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A Comparison of Soil Organic Matter Content in 1932, 1984, and 2005/6 in Forests of the Adirondack Mountains, New York

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We quantified the organic matter content of organic and mineral horizons in 1932, 1984, and in 2005/6 at 54 sites in a mixed hardwood-softwood stand and in northern hardwood (NH), pine-dominated (PW), and spruce-fir (SF) forests of the Adirondack Mountains, NY to determine if there were measurable changes in soil organic matter (SOM) pools over the ~75-yr interval. Further, the different land-use histories of these sites provided an opportunity to evaluate the influence of land-use history on forest SOM since the early 1930s. Overall, there were no significant differences in combined organic + mineral horizon (whole-profile) SOM amounts over the interval. There was, however, a significant increase in whole-profile SOM content between 1932 and 2005/6 at 16 sites that had a history of agriculture or fire which amounted to an increase in C content of approximately 0.5 Mg C $ha^{-1}yr^{-1}$. This indicated that at least some Adirondack forest soils were accumulating C during the 20th century.

Abbreviations: LOI, loss-on-ignition; MSD, minimum significant difference; NC, Newcomb; NH, northern hardwood; OM, organic matter; PW, pine-dominated; SF, spruce-fir; SOM, soil organic matter.

Repeated measures and chronosequence investigations of northeastern U.S. forest soils provide an opportunity to document changes in pools of major plant nutrients associated with the legacy of past disturbances (e.g., Aber and Driscoll, 1997; Compton and Boone, 2000; Johnson and Curtis, 2001). In the Adirondacks, major disturbances since the late 19th century include logging and associated industries, clearing for agriculture, widespread and severe fire, blowdown from windstorms, and severe red spruce (*Picea rubens* Sarg.) mortality in the subalpine SF forests (e.g., Schmitt, 1916; McMartin, 1994; Niering, 1998; Bedison et al., 2007). Given the history of agriculture, fire, logging, and subsequent afforestation throughout the Adirondacks during the past century (e.g., McMartin, 1994), there is the potential that some forest stands in this region have accumulated C in the soil pools during this interval.

Conversion of native forest land to agriculture can deplete SOM stocks by 20 to 50% (Davidson and Ackerman, 1993; Guo and Gifford, 2002), and fire can reduce forest floor organic matter content (e.g., Raison, 1979). Hooker and Compton (2003) used a chronosequence of mixed oak and mixed conifer-softwood stands within the Scituate Watershed, RI to show that total-soil C accumulated in previously cultivated sites for approximately 100 yr after abandonment. Further, Latty et al. (2004) showed that Adirondack old-growth stands had more SOM than did similar forest soils that had been logged and then burned in 1903, thus demonstrating the potential for C accumulation over time in forest soils with a similar land-use history. In contrast, logging by itself typically does not deplete SOM (Johnson et al., 1991; Johnson and Curtis, 2001). It is also unlikely that blowdown or widespread mortality influences large-scale SOM pools, except perhaps to affect local-scale increases in SOM in subsequent decades.

We undertook this study to determine if there were measureable differences in SOM between the early 1930s and 2005/6 in an array of Adirondack forests with different disturbance histories. In this paper we report repeated measurements of SOM at 54 forested sites in the Adirondack Mountains made over a period of ~75 yr. As this represents the longest period of repeated measurements of SOM in forests of the northeastern USA, it maximizes the chance of detecting changes in SOM pools which have very high spatial variability and slow rates of change relative to their size. Given the different disturbance histories in these plots, we predicted that sites subject to logging (only), blowdown, or recent red spruce mortality would not show changes in SOM. We also predicted that the plots with late 19th and early 20th century agriculture or fire history would show increases in SOM over the ~75-yr interval.

