 2000; Ostaff et al., 2006), the bole was removed and tops of the cut trees left (Skovsgaard et al., 2006), or the whole tree was removed (Jacobson et al., 2000; Smolander et al., 2008). When whole-tree thinning is used, the amount of C and N left in logging residue is much less (Van Lear et al., 1995; Misson et al., 2005).

Since thinning is assuming greater importance in many silvicultural prescriptions to reduce wildfire risks and supply wood for increased bioenergy production in the United States (McIver et al., 2003; Page-Dumroese et al., 2010), more information is needed on the effects of thinning regimes on forest soil properties. Consequently, the objective of our study was to determine the long-term impacts of different thinning intensities on soil C and N pools in two important forest types in the northern Great Lakes Region: red pine in Minnesota, and northern hardwoods in Wisconsin.

## MATERIALS AND METHODS

### Study Location and Description

The red pine stands were established after a wildfire in 1864, and are located on a nearly level glacial outwash sand plain in the United States Forest Service (USFS) Cutfoot Experimental Forest in north-central Minnesota (47°32′00″ N, 94°05′00″ W). The shrub layer is comprised of mainly beaked hazel (*Corylus cornuta* Marsh.) and balsam fir [*Abies balsamea* (L.) P. Mill.] seedlings. The soil is predominately a Menahga loamy sand (mixed, frigid Typic Udipsamment) with few rocks (<2%), with a bulk densities of 0.97 Mg $m^{-3}$ in the A horizon and 1.66 Mg $m^{-3}$ in the B horizon, and a soil pH averaging 4.80 in both horizons.

The northern hardwood stands are on the USFS Argonne Experimental Forest in north-central Wisconsin (45°45′00″ N, 89°03′00″ W) that was selectively cut in 1905. The overstory is predominately sugar maple (*Acer saccharum* Marsh.) with a white ash (*Fraxinus americana* L.), basswood (*Tilia americana* L.), yellow birch (*Betula alleghaniensis* Britt.), and eastern hemlock [*Tsuga canadensis* (L.) Carr.] component. The soil is an Argonne sandy loam (coarse-loamy, mixed, superactive, frigid Alfic Oxyaquic Fragiorthod), which was formed on a glacial till plain with a 5 to 15% rock content. Soil bulk density was 0.95 Mg $m^{-3}$ in the A horizon and 1.52 Mg $m^{-3}$ in the B horizon, and. soil pH averaged 5.04 and 5.33 in the A and B horizons.

### Study Histories and Experimental Design

Both red pine and northern hardwood stands had three 2-ha replicates of varying residual basal areas. Beginning in 1949 (red pine) and 1951 (northern hardwoods), BA levels were maintained for up to 50 yr by thinning at 5- to 10-yr intervals. Single-tree selection was used at both sites: *red pine*-thinned from below based on diameter and spacing; *hardwoods*-cut to obtain a size class distribution with a $q$ value of 1.3 by removing cull and high risk trees, trees in overstocked size classes, and trees >60 cm diameter breast height (DBH). All stands were bole-only harvested during the winter when snow depths were 40 to 100 cm. All logging slash was left on the site. Permanent log landings created in both stands were used with successive harvests to minimize the affected stand area.

In 1949 five residual BA treatments of 13.8 $m^2$ $ha^{-1}$ (50% BA removal), 18.4 $m^2$ $ha^{-1}$ (35% BA removal), 22.7 $m^2$ $ha^{-1}$

(25% BA removal), 27.6 $m^2\ ha^{-1}$ (10% BA removal), and 32.1 $m^2\ ha^{-1}$ (maintain BA of stand at first thinning) were established in 85-yr-old red pine stands, and were thinned on a 5 and 10 yr cutting cycle. Hand-felling and horse (*Equus caballus*)-skidding were used from 1949 to 1965 (four thinnings), and conventional logging with hand-felling and tractor or grapple skidding were used after 1974 (three thinnings). The 13.8 and 18.4 $m^2\ ha^{-1}$ red pine stands were thinned five times, the last one occurring in 1974. The 23, 27.5, and 32.1 $m^2\ ha^{-1}$ BA stands were thinned seven times, the last harvest occurring in 1995. Consequently, the BA's in all stands were higher than their original prescriptions when we conducted our study, especially the 13.8 and 18.4 $m^2\ ha^{-1}$ thinning treatments (Table 1). Unthinned control plots were established in adjacent stands having no known history of timber removal or management.

