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Brief Communication

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Partial Harvest Effects on the Forest Floor at Four Northern Hardwood Sites in the Green Mountains of Vermont, USA

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Abstract

Harvesting activities are known to decrease forest floor carbon pools, but the response varies with harvest intensity. We examined partial harvesting (33–55% of basal area removed) effects on the forest floor at four northern hardwood sites in Vermont, USA. Six baseline quantitative samples were taken at each site and 9–36 new locations were sampled 1.5–2.6 years after harvesting. Forest soil disturbance was estimated, and basal area was tallied pre- and post-harvest. The forest floor consisted primarily of Oi and Oe horizons. The pre-harvest site means in carbon stock ranged from 6.8 to 12.3 Mg ha^{-1} and were not significantly different after harvesting. The pre-harvest site means in depth ranged from 2.8 to 4.5 cm and, post-harvest, there was significantly decreased thickness at one site and significantly greater density at two sites postharvest. This compaction was also visually observed in the field. Partial harvesting, which included single-tree and group selection, created highly variable conditions that challenged our experimental design. However, the two sites with the higher number of resampling locations (35–36) had relatively low variability in forest floor metrics and showed significant responses in thickness and density. Continued monitoring is needed to determine long-term trends.

Keywords: soil carbon, forest harvest, partial harvest, thinning, forest soil disturbance, carbon sequestration

The impact of forest management on soil carbon has been the subject of recent reviews (Ameray et al. 2021; Mäkipää et al. 2023; Mayer et al. 2020) and meta-analyses (Achat et al. 2015; James and Harrison 2016; James et al. 2021). There are myriad interacting factors that affect the gain or loss of carbon and a new focus on regional studies has provided a more site-specific understanding (Nave et al. 2021, 2022a, 2022b). The impact of harvesting on soil carbon status appears to be somewhat dependent on intensity, that is, clearcut versus partial harvesting, but also influenced by soil order, parent material, and forest cover type (James and Harrison 2016; Nave et al. 2021). Most meta-analyses find that harvesting activities can result in the loss of soil carbon, especially in the forest floor. Partial harvesting approaches can result in lower losses and in some cases, even enhanced carbon sequestration (Mäkipää et al. 2023; Mayer et al. 2020).

Deforestation in the northeastern USA peaked in the mid-nineteenth century, with much of the cleared land allowed to reforest in the early-to-middle twentieth century (Cogbill et al. 2002). Recent silvicultural practices include strategies to create more uneven-aged stands that are expected to provide ecosystem services beyond wood products (D'Amato et al. 2014). This approach uses partial harvests that can include both single-tree and small-group selection (Leak et al. 2014). Since 2003, these partial harvests have comprised 32–36% of the harvesting activity in Massachusetts, New Hampshire, New York, and Vermont (Belair and Ducey 2018). Studies specifically on the effect of partial harvesting on soil carbon in this region are relatively few and most report high variability (Hoover 2011; Puhlick et al. 2016; Warren and Ashton 2014). This study sampled the forest floor preharvest and approximately two years after partial harvesting at four upland sites in Vermont to determine whether there were any changes in carbon stocks and in the physical properties of the soil (forest floor depth, weight, and density).

Methods

The four sites (figure 1) are a parcel owned by the Atlas Timberland Partnership (SQU); Sterling Forest (STE), the town forest of Stowe; PCB in Coolidge State Forest; and NFS in the Green Mountain National Forest. Elevation ranged from 490–650 m. Tree species were predominately sugar maple (*Acer saccharum* Marshall), and soils were primarily Haplorthods and Dystrudepts in USDA Forest Service (Forest Service) taxonomy (Soil Survey Staff 2022), (Table 1). Prior land use at SQU was a farm woodlot until 1960 whereas the other three sites were pasture through 1940–1950 (Ross et al. 2021).