MATERIALS AND METHODS

Study Plots

In 1984, Andersen (1988) established the 54 permanent vegetation plots sampled for this study at sites sampled by Heimburger (1933) in the early 1930s. These plots have been described in detail in Andersen (1988) and have been used in several comparative studies of vegetation and soil chemistry (Andersen, 1988; Johnson et al., 1994, 2008; Bedison et al., 2007; Bedison and McNeil, 2009; Bedison and Johnson, 2009). The plots were all located on well-drained upland soils which were Spodosols, occasionally Inceptisols, or Histosols at higher elevations where bedrock was directly overlain by thick organic horizons. Forty of the sites were located across the Adirondack Mountain region and represented typical northern hardwood (NH, n = 20), subalpine spruce-fir (SF, n = 11), and white or red pine-dominated (PW, n = 9) forests (Bedison et al., 2007). The age and size distribution of trees in the NH plots suggested selective logging in the past. While the SF plots were generally inaccessible to 19th and 20th century logging, blowdown, and red spruce mortality have been important disturbances in these sites. Further, as these 40 sites are located on public land in the Adirondack Forest Preserve, they have been protected from logging for about a century. Fourteen additional plots were located on

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private land in a second-growth mixed hardwood-softwood forest near Newcomb, NY (NC) that had been used in the early- to mid- 20th century for thinning experiments, but have remained unmanaged since the early 1950s (Andersen, 1988).

This set of plots afforded an opportunity to determine whether fire or an agricultural history had an effect on 20th century SOM accumulation as several pine plots had charcoal in the soil or were located on abandoned agricultural land ($n = 6$) and some of the NH plots had charcoal in the soil ($n = 10$) indicating past fires. The presence of charcoal was determined by visual identification of macroscopic charcoal particles in excavated material, both in the field or in the laboratory. The remaining NH plots had likely been logged in the distant past and nearly all of the subalpine SF plots were subject to severe red spruce mortality or blowdown during the past three decades. Due to the criteria for locating plots in the original investigation (areas deemed typical of the variety of 'forest types' of the region by Heimburger [1933]), we confine our conclusions to this network of sites. However, we are unaware of any reasons why these plots would be different from a stratified random sample of well-drained Adirondack forest soils.

Soil Sampling

Loose litter (Oi horizon) was brushed away, and Oe, Oa and mineral horizons at each site were qualitatively sampled in 1930 through 1932 (Heimburger, 1933) and 1984 (Andersen, 1988; Johnson et al., 1994) from an exposed pit face. In the summers of 2005 and 2006, a single quantitative pit (*sensu* Hamburg, 1984) was excavated at each of the 54 plots. Organic horizons (Oe and Oa) were subsampled and weighed. Rocks, roots, and mineral soil in the following increments: 0 to 10 cm, 10 to 20 cm, and 20+ cm to the bottom of the rooting zone, which was Andersen's (1988) definition of the bottom of the B horizon, were all weighed.

Because the mineral soil was sampled in 2005/6 as 0- to 10-cm, 10- to 20-cm, and 20+–cm layers but as individual horizons by Heimburger (1933) and Andersen (1988), we pooled SOM measurements from the 1932 and 1984 horizons into the appropriate depth intervals as sampled in 2005/6. As the depth to the bottom of the B horizon varied among years, the 20+–cm depth increment at each site was normalized to the shallowest depth measured in the three studies and only the OM content measured to that depth was compared between dates. Further, some Oa horizons were subsampled as Oa1 and Oa2 horizons in 1932 and 1984. These were pooled into a single measurement as the Oa was sampled in 2005/6 as a single horizon.

All soil samples were processed and analyzed according the methods of Heimburger (1933). Air-dry soils were sieved according to horizon (Oe, 5 mm; Oa, 2 mm; mineral, 1 mm). As a result, we did not include dead roots, buried stems or other large plant parts as part of the SOM pool. Oven-dry mass was obtained by drying 2.0 g of each sample at 95°C for 12h. Soil organic matter concentration (%OM) was determined with mass loss-on-ignition (LOI) by igniting the oven-dry soil at 550°C for 12h. The results are reported on an oven-dry-mass basis in accordance with Heimburger (1933).

The source of data for the 1932 measurements was Heimburger's (1933) appendices. The data for the 1984 study were either reported in Andersen (1988) or were obtained by analyzing archived samples from that study. Due to the small amount of sample available from the 1984 archive, only a limited number of samples ($n = 76$) from the archive were reanalyzed to check for method agreement.