The northern hardwood study design consists of three 1-ha thinning treatments having a residual BA of 13.8 $m^2\ ha^{-1}$ (27% BA removal), 17.2 $m^2\ ha^{-1}$ (21% BA removal), and 20.7 $m^2\ ha^{-1}$ (15% BA removal), which have been cut every 10 yr since 1951. Adjacent stands selectively harvested in 1905 were used as controls. Logs were removed by horses in the first harvest (1951), and mechanical logging equipment (tractors, tracked Iron Mule, rubber tire forwarders) was used in subsequent cuttings until the last thinning in 2001. Bole-only harvesting and slash retention was also implemented at each harvest. The northern hardwood stands were thinned five times, and BA's were 8 to 17% above prescription when we sampled the soil (Table 1). More detailed stand and thinning information is given in Strong (1997), D'Amato et al. (2010) and Powers et al. (2011).

## Sampling

A series of 20 grid points, approximately 20 m apart, were established in each treatment stand during June 2003 (red pine) and June 2004 (northern hardwoods). Points not representative of the stand treatment (i.e., skid trails or landings) were thrown out and another point established within 5 m. All points were at least 20 m from the perimeter of each stand to eliminate the impact of surrounding stands and roads on point conditions. At each grid point, a forest floor sample was collected with a 15.2 cm diam. (height 10 cm) plastic cylinder, and a 0- to 30-cm mineral soil sample was taken with a 5 cm diam. soil core sampler with plastic inserts. Surrounding tree basal area was measured at each of the 20 grid points using a BAF 10 prism. The forest floor samples and mineral soil cores were taken to the USFS Forestry Sciences Laboratory in Grand Rapids, MN, or to Michigan Technological University in Houghton, MI, for analysis. In the laboratory forest floor samples were dried at 70°C for 24 h, weighed, and ground to pass a 60 mesh screen. Mineral soil cores were separated into surface A horizon and B horizon (all soil below the A horizon to a 30-cm depth), and then dried at 105°C until a constant weight. Soil samples were passed through a 2-mm sieve, and weighed for dried soil weight after calculation of horizon bulk density. All samples were analyzed for total C and N with a Thermo Elemental Iris Intrepid (model 14410300) elemental analyzer.

## Data Analysis

Analysis of variance was used to test for differences in forest floor and mineral soil C and N properties among thinning treatments and uncut controls. The Student-Neuman-Keuls multiple range test was used to assess differences of means among the thinning treatments at $p < 0.05$. An exploratory analysis was conducted using all grid points for each stocking density treatment to develop a regression model to predict sample point N and C pools, as a function of surrounding tree BA. The measures of C and N pools predicted were the forest floor, A horizon, the A horizon and forest floor combined, and mineral soil to a 30-cm depth. The goal of this analysis was to determine the strength of the relationship among soil C and N pools, current stand stocking levels, and the past thinning history.

**Table 1. Basal area and soil C after different thinning treatments in: (A) red pine on the Cutfoot Experimental Forest, Minnesota, and (B) northern hardwood on the Argonne Experimental Forest, Wisconsin. Standard error of the mean is given in parentheses.**