The plot design was adapted from the Forest Service Forest Inventory and Analysis (FIA) (USDA Forest Service 2005). Pre-harvest (Ross et al. 2021), six sampling points were located every 60° from magnetic north at 27.4 m from the plot center (figure 2). Post-harvest, 9–36 new points were established along the same circumference, relocated via a

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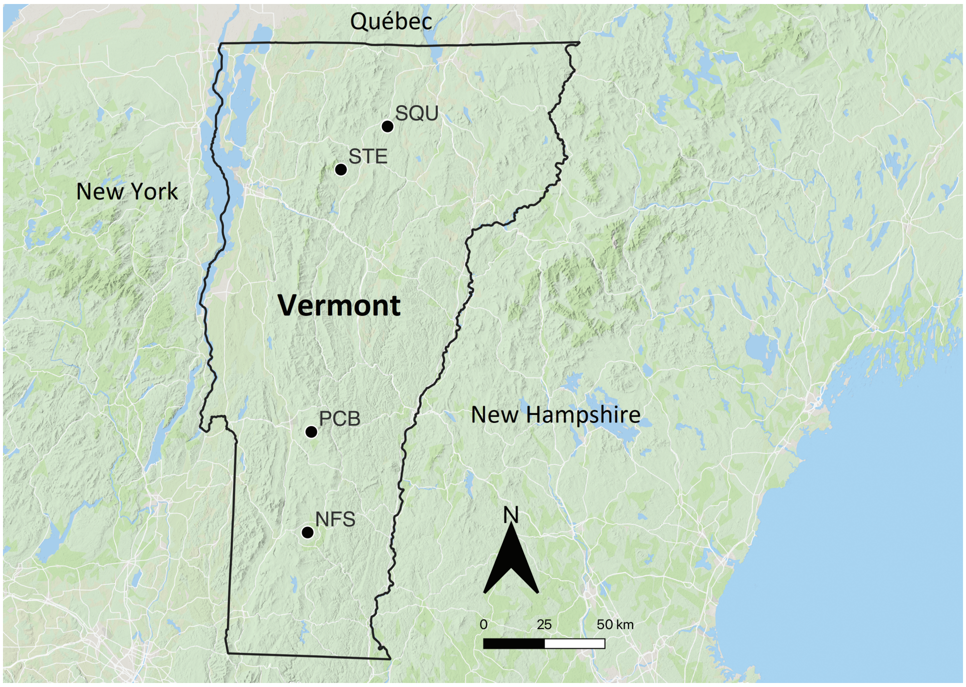

Figure 1 Location of the four sites near the main ridge of the Green Mountains in Vermont. Sites are SQU (Atlas Timberland Partnership parcel), STE (Sterling Forest, Town of Stowe), PCB (Coolidge State Forest parcel), and NFS (Green Mountain National Forest parcel).

Table 1. Site characteristics including elevation, tree species ≥ 5 cm dbh, and soil subgroup (Soil Survey Staff 2022).

Site	Elevation	Tree species	Soil series	Soil subgroup
	(m)	(% of basal area)		
STE	528	87% sugar maple (*Acer saccharum* Marshall)	Colonel	Aquic Haplorthods
		8% yellow birch (*Betula alleghaniensis* Britton)	Fullam	Oxyaquic Dystrudepts
		4% American beech (*Fagus grandifolia* Ehrh.)	Peru	Aquic Haplorthods
NFS	493	43% sugar maple, 22% red maple (*Acer rubrum* L.)	Marlow	Oxyaquic Haplorthods
		17% paper birch (*Betula papyrifera* Marshall var. *cordifolia* (Regel) Fernald), 16% red spruce (*Picea rubens* Sarg.)	Peru	Aquic Haplorthods
PCB	651	54% sugar maple, 20% white ash (*Fraxinus Americana* L.)	Colonel	Aquic Haplorthods
		17% yellow birch, 8% American beech	Peru	Aquic Haplorthods
SQU	589	97% sugar maple, 8% white ash	Buckland	Aquic Humudepts
		2% yellow birch	Shelburne	Oxyaquic Dystrudepts

permanent center stake, to provide a broader representation of the plot needed due to the uneven harvesting activity. These were evenly spaced, except for PCB, where the resampling points were biased somewhat to the north because the southern tip of our plot was unintentionally outside the harvest boundary (figure 2). The fewer post-harvest samples taken at PCB (12) and SQU (9) were because of a lack of resources. Forest floor samples were obtained using a 15 × 15 cm frame and collecting the entire Oi, Oe, and Oa horizons. These layers were collected and analyzed separately, but data were combined and results presented as the "forest floor" because some horizons were too thin to be successfully separated, resulting in some combined Oi/Oe and Oe/Oa samples. Any woody debris on top of the Oi was not collected. Pre-harvest, three replicates at each of the six points were obtained within ~1 m of each other and averaged before statistical analysis. Post-harvest, a disturbance class code was assigned to each point using the Forest Service Disturbance Monitoring Protocol of Page-Dumroese et al. (2009). Codes ranged from 0 (no visible impact) to 3 (severe impact) and are further described in Supplemental Table S1. In each of the four vegetation subplots (figure 2), both pre- and post-harvest, all trees with a dbh (137 cm) of ≥5 cm were tallied by species. The time interval varied somewhat between harvest and sampling (Table 2).

