CHANGES IN SOIL ORGANIC CARBON CONCENTRATION AND QUANTITY FOLLOWING SELECTION HARVESTING

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ABSTRACT.—Timber harvesting operations are known to influence the physical properties of forest soils, especially soil density. However, changes in soil chemistry also may occur as a result of perturbation. Two selection harvests were monitored— one using skidders and one using draft animals— to compare changes in soil organic carbon (SOC) 9 to 12 months following harvest operations. Bulk density changes also were measured, so that changes in SOC mass could be quantified. Minimal soil compaction in primary and secondary skid trails for both harvesting systems was observed, but the extent of soil compaction and scarification differed by a factor of three between systems. Furthermore, compaction from soil sampling confounded precise quantification of skidding compaction. Carbon concentrations were not different between skid trails and control areas on either site when surface and subsurface horizons were considered, but carbon content was higher in the subsurface horizons of the animal-skidded site. SOC quantities increased negligibly in the skid trails of both sites, which was likely due to decomposition of fresh logging slash in contact with scarified soil. Higher bulk densities and lower rock contents in skid trails compared with controls also may have contributed to the increased carbon content per unit volume, since coarse fragments accounted for 20 to 40% of sample volume on both sites.

Introduction

Maximizing private and societal benefits from forest resources often involves timber management. However, some forest management policies limit or prohibit harvesting in sensitive or recreational areas. While the use of low productivity harvesting systems, such as animal skidding, is not appropriate for large-scale timber production, there is a niche market in many states for such operations. Furthermore, if animal skidding does reduce the negative soil impacts associated with logging, it may be possible and preferable to permit logging in forest tracts not well suited for mechanical logging.

Public concern for perceived environmental degradation and forest mismanagement often has been based on the visual or aesthetic changes to forest ecosystems; however, unseen changes due to disturbance may be of greater significance for the long-term sustained productivity of the ecosystem. Traditional forest harvest techniques have the potential to reduce site productivity through nutrient loss and altered soil properties (Reisinger and others 1992). Off-site environmental degradation following timber harvesting may result from nutrient and sediment loading of perennial drainage networks. Soil erosion occurs for several years after harvesting, so the effects of timber harvesting in deciduous forests are best summarized in reviews of long-term research (Likens and others 1977, Swank and Crosley 1988).

To address public concerns about timber harvesting, public land management agencies such as the USDA Forest Service and the Missouri Department of Conservation have started to emphasize the use of selection harvesting techniques instead of clearcuts. Selection cutting offers promise for reducing the losses of soil and soil nutrients, but the dynamics of soil organic carbon [SOC] cycling are unknown under selection cutting regimes. By examining the effects of disturbance on SOC, it will be possible to better model the relationship of ecosystem perturbation with site productivity and global climate change (Anderson 1992, Schlesinger 1990).

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Soil organic matter and soil compaction are perhaps the most important determinants of future forest productivity. Understanding the interrelationships of these key parameters is essential to preserving ecosystem integrity (Powers and others 1990). Data on the cycling of carbon under selection harvesting schemes are needed to provide information on the magnitude, distribution and dynamics of the SOC pool. Quantifying soil organic matter in forested ecosystems is difficult because of the number of factors affecting its distribution.

Temporal and spatial heterogeneity within natural systems can be large (Wilding and Drees 1983). Separating spatial from temporal variability is difficult and is dependent upon scale, techniques and perspectives (Anderson 1972, Hammer and others 1987). Furthermore, the quantification of SOC pools is confounded by difficulties in the measurement of bulk density, especially in soils with high coarse fragment contents (Kern 1994). While skeletal or near-skeletal soils present problems for bulk density determination, there also is some evidence that the concentration of SOC may be higher in soils with high coarse fragment contents (Schaetzl 1991).

A factor that confounds our understanding of harvest impacts on SOC is that most published studies of soil organic matter report results as concentrations instead of quantities. Brandt (1993) conducted an exhaustive review of literature and concluded that very little of the SOC literature was conducted with sufficient rigor or reported in usable units for estimating the magnitude of soil carbon pools. Understanding impacts of various sources of carbon upon global climate requires more precise knowledge of pool sizes or quantities. In this study, SOC quantities were determined for both surface and subsurface mineral soils. Additionally, the sampling scheme permitted extrapolation to broader landscapes on the basis of the percentages of areas represented by different geomorphic surfaces of similar soils and landscapes in the region.