| Basal area | | Forest floor | A horizon | | | | Forest floor + A Horizon | B horizon | Total mineral soil |
|---|---|---|---|---|---|---|---|---|---|
| Treatment | actual | Carbon | Depth | BD† | | Carbon | | | |
| $m^2\ ha^{-1}$ | | $Mg\ ha^{-1}$ | cm | $Mg\ m^{-3}$ | % | $Mg\ ha^{-1}$ | | | |
| A. | | | | | | | | | |
| 13.8 | 23.9a‡ | 10.6 (1.53) | 6.5 | 0.96 | 8.69 | 47.2a (0.8) | 57.8a (2.3) | 25.6 (0.9) | 72.8 (1.6) |
| 18.4 | 27.8b | 12.3 (1.26) | 6.4 | 1.06 | 5.60 | 34.6b (3.1) | 47.0b (3.2) | 29.1 (5.1) | 64.0 (6.2) |
| 23.0 | 27.1b | 8.0 (1.15) | 6.1 | 0.86 | 8.31 | 39.3b (2.6) | 47.3b (3.7) | 23.1 (1.0) | 62.5 (2.3) |
| 27.5 | 31.1c | 8.7 (0.93) | 6.2 | 0.98 | 6.33 | 36.3b (1.0) | 45.0b (1.8) | 24.8 (0.4) | 61.1 (1.1) |
| 32.1 | 35.0d | 9.4 (0.74) | 6.0 | 0.91 | 7.48 | 35.5b (3.8) | 44.9b (3.1) | 24.1 (3.2) | 59.6 (6.4) |
| Uncut | 38.5e | 9.9 (0.58) | 7.8 | 1.08 | 6.74 | 50.7a (5.3) | 60.6a (5.9) | 24.3 (1.7) | 74.9 (6.8) |
| B. | | | | | | | | | |
| 13.8 | 16.1a | 4.4 (1.01) | 6.8 | 0.97 | 6.64 | 38.4 (5.4) | 42.8 (5.7) | 63.8 (8.2) | 102.2 (3.6) |
| 17.2 | 19.0b | 4.3 (0.80) | 6.8 | 0.97 | 6.78 | 41.2 (8.3) | 45.5 (4.4) | 58.7 (6.1) | 99.9 (2.2) |
| 20.7 | 22.4c | 4.9 (1.27) | 6.8 | 0.92 | 8.39 | 43.2 (14.2) | 48.1 (13.2) | 61.2 (13.2) | 104.4 (1.2) |
| Uncut | 34.2d | 6.1 (1.89) | 6.3 | 0.93 | 8.17 | 42.0 (8.4) | 48.2 (6.9) | 63.8 (2.6) | 105.8 (7.8) |

† Mineral soil bulk density.

‡ Values with different letters are statistically different at $p < 0.05$.

## RESULTS

### Soil Carbon

No significant differences in forest floor C pools were found in red pine stands among the five thinning treatments and the uncut control ($p$ = 0.15). In contrast, C contents of the mineral A horizon were lower in four thinning treatments, as compared to the heaviest-thinned 13.8 $m^2$ $ha^{-1}$ stands and the uncut control (Table 1A). The higher C content of the uncut stand A horizon was due to a thicker A horizon depth, since there were no significant differences in A horizon bulk density ($p$ = 0.10) and C concentration ($p$ = 0.13) among thinning treatments. The A horizon depth, bulk density, and C % were relatively similar in all thinned stands, but when combined to calculate soil C content, C pool size was significantly higher in the 13.8 $m^2$ $ha^{-1}$ BA residual stands. Since difficulty in accurately separating the $O_a$ in the forest floor from mineral A horizon can cause anomalies in determining surface soil C pool sizes (Yanai et al., 2000), we combined the C amounts in the forest floor and A horizon to address this possibility (Table 1A). The combined forest floor/A horizon C pools were still higher in the 13.8 $m^2$ $ha^{-1}$ BA residual and uncut control stands. However, B horizon and mineral soil C pools (30-cm depth) were similar ($p$ = 0.63; $p$ = 0.17) in all thinned and uncut stands, as were combined forest floor and mineral soil C pools ($p$ = 0.14).

In contrast to red pine, there were no significant differences in forest floor and mineral soil C pools among the uncut control and any thinning treatment in the northern hardwood stands (Table 1B). As expected, C amounts in the forest floor of the hardwood stands were much less than in red pine, but total soil C pools were 20 to 40 Mg $ha^{-1}$ higher. This was due to the high C contents in the finer-textured $B_s$ in northern hardwood soil, in contrast to the weakly developed $B_w$ horizon in the sandy red pine soil.

### Soil Nitrogen

The response of forest floor and mineral soil N pool size to thinning was similar to C in both red pine and hardwood stands. The combination of N concentration, bulk density, and horizon depth to calculate N amounts in the A horizon gave significantly larger N pools in the 13.8 $m^2$ $ha^{-1}$ and uncut red pine stands (Table 2A). Forest floor N pools were not different among thinning treatments ($p$ = 0.13), as were N amounts in the B horizon and total mineral soil ($p$ = 0.96; $p$ = 0.40). As found with C, thinning the hardwood stands had no effect on N contents of the forest floor and mineral soil (Table 2B). As expected, C/N values in the hardwood stands were lower in the forest floor (24.4) and A horizon (14.8) than in the red pine (forest floor 39.0, A horizon 22.8), but they were not affected by thinning treatment in either stand type.