The prescribed silvicultural treatment at STE was variable density thinning with canopy gap creation, following guidelines in Hagenbuch et al. (2011). The NFS site was prescribed single-tree selection with groups to both remove poor-quality growing stock and move towards a balanced age-class distribution. The PCB and SQU sites both also used single-tree and group selection to move towards an all-age condition. At STE, felling was by hand chainsaw and only a cable skidder was used. At the other sites, harvesting equipment was a tracked feller buncher, grapple skidder, and cable skidder. Equipment was used during the winter months when the presence of snowpack could minimize soil compaction. Harvests at all sites removed merchantable sawlogs and fuelwood/pulpwood, leaving remaining branch tops and slash onsite. In addition to tree removal, a new logging road (3.5 m width) was installed through the PCB site (figures 2 and S1).

The horizon samples were oven-dried at 60°C and any rock fragments, roots, or woody debris greater than ~0.5 cm diameter, if present, were removed before weighing. Samples were then finely ground and redried, and carbon was determined by an elemental analyzer in duplicate or triplicate. Individual horizon results were summed for each square to give the forest floor weight, depth, and carbon stock (or pool, Mg ha^{-1}). "Rough" density was calculated from these totals and so termed because the field thickness measurements were not considered precise and the volume of the occasional rock fragment, root, or woody debris was not accounted. One postharvest point from STE had unusually thick horizons and a carbon stock that was 4.9 standard deviations above the mean; because of the potential for this outlier to mask an overall decline in carbon stock, all data from this point were omitted. At PCB, sampling points either had a high-carbon A horizon or a relatively low-carbon Oa horizon but not both (i.e., the carbon varied above and below the defined changepoint of 200 g/kg [Soil Survey Staff 2022]). Because of their uneven distribution, these Oa horizons were not included in the analysis.

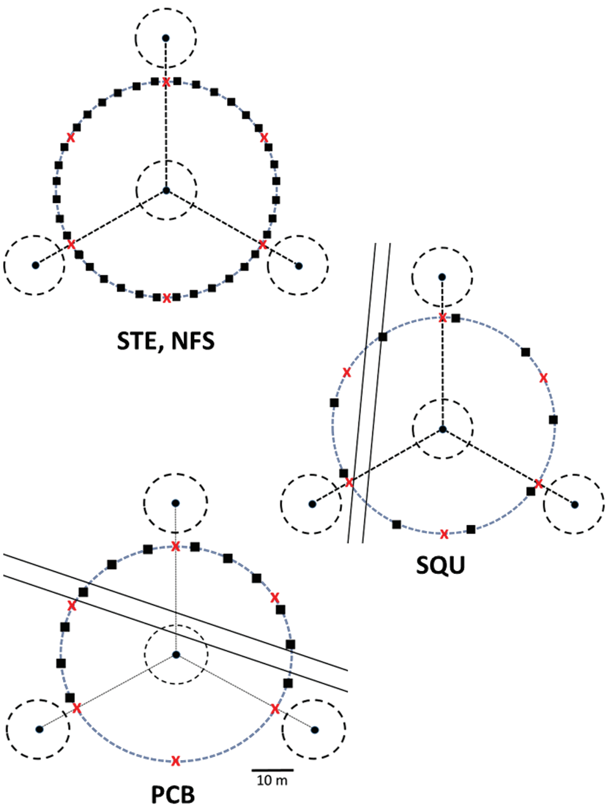

Figure 2 Plot layout at the four sites modeled on the Forest Inventory and Analysis Program (USDA Forest Service, 2005). Small dashed circles are the typical subplots for tallying overstory trees. The X's denote original forest floor sampling points and solid dots are the resampling points. The logging road through the PCB site was new and the road through SQU was old and not improved.