Determination of Soil Organic Matter Mass

Soil bulk density (D_b) is related to the organic matter concentration of forest soils (Curtis and Post, 1964; Federer et al., 1993). Since soil mass was not reported in either Heimburger (1933) or in Andersen (1988), we needed to estimate D_b using available %OM data and horizon thickness measurements from these investigations. We used a polynomial regression to model the relationship between measured %OM and D_b using the 2005/6 data ($R^2 = 0.79$, $P < 0.0001$, $n = 164$):

$$D_b = 0.80–0.013\%OM + 0.00016\ (\%OM-34.61)^2 \quad [1]$$

where D_b is bulk density of the non-rock soil (Mg m^{-3}) and %OM is the organic matter concentration. To determine the D_b for each horizon sampled in 1932 and 1984, we used Eq. [1] and either the reported or measured %OM data from those years. Fundamental to this approach were the assumptions that rock volumes in the mineral horizons, measured in 2005/6, were not different between sampling dates and that the relationship between D_b and %OM has remained constant through time. Soil organic matter content for each horizon or layer in 1932, 1984, and 2005/6 was then calculated as:

$$SOM = 10{,}000\left(\frac{\%OM}{100} D_b T_h\right) \quad [2]$$

where SOM is soil organic matter content (Mg ha^{-1}), 10,000 is the conversion factor between m^2 and ha, %OM is the organic matter concentration, D_b is the bulk density of the non-rock soil (Mg m^{-3}), and T_h is the horizon thickness (m).

Statistical Analyses

Univariate linear regression was used to compare the 1988%OM analysis results (Andersen, 1988) with those obtained in a reanalysis of archived samples from that investigation conducted as part of the current investigation.

We used paired comparison tests to evaluate the significance of differences in SOM content between sampling dates. We used a Shapiro-Wilk test to determine if the data were normally distributed. Data that were normally distributed, either untransformed or $\log_{10}$ transformed, were compared using a paired *t* test. A Wilcoxon's signed-ranks test was used when data were not normally distributed. Since the majority of data were not normally distributed due largely to the presence of 0's, primarily from the SF plots where organic horizons overlie bedrock, we report median values. The minimum significant difference (MSD), which represents the minimum change necessary to detect a significant change in mean SOM storage between the sampling dates, was calculated following Sokal and Rohlf (2001). All data were analyzed with JMP (v 7.0.1, SAS Institute, Cary, NC; $\alpha = 0.05$) and statistical significance was evaluated at $P \leq 0.05$.

RESULTS AND DISCUSSION

Reanalysis of Archived Samples

New analyses of archived 1984 samples ($n = 76$) were highly correlated ($R^2 = 0.99$, $P < 0.0001$) with the original analyses reported in Andersen (1988). Both investigations used the same method as reported in Heimburger (1933) and we did not expect that there would be any influence of storage on %OM of the archived samples. Accordingly, as indicated by the high R^2 value, the new analyses revealed that there was little difference in %OM between the two investigations. Due to the small amount of sample available from the 1984 archive, not all of the 1984 samples were reanalyzed. However, the strong correlation between the samples that were reanalyzed suggested that there was no measurable influence of storage on %OM in this set of forest soil samples. Further, these results suggest that comparisons of SOM between Heimburger (1933), Andersen (1988), and the current investigation were viable.

Pooled Data

Considering all 54 plots, the organic horizon (Oe + Oa) SOM content was significantly lower in 2005/6 than in either 1932 or 1984, which were not different (Table 1). The median organic horizon SOM content was ~18 Mg ha^{-1} less in 2005/06 than it was in the early 1930s. Given that median SOM content in the top 20 cm of mineral soil in 2005/6 was about 19 Mg ha^{-1} greater than in 1932 and the total mineral horizon SOM pool was significantly larger in 2005/6, the differences in organic and mineral horizon SOM were most likely due to sampling differences among the three different investigations (see Federer, 1982; Yanai et al. (2000) for similar findings). Another, less likely reason for the low organic horizon SOM mass in 2005/6 might have been procedural differences in the way the Oi horizon was removed before sampling. We cannot rule out a vertical redistribution of SOM from organic to the upper mineral horizons, but we are unaware of any reasons why this may have occurred.

Most importantly, the median whole-profile SOM contents for the pooled data were not significantly different across the three studies and were nearly identical in 1933 and 2005/6 (Table 1). The lack of overall change is in agreement with a meta-analysis of forest management practices and soil C storage (Johnson and Curtis, 2001). Logging was extensive throughout the Adirondacks until the early 20th century but forest harvesting has little effect on soil C storage (Johnson et al., 1991; Johnson and Curtis, 2001). Most of the sites in this investigation, especially the NC and NH sites, were in areas with a history of logging without fire, thus the lack of change in whole-profile SOM content was not unexpected (Table 1). As an approximation of the magnitude of change in SOM necessary to detect a significant difference, the minimum significant difference (MSD) necessary to detect a change in mean SOM content was 35 Mg ha^{-1}, or about 11% of the mean whole-profile SOM content.