### Soil Carbon and Nitrogen Pool Variability

The wide range of residual stocking densities (13.8–32.1 $m^2$ $ha^{-1}$) implemented in the red pine treatments caused a high degree of within stand BA variability. Such spacing differences could change soil C and N inputs from both tree and understory litter and fine root turnover (Vesterdal et al., 1995), and affect the distribution of soil C and N pools within the stands. We tested this possibility by developing regression models to predict C and N pools in the forest floor, A horizon, and total mineral soil (30-cm depth) for each thinning treatment by using tree BA measurements taken around the 20 soil sampling points in each plot. Our results showed that only the lightest-thinning treatment (32.1 $m^2$ $ha^{-1}$) showed a positive correlation between forest floor sampling point C ($p$ = 0.04) and N ($p$ = 0.06) pools and surrounding tree BA. In contrast, A horizon N pools at soil sample points in these stands were negatively correlated with surrounding tree BA ($p$ = 0.02), as was C ($p$ = 0.13). However, point BA only accounted for <10% of C and N pool variability in this thinning treatment, and no strong positive or negative relationships were found between soil sampling point and tree BA in any other thinning treatment.

**Table 2. Soil N after different thinning treatments in: (A) red pine on the Cutfoot Experimental Forest, Minnesota, and (B) northern hardwoods on the Argonne Experimental Forest, Wisconsin. Standard error of the mean is given in parentheses.**

| Basal area | Forest floor | A horizon | | Forest floor + A horizon | B horizon | Total mineral soil |
|---|---|---|---|---|---|---|
| $m^2$ $ha^{-1}$ | Mg $ha^{-1}$ | % | Mg $ha^{-1}$ | | ———— Mg $ha^{-1}$ ———— | |
| A. | | | | | | |
| 13.8 | 0.32 (0.06) | 0.29 | 2.05a†(0.12) | 2.37a (1.49) | 1.82 (0.21) | 3.87 (0.37) |
| 18.4 | 0.34 (0.04) | 0.25 | 1.49b (0.04) | 1.83b (0.06) | 1.80 (0.13) | 3.29 (0.19) |
| 23.0 | 0.22 (0.05) | 0.26 | 1.69ab (0.09) | 1.91ab (0.13) | 1.82 (0.07) | 3.51 (0.15) |
| 27.5 | 0.21 (0.03) | 0.14 | 1.53b (0.01) | 1.74b (0.04) | 1.77 (0.16) | 3.31 (0.13) |
| 32.1 | 0.24 (0.01) | 0.21 | 1.55b (0.13) | 1.79b (0.14) | 2.00 (0.10) | 3.55 (0.23) |
| Uncut | 0.27 (0.03) | 0.20 | 2.26a (0.26) | 2.53a (0.28) | 1.81 (0.11) | 4.07 (0.36) |
| B. | | | | | | |
| 13.8 | 0.19 (0.06) | 0.46 | 2.54 (0.11) | 2.73 (0.17) | 3.09 (0.54) | 5.63 (0.41) |
| 17.2 | 0.18 (0.04) | 0.57 | 2.63 (0.27) | 2.81 (0.24) | 2.66 (0.38) | 5.29 (0.19) |
| 20.7 | 0.22 (0.08) | 0.56 | 2.75 (0.67) | 2.97 (0.74) | 3.46 (0.56) | 6.21 (0.20) |
| Uncut | 0.30 (0.11) | 0.55 | 2.79 (0.41) | 3.09 (0.39) | 3.30 (0.29) | 6.09 (0.48) |

† Values with different letters are statistically different at $p < 0.05$.