The primary objective of this study was to quantify the change in SOC following selection timber harvests. Based on the characterization of soil samples from two upland Missouri Ozark sites, changes in the amount of SOC was determined, and the data are now part of a larger database for modeling changes in the global climate. Specific objectives were: 1) to determine if the quantity of SOC and the soil bulk density changed following selection harvesting, and 2) to determine if the use of alternative harvesting techniques reduced or eliminated changes in SOC and bulk density that would have negative effects on future forest productivity.

Study Areas

This study was installed on two upland oak/pine forest sites in Wayne and Reynolds counties of southern Missouri. Soil survey data are not available for these counties; however, the soils in both areas were formed in limestone residuum. Summit positions consisted of soils formed primarily in Roubidoux geologic strata minerals, and midslope and footslope position soils were formed in Gasconade deposit parent materials. A thin loessial veneer was noted on both areas, and footslope positions had a thicker silty textured surface horizon as a result of the movement of the original loess deposits from summit and shoulder positions to footslope positions. The soils on both sites were rocky, and chert (SiO_2) fragments were ubiquitous both on the soil surface and in the subsurface.

Both sites were under an uneven-aged management regime, which incorporated both group and individual tree selection harvests for natural stand regeneration. The group selection areas provided 70' openings in the canopy to encourage regeneration of shortleaf pine (*Pinus echinata* Mill.), and individual-tree selection was used between the group openings for stand improvement. The sampling areas within each of the timber sales were approximately 20 acres in size which was large enough to establish plots across multiple landscape positions. One of the study sites was logged using conventional rubber-tired cable skidders, and the other site was logged using mules to skid logs, since logging with draft animals is purported to be a low-impact alternative harvesting system. The logs skidded using mule power were ground skidded without a sulky to lift the front end of the log. Conversely, most of the logs skidded by the cable skidder did have the lead end of the log elevated during skidding.

Methods

To address potential differences in site and stand conditions between the two study/harvest areas, pre- and post-harvest forest inventory measurements were taken using six 0.8–acre rectangular plots that encompassed all of the major landforms within the sites. The inventory data were used to determine the intensity of harvest and residual stocking on each study site. These measurements were essential for interpreting treatment responses on both the animal and rubber-tired skidded sites, since both types of operations cannot exist in the same stand. A Wilcoxon rank test was performed to compare the medians of plot measurements between the two study sites. These fixed area plots also were used to calculate the percent of soil area disturbed during harvesting.

Most soil properties are not normally distributed (Young and others 1993), so Hammer (1991) and Daniels and Hammer (1992) have recommended that soil sampling be stratified using geomorphic surfaces as sampling "treatments", with intensive sampling within each area to better allow determination of site variability. The geomorphic features delineated in this study include summit, footslope, southwest midslope and southeast midslope landscape positions.

Another limitation to our understanding of SOC distribution and dynamics is the misconception that most SOC is in the surface soil horizons, which often leads to sampling by depth increment rather than by genetic horizons (Hammer and others 1995). By comparing soil nutrient values within horizons that formed similarly, sampling variability is reduced compared to depth sampling methods; therefore, this study compared changes in soil properties by horizon instead of by depth.

To provide the best comparison of SOC changes in skid trails due to harvesting activities, the data reported in this paper are from skid trails and control (undisturbed) areas adjacent to skid trails within the harvested areas. The post-harvest samples were taken before a growing season passed, so changes in control versus skid trail SOC due to changes in stand density, new herbaceous growth, and altered hydrology did not have time to occur. Pre-harvest soil samples were taken initially as a baseline against which post-harvest samples were to be compared. However, delays in harvesting on both study sites made pre- and post-harvest comparisons of SOC problematic. The pre-harvest samples were processed, but these data are not presented in this manuscript due to the potential effect of delayed harvesting on SOC comparisons.