Influences of Past Disturbance and Forest Type

We stratified the data by forest type and by land-use histories to evaluate temporal changes in forest soils in this network of plots as the different forest types have different land-use histories and various past land uses (e.g., fire and agriculture) have been shown to influence SOM dynamics. We were able to determine from the presence and vertical distribution of charcoal, and the presence of plowed horizons that the NC, NH, SF, and PW plots had different past disturbances. Charcoal in the profiles of 10 NH plots indicated past fire history. Of the nine PW plots sampled for this study, six were judged to have either an agricultural or fire history, one was thought to have no evidence of either agriculture or fire, one had an undetermined history, and one had substantially different horizons in 1932 and 2005/6 making proper interpretation difficult. Considering only these NH and PW sites with evidence of past fire or agriculture (n = 16), whole-profile SOM content increased significantly (P = 0.05) between 1932 and 2005/6 (Fig. 1). Assuming that 50% of the SOM mass was C, whole-profile C accumulated at an average rate of 0.50 Mg C ha^{-1}yr^{-1} between 1932 and 2005/6 in those sites.

Whole-profile SOM content in the nine PW plots was not significantly different over the ~75-yr interval (Fig. 2). Considering only the six PW plots with a clear agricultural or fire history, our comparisons indicated a trend toward increased whole-profile SOM content, though it was not significant (P = 0.3). Using the same assumptions described previously, the rate of C increase in those sites between 1932 and 2005/6, 0.40 Mg C ha^{-1}yr^{-1}, was consistent with the results of several studies in similar northeastern U.S. forests. In white pine (*Pinus strobus* L.) stands with an agricultural history in Rhode Island, Hooker and Compton (2003) reported that C accumulated at a rate of 0.52 Mg C ha^{-1}yr^{-1} during 115 yr of regrowth. Further, Gaudinski et al. (2000) measured a C accumulation rate of 0.34 Mg C ha^{-1}yr^{-1} in a mixed hardwood-conifer stand in the Prospect Hill Tract in the Harvard Forest between the late 1800s and 1996. Between 1984 and 2005/6, soil C gains were small in the six PW sites sampled here and the C accumulation rate was low (0.24 Mg C ha^{-1}yr^{-1}), which suggested that future C accumulation in these soil pools will likely be small.

The NH stands sampled here were generally accessible for logging and the age and size distribution of the trees suggested, at a minimum, selective logging at many sites. In NH plots, the median organic horizon and whole-profile SOM contents were nearly identical among years (Fig. 2). However, there are substantial areas of NH forest in the Adirondacks that were burned in the early 20th century (e.g, Schmitt, 1916; McMartin, 1994) which may show an increase in SOM over time (e.g., Latty et al., 2004). We found a marginally significant (P = 0.1)

Table 1. Median soil organic matter content (Mg ha^{-1}) for each sampling year for the pooled sites (n = 54). Years for a given horizon not sharing the same letter are significantly different ($P \leq 0.05$) as determined with either a Wilcoxon's signed-ranks test or a *t* test. A Wilcoxon's signed-ranks test was used when the data were not normally distributed. A *t* test was used when either transformed or log transformed data were normally distributed.

Horizon	1932	1984	2005/6
Oe†	27.1 a	37.9 a	22.2 b
Oa‡	71.5 a	70.1 a	63.8 a
Total Organic‡	105.7 a	113.5 a	88.3 b
0–10 cm†	60.0 b	73.6 a	70.1 ab
10–20 cm†	58.1 b	80.6 a	67.6 ab
20+ cm†	34.0 a	61.6 a	68.5 a
Total Mineral§	170.0 b	216.9 a	218.1 a
Whole-Profile†	322.7 a	374.3 a	321.8 a

† Wilcoxon signed-ranks test on untransformed data.

‡ *t* test on log transformed data.

§ *t* test on untransformed data.