Table 3. Long-term effects of silvicultural thinning on C and N pools in the forest floor (FF) and mineral soil (MS) in North American and Europe forests.

| Tree species | Thinning treatments | | | | | | | Forest Floor | | Mineral Soil | | | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Basal area | Trees | Age first thinned | No.† | Harvest method | Sampled after last thinning | C pool | N pool | Sample depth | C pool | N pool | |
| | | $m^2$ $ha^{-1}$ | ha | yr | | | yr‡ | Mg $ha^{-1}$ | kg $ha^{-1}$ | cm | – Mg $ha^{-1}$ – | | |
| *Pinus resinosa* | Control | 38.5 | | 82 | 7 | SO§ | 9 | 9.9 | 270 | 30 | 74.9 | 4.1 | This study |
| | Thinned | 32.1 | | | | | | 9.4 | 240 | | 59.6 | 3.6 | |
| | | 23.0 | | | | | | 8.0 | 220 | | 62.5 | 3.5 | |
| | | 13.8 | | | | | | 10.6 | 320 | | 72.8 | 3.9 | |
| Northern hardwoods | Control | 34.2 | | 50 | 6 | SO | 3 | 6.1 | 300 | 30 | 105.8 | 6.1 | |
| | Thinned | 20.7 | | | | | | 4.9 | 220 | | 104.4 | 6.3 | |
| | | 17.2 | | | | | | 4.3 | 180 | | 99.9 | 5.3 | |
| | | 13.8 | | | | | | 4.4 | 190 | | 102.2 | 5.6 | |
| *Picea abies* | Control | | 3190 | 18 | 1 | SO | 33 | ns | ns | 100 | ns | ns | Nilsen and Strand, 2008 |
| | Thinned | | 2070 | | | | | 26.3 | 885 | | 82.5 | 6.1 | |
| | | | 1100 | | | | | 25.5 | 815 | | 92.9 | 6.8 | |
| | | | 820 | | | | | 25.3 | 850 | | 88.9 | 7.2 | |
| | Control | 52.5 | | 21 | 11 | SO | 2 (FF) | 17.0a¶ | 691a | 30# | 70.9 | – | Vesterdal et al., 1995; |
| | Thinned | 44.4 | | | | | 9 (MS) | 14.7a | 607ab | | 76.4 | – | Skovsgaard et al., 2006 |
| | | 36.8 | | | | | | 14.2a | 587ab | | 75.1 | – | |
| | | 28.8 | | | | | | 10.9b | 489b | | 79.2 | – | |
| | Control | 55.1 | | 20 | 11 | SO | 2 | 13.2a | 549a | ns# | | | Vesterdal et al., 1995; I. Stupak, |
| | Thinned | 47.0 | | | | | | 7.8b | 317b | | | | personal communication, 2011 |
| | | 38.9 | | | | | | 6.8b | 261b | | | | |
| | | 30.4 | | | | | | 2.3c | 92c | | | | |
| | Control | 45.6 | | 17 | 11 | SO | 2 | 47.9 | 1722 | ns# | | | |
| | Thinned | 38.5 | | | | | | 56.0 | 2086 | | | | |
| | | 31.6 | | | | | | 53.2 | 2024 | | | | |
| | | 25.0 | | | | | | 40.8 | 1538 | | | | |
| | Thinned | 27–39% stand Volume | | 30 | 2 | SO | 4 | 19.9 | 800 | 10 | 34.5 | 1.4 | Jacobson et al., 2000; |
| | | | | | | | | 13.8 | 500 | | | | Rosenberg and Jacobson, 2004 |
| | | | | | | WTH | | | 35.1 | | 1.4 | | |
| *Pinus ponderosa* | Control | 35–40% BA | | NA | 1 | SO | 6–15 | 13.6a | 411a | 15 | 30.1 | 1.7 | Grady and Hart, 2006; K. Grady, |
| Douglas ex Lawson | Thinned | | | | 9.3b | | 279b | 32.6 | 1.8 | | | | personal communication, 2011 |
| | Control | 42 | 554 | 28 | 1 | SO | 16 | 2.0†† | – | | | | Campbell et al., 2009 |
| | Thinned | 16 | 186 | | | | | 1.6 | | | | | |
| *Pinus taeda* L. | Control | 16.8 | | 8 | 1 | SO | 14 | – | – | 30 | 34.5 | – | Selig et al., 2008 |
| | Thinned | 9.4 | | | | | | | | | 45.5 | – | |
| *Pinus sylvestris* L. | Thinned | 27–39% stand | | 27–36 | 2 | SO | 4 | 15.9 | 500 | 10 | 25.2 | 0.8 | Jacobson et al., 2000; |
| | | Volume | | | | WTH | | 12.7 | 400 | | 27.9 | 0.9 | Rosenberg and Jacobson, 2004 |

† Number of thinnings.

‡ Time since last thinning when soil sampled.