Following the completion of harvest activities in 1996, soil cores were taken from both sites using a two-person power auger similar to the device used by the USDA Forest Service for initial measurements in the Long-Term Soil Productivity (LTSP) study (Ponder and Mikkelson 1995, Ponder and Alley 1997). Eight 10-cm diameter cores were taken to a depth of 30 cm within two skid trail types (primary and secondary) within the four aforementioned landscape/slope positions. Four cores were extracted from undisturbed areas adjacent to the skid trails within each of the positions. This study design provided 16 control cores and 64 treatment cores from both primary and secondary skid trails per study site, so a total of 160 cores were taken from the two study sites. The GLM procedure of SAS was used to accommodate the unequal sample size between control and skid trail (treatment) samples. The resulting linear statistical model contained the effects of site, landscape/slope position (plot) within site, skid trail type, soil horizon, and all possible interactions of these factors.

Since determination of bulk density was a prerequisite for the quantification of SOC, validation of the core sampling technique was deemed prudent. Unfortunately, a paired t-test comparison of soil core volumes and core hole volumes performed on a subsample of the pre-harvest cores revealed that the coring technique was compacting the soil samples ($p=0.0001$); therefore, adjustments to horizon thicknesses for both sites were made based on the ratio of the depth of the hole to the length of the core. All post-harvest core-hole volumes were adjusted in this manner. While this hole:core ratio adjustment improved estimates of bulk density, the underlying assumption that each horizon was compacted proportionally to its thickness is suspect. Subsequent research on the power-auger sampling technique has shown that subsurface horizons are more susceptible to compaction from power auger sampling than are surface horizons (Ficklin 2002).

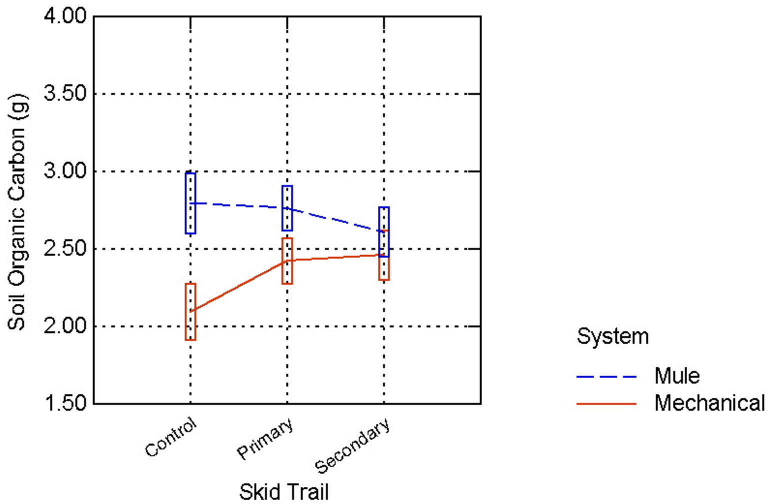

Figure 1.—Mean SOC quantities with standard error boxes for cores extracted from skid trails and control areas by system.

Each core was described in the laboratory by physical and color characteristics, and horizons were delineated for further analysis of the parameters of interest: bulk density, coarse fragment content and carbon concentration. Adjustments to bulk density were made for coarse fragment content in addition to the adjustments made for the compaction from sampling. SOC concentration was determined by combustion in a Leco C-144 carbon analyzer, and two replications were made for each horizon to assure the repeatability of carbon measured. In the final analyses, the average of the two concentrations was used for the comparisons of carbon concentrations, and the quantity of carbon in each horizon was determined based on the mean SOC concentration and the soil mass without rock.

Results

Test results indicated that residual trees per acre (p=0.630), residual sawtimber volumes (p=0.749) and residual basal areas (p=0.420) were not significantly different between sites. Based on these observations, we concluded that stand conditions would not influence the extent of soil disturbance. However, more trees were cut on the animal-skidded tract than on the rubber-tired skidder tract (p=0.005), and a greater amount of basal area was cut on the animal-skidded site (p=0.037). Since harvesting more trees requires more turns in the stand, it was assumed that the animal-skidded site would be predisposed to greater soil disturbance than the rubber-tired skidder site. Interpretation of results must be made within this context.

The area of skid trails within the 4.8 acres of plots on the animal-skidded site was 4,400 ft^2 for primary trails and 2,000 ft^2 for secondary trails- 2.1% and 1.0% of the total harvest area, respectively. The rubber-tired skidder site had 10,700 ft^2 of primary skid trails and 9,600 ft^2 of secondary skid trails- 5.1% and 4.6% of the total harvest area, respectively. Given the difference in the extent of skidding disturbance, inferences about the impact of harvesting on changes in soil density and SOC require consideration of both the magnitude of change and the proportion of the stand affected by the soil density and SOC changes.