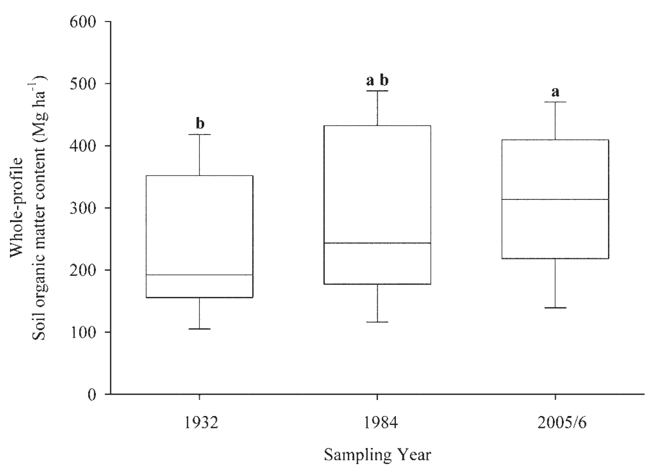

Fig. 1. Whole-profile soil organic matter content (Mg ha^{-1}) in sites with an agricultural or fire history (n = 16). The boxes represent the upper and lower quartiles while the bars in the center show the median. The whiskers represent the 5th and 95th percentile of the data. Years not sharing the same letter are significantly different ($P \leq 0.05$).

increase in whole-profile SOM content between 1932 and 2006 in the 10 NH plots with evidence of past fire or agriculture. Over this interval, C accumulated at a rate of 0.56 Mg C $ha^{-1}yr^{-1}$. This apparent rate of soil C increase seems reasonable given the results of similar studies, and that combined C inputs to soils from litterfall, root turnover, and coarse woody debris at the Huntington Forest in the central Adirondack Mountains was 2.6 Mg C $ha^{-1}yr^{-1}$ (Mitchell et al., 1992).

The SF sites were high-elevation (> 800 m) stands with deep organic horizons over a thin mantle of glacial till, bedrock, or congelifract that were inaccessible to 19th and 20th century loggers. In recent decades, severe red spruce mortality and blowdown have been active disturbances in most of these plots (e.g., Battles et al., 1992; Bedison et al., 2007) and there are currently large amounts of downed timber that will likely have an impact on future SOM and nutrient pools in these forests. While widespread red spruce mortality is a more recent disturbance than blowdown, the presence of stumps and logs buried in the organic horizons of these sites indicated a long history of natural disturbances and canopy turnover. These factors have created a large amount of variability in soil thickness and composition in these forests. As a result, the range of SOM mass in both organic and mineral horizons was so large (e.g., Fig. 2) that meaningful interpretation of temporal differences was difficult given the small number of plots.

There were no differences in whole-profile SOM content between 1932 and 2005/6 in the NC plots (Fig. 2). Interestingly, compared with the NH plots having similar tree species, the NC plots had larger organic horizon SOM pools, > 500 Mg ha^{-1}. Relative to the NH plots, eastern hemlock (*Tsuga canadensis* (L.) Carrière) was more abundant in a number of the NC plots and this was likely responsible for high values of SOM in the NC plots as the recalcitrant nature of eastern hemlock litter would promote larger SOM pools.

CONCLUSIONS

Measurements of the SOM content in Adirondack forest soils over seven decades suggested that overall, the soils of this region had not been a strong sink for C during the 20th century. For the pooled data, comparisons of organic and mineral horizon SOM contents showed few differences that could not be explained by procedural differences arising from the separation of organic horizons and mineral soil in the field.