§ SO = stem only; tree boles were removed, branches and foliage left on-site. WTH = whole-tree harvest; tree boles, branches, and foliage removed from the site.

¶ Values with different letters are statistically different at $p < 0.05$.

# A horizon pH (CaCl2) of Vesterdal et al. (1995) in descending order: 3.9; 6.3; 2.7.

†† Assume a C content of 50%.

## DISCUSSION

Results from our study showed that multiple thinning of red pine had lowered the C and N contents of the mineral A horizon in all treatments, except in stands where the greatest BA (50%) was removed. In contrast, thinning had little effect on C and N pools in the forest floor, mineral soil (30-cm depth), and combined forest floor and mineral soil in both red pine and northern hardwood stands. Other long-term thinning studies in the United States and Europe also reported few changes in soil C and N pools (Table 3). Skovsgaard et al. (2006) speculated that thinnings are unlikely to substantially affect mineral soil C pools in one stand rotation, and would be dependent on thinning interval, intensity, and method (stem-only or whole-tree). The higher amounts of C and N usually found in mineral soil would also make it more difficult to detect thinning-caused changes in pool sizes than in the forest floor.

While differences in experimental design, number of stand entries, soil sampling depths, and BA removed in thinnings make it difficult to directly compare long-term results, several studies reported decreased C and N contents in the forest floor after some thinning regimes (Table 3). Vesterdal et al. (1995) found that thinned Norway spruce stands growing in calcareous soil had large reductions in forest floor C and N pools, as compared to stands growing on acid soils. This forest floor decrease was caused by earthworms (*Lumbricus terrestris*), which came into the stand after thinning in response to the development of a vigorous herbaceous understory. In contrast, thinning stands on acid soils produced an understory comprised mostly of mosses, which did not favor earthworm activity.

The time interval between soil sampling and the last thinning operation could also be an important variable in thinning study results, as logging slash is incorporated into the forest floor, or understory plants change in response to increased light conditions (Campbell et al., 2009). For example, the stands in Vesterdal et al. (1995) were repeatedly thinned over short time intervals, and sampled 2 yr after the last thinning. The amount of slash added to the forest floor over these short-term sequential thinning might be similar to what would occur naturally in litterfall and mortality. These thinned stands also would have had very little stand closure, and allowed the development of an extensive understory plant community. In contrast, Nilsen and Strand (2008) sampled their stands 33 yr after the thinning treatments, which would be ample time for logging slash to be decomposed and crown closure to occur.

All of the studies in Table 3, except one, compared unthinned stands to conventional or stem-only thinning, where branches, leaves, and tops of cut trees are left on-site. Rosenburg and Jacobson (2004) found no significant differences in forest floor and surface mineral soil C and N pools between stem-only and whole-tree thinning of Norway spruce stands. This result was a little surprising, as an earlier study in these stands indicated whole-tree thinning reduced tree growth due to lower N availability (Jacobson et al., 2000). However, whole-tree thinning can reduce soil organic matter decomposition rates (Smolander et al., 2008), which could lower N mineralization without appreciably changing total N pools. Frey et al. (2003) concluded that differences in soil N after thinning boreal mixed wood stands in Canada were not controlled by thinning intensity or canopy retention, but by the amount of forest floor disturbance.

## CONCLUSIONS

Our study showed that C and N contents in the surface A horizon of red pine stands decreased in all thinning regimes, except in stands where 50% of the BA was removed. However, thinning had no impact on C and N amounts in the forest floor and combined A and B mineral horizons (30-cm depth) in both red pine and northern hardwood stands. Within stand BA variability was positively correlated to C and N pools in the forest floor of the lightly-thinned (32.1 $m^2$ $ha^{-1}$) red pine treatment, but was negatively correlated to C and N pools in the A horizon. However, stand BA relationships accounted for <10% of C and N pool variability in this thinning treatment. Some long-term studies have shown decreased C and N in the forest floor after thinning, but comparing results among studies is difficult due to differences in thinning intensities, number of thinning conducted, slash-removal treatments, and the time interval between last thinning and soil sampling. Our study and the literature indicate that stem-only thinning for wildfire risk reduction and bioenergy production would have little impact on total soil C and N pools. However, more information is needed on the effects of whole-tree thinning regimes on soil C and nutrient contents.


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