Because of the unbalanced design—that is, different numbers of replications—a simple analysis of variance was not appropriate and a general linear model was used instead (PROC GLM in SAS 9.4, SAS Institute 2016). All sites were combined to avoid error inflation and the two classes were site (1-4) and time (1-2). To ensure normal distribution of residuals and homogeneity of variance, the test variables carbon, depth, and rough density were square-root-transformed (weight did not need transformation). Because of the unbalanced design, F-tests for type III sums of squares were used to determine whether there were significant effects. If there was a significant interaction between site and time ($p < 0.05$), simple effects were estimated at each site as the least squared mean difference of the transformed variable pre- and postharvest. Documentation for this approach can be found in the SAS User's Guide (SAS Institute 2018) and recent texts on statistical methods (e.g., Montelpare et al. [2020]).

Results

The pre-harvest live basal area ranged from 28.4 m^2 ha^{-1} at PCB to 33.8 m^2 ha^{-1} at NFS (Supplemental Table S2). Harvesting removed an average of 41%, 55%, 33%, and 54% of the live basal area at STE, NFS, PCB, and SQU, respectively. Because of the patchy nature of the harvest (Supplemental figures S1 and S2), this was highly variable among the four vegetation subplots at each site (figure 3). The amount of basal area loss in individual vegetation subplots ranged from a low of 0–29% across the four sites to a high of 79–98% (Supplemental Table S2). The mean site disturbance classes were 1.3, 0.7, 0.4, and 1.2 for STE, NFS, PCB, and SQU respectively. Disturbance class 1 is defined as having some evidence of compression but with the forest floor still intact and no evidence of mixing with the mineral soil (Page-Dumroese et al. 2009). The STE site had a fairly extensive network of skid trails that was captured by nine of the 36 sampling points. One of the nine sampling points at SQU was in the existing logging road and, along with one other

Table 2. Dates of soil sampling, tree measurements, and harvest.

Site	Preharvest soil sampling	Preharvest tree tally	Harvest	Postharvest soil sampling	Postharvest tree tally	Harvest to 2nd sampling, years
STE	May 2008	May 2008	Fall/winter 2008/09	June 2011	July 2011	2.5
NFS	July 2009	November 2009	Winter 2009/10	July 2011	August 2011	1.5
PCB	June 2009	June 2009	Winter 2013/14	September 2016	August 2016	2.6
SQU	August 2008	August 2008	Winter 2013/14	October 2015	July 2016	1.8

sampling point, was put in disturbance class 3, both showing rutting and erosion. Disturbance class 0 (no evidence of compaction) was the most assigned category at both the NFS and PCB sites (Supplemental Table S1) and is reflected in their low means. Although the PCB site had a new logging road installed, only one sampling point was located on it and little disturbance was evident beyond the width of the road (3.5 m).

There were no significant differences ($p < 0.05$) pre- versus post-harvest in either the carbon stock (Mg ha^{-1}) or weight of the forest floor (Table 3, Supplemental Table S3). The results trended in both directions but the differences in carbon were < 10% at both STE and PCB. There was a significant decrease ($p = 0.017$) in the depth of the forest floor at STE. This was accompanied by a significant three-fold increase ($p < 0.001$) in rough density. There was also an almost two-fold increase in rough density at NFS that was significant ($p = 0.012$), although there was a nonsignificant upward trend in weight and a downward trend in depth (Table 3, Supplemental Table S3). The increase in density was supported by the disturbance classification (Supplemental Table S1).

Discussion

A recent meta-analysis specifically on thinning effects (Zhang et al. 2018) found that "moderate" thinning, defined as 33–65% removal of basal area or stems, had no effect on soil carbon. This is consistent with our findings, as our site average basal area removed ranged from 33% to 55%, although the group selection cuts created a much broader range among the individual vegetation subplots (0–98%). More general meta-analyses of harvesting effects have shown a significant decrease in forest floor carbon ranging from 22% loss (Achat et al. 2015) to 30% loss (James and Harrison 2016). Post-harvest loss of carbon from the forest floor has been ascribed to two processes: increased decomposition from exposure-related increased soil temperature and decreased inputs from lack of litter (Mayer et al. 2020). The slash, along with a rapid regrowth of the undergrowth, may have minimized the latter. Further, Brooks and Kyker-Snowman (2008) found only a minor temperature increase (<1°C) after partial harvests in southern New England. There can also be increased erosional losses both from traffic damage, for example, rutting and soil compaction that increase overland flow (Puhlick and Fernandez 2020). The relatively minor evidence of disturbance and erosion at the four sites is likely the result of winter harvesting on a snowpack that should limit compaction and rutting. We also explored possible spatial effects of exposure and disturbance at STE, looking at each sampling point's canopy closure, disturbance class, and distance to a skid trail, but no patterns emerged relative to forest floor carbon. The effect of forest harvesting in this study may be too subtle to observe, especially relative to other drivers of forest floor change, such as prior land use and the presence or absence of earthworms (Ross et al. 2021).