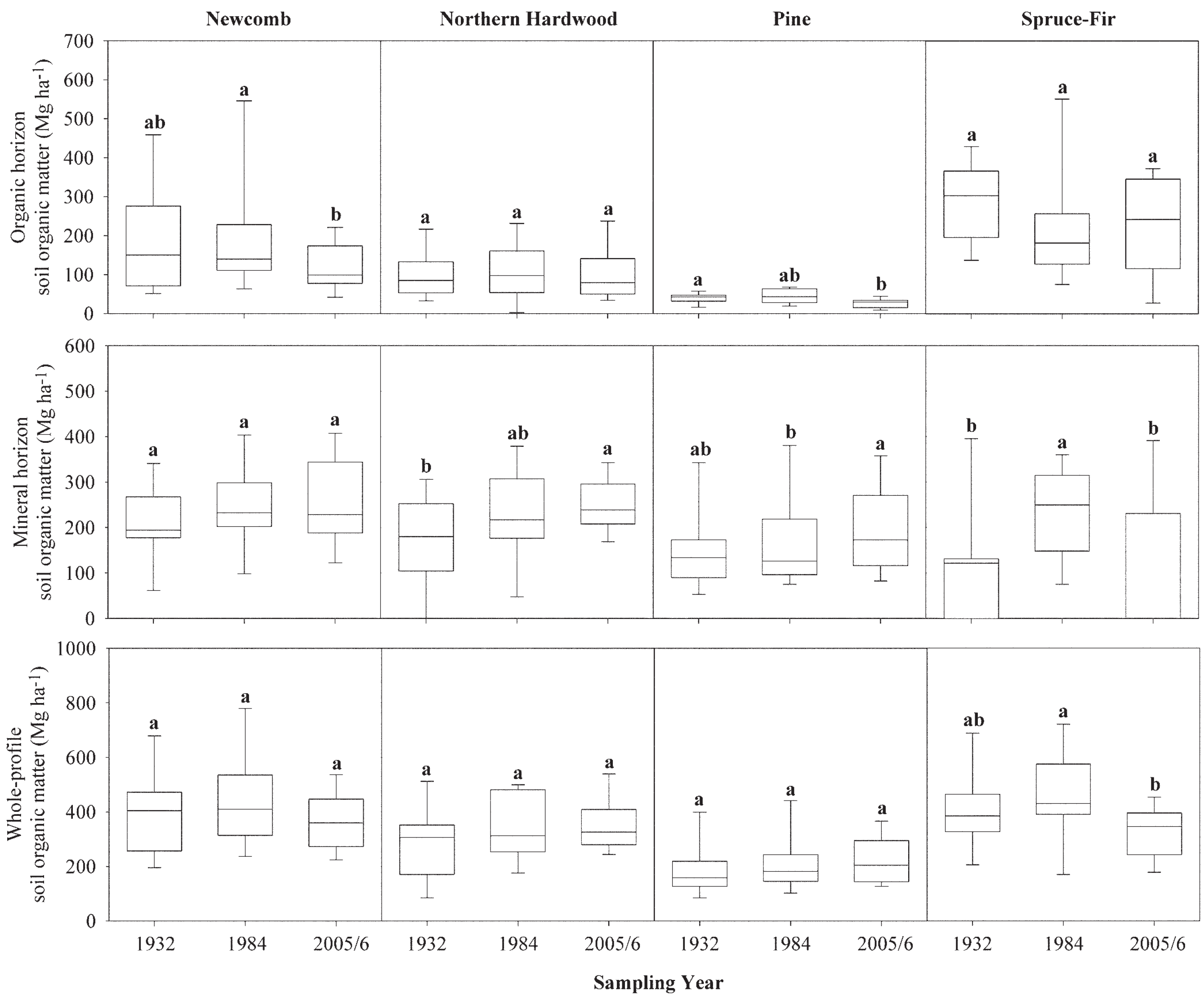

Fig. 2. Soil organic matter content (Mg ha^{-1}) in organic (top row), mineral (middle row), and whole-profile (bottom row) pools in Newcomb, northern hardwood, pine, and spruce-fir plots. The boxes represent the upper and lower quartiles while the bar in the center represents the median. The whiskers represent the 5th and 95th percentile of the data. Years not sharing the same letter are significantly different ($P \leq 0.05$) as determined with either a Wilcoxon's signed-ranks test or a paired *t* test.

There was, however, evidence of a trend toward increased whole-profile SOM content between 1932 and 2005/6 in plots with an agricultural or fire history, and the rates of C increase were similar to rates determined for similar conditions in other forests in New England. The large areas of northern hardwood and mixed forests that were cut over and burned nearly a century ago (McMartin, 1994) were probably a strong sink for C during the 20th century, and some of the net accumulation occurred in the soil. Subalpine spruce-fir forests constitute only a small fraction (<1%) of the Adirondack Park (McMartin, 1994) and while the soils in those forests can contain substantial amounts of SOM (>500 Mg ha^{-1}), it would be difficult to measure changes in SOM pools in these forests without a much greater sampling intensity.

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