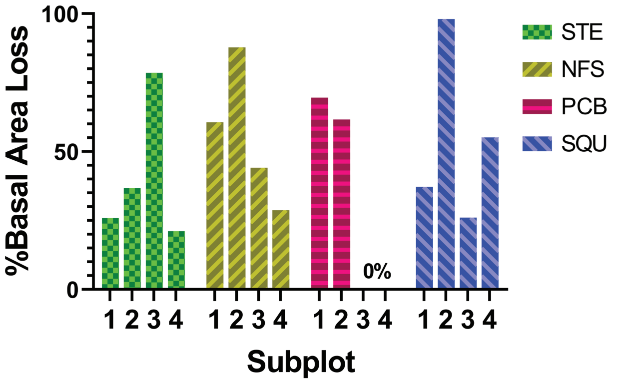

Figure 3 The percentage of live basal area lost from each subplot postharvest, calculated from the preharvest measurement and postharvest missing stems.

Our study has a few limitations that need acknowledgement. First, we only had one plot at each of the four sites and we cannot draw general conclusions about the entire harvested area. Second, our sampling design may have not fully captured the impacts of harvesting activity because of the innate variability in forest soils and the pattern of the single-tree and small-group selections. This was more likely a problem at the two sites with a lower postharvest sample n (PCB and SQU). Finally, our data are a snapshot in time and continued sampling may be needed to discern any change.

Studies of soil carbon losses from repeated partial harvesting activities have found mixed results (Jurgensen et al. 2012) but there may be a greater impact on the forest floor (Reátegui et al. 2021). Future harvesting activities may result in greater carbon losses in our region because climate change has lessened

Table 3. Forest floor carbon, weight, depth, and rough density at the four sites pre- and post-harvest. Std err is the standard error of the mean. Pairs of pre- and postharvest results in bold were significantly different at a site ($p < 0.05$).

Site/time	Sample	Carbon		Weight		Depth		Rough Density	
	n	Mean	Std err	Mean	Std err	Mean	Std err	Mean	Std err
		(Mg ha^{-1})		(Mg ha^{-1})		(cm)		(Mg m^{-3})	
STE-pre	6	6.8	1.2	14.4	2.5	**3.83**	0.46	**0.037**	0.004
STE-post	35	7.1	0.7	18.6	1.8	**2.13**	0.26	**0.117**	0.010
NFS-pre	6	10.7	0.8	25.2	1.6	4.33	0.54	**0.062**	0.005
NFS-post	36	13.2	1.1	34.1	2.8	3.28	0.27	**0.112**	0.007
PCB-pre	6	12.3	1.7	29.4	3.9	4.53	0.78	0.070	0.007
PCB-post	12	11.2	1.8	24.7	3.8	5.10	0.89	0.086	0.024
SQU-pre	6	7.0	0.6	16.3	1.3	2.81	0.38	0.065	0.010
SQU-post	9	4.4	0.9	10.0	2.0	2.85	0.81	0.044	0.004

the likelihood of winter conditions that can lessen the impact of traffic (Puhlick and Fernandez 2020). As observed by Mayer et al. (2020), the effect of harvesting on soil disturbance and carbon loss can vary not only with harvesting method and soil type but with soil moisture conditions at the time of harvest and even the approach of individual equipment operators. Our results support the concept that although some degree of soil disturbance may be inevitable, it does not necessarily have to lead to soil carbon losses.

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Conflict of Interest

The authors have no conflicts of interest to declare.

Supplementary Materials

Supplementary data are available at *Forest Science* online.

Supplemental Table S1: Forest Disturbance Monitoring code information.

Supplemental Table S2: details of the data shown in figure 3.

Supplemental Table S3: example SAS code and SAS output.

The two supplemental figures provide aerial imagery pre- and post-harvest.

Supplemental Data Excel file: all the compiled data used in this article, including forest floor metrics, basal area, and disturbance codes.

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