When both surface and subsurface horizons were examined, the quantity of SOC was higher for skid trails and control areas on the animal-skidded tract than on the mechanically harvested tract (p=0.035) (Figure 1), but the concentration of SOC and the bulk density of soil did not differ (p=0.323 and p=0.853, respectively) (Figures 2 and 3). The trend in SOC concentration across skid trails and control areas was slightly lower on the mechanically skidded site. However, a statistically significant difference between systems was not observed for the horizon*skid trail interaction (p=0.193). No differences between systems were observed for any treatment combination within the surface A horizons, but the quantity of SOC in Bt subsurface horizons differed (p=0.0001) with the mule skidded site having 40% more SOC in primary and secondary skid trails. The concentration of SOC in the subsurface did not vary between systems (p=0.212). Bulk density did not differ between systems for both surface or subsurface horizons, and skid trail and system*skid trail factors also did not differ. When only control areas outside skid trails were examined, mean SOC quantities were similar for surface and subsurface horizons; however, antecedent

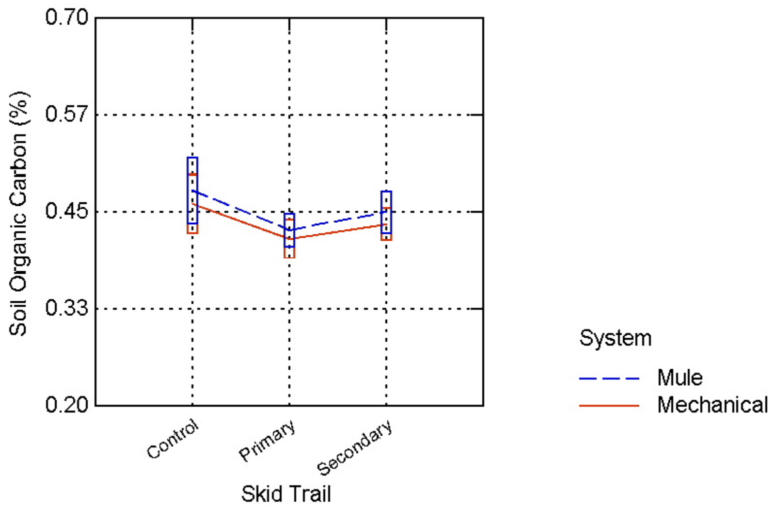

Figure 2.—Mean SOC concentrations with standard error boxes for cores extracted from skid trails and control areas by system.

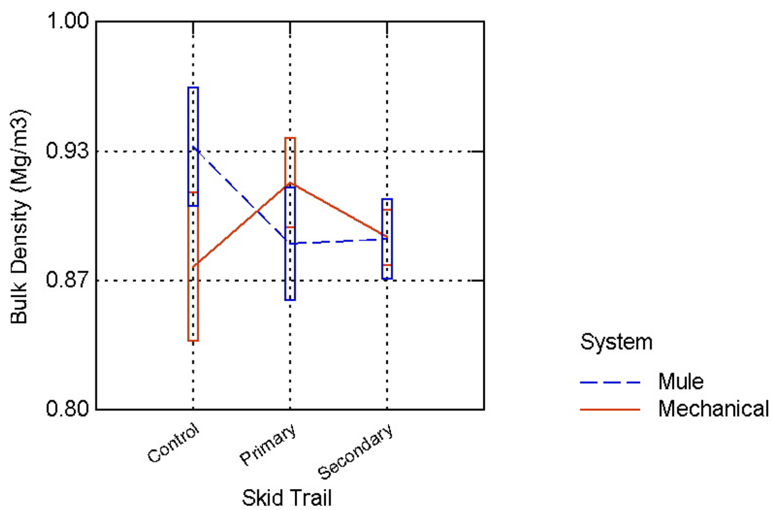

Figure 3.—Mean bulk densities with standard error boxes for cores extracted from skid trails and control areas by system.

subsurface SOC quantities and concentrations were higher on the mule skidding study site ($p=0.046$ and $p=0.022$, respectively).

Discussion

The patterns and processes of natural soil heterogeneity, particularly at the landscape or watershed scale, make treatment replication difficult or impossible. Therefore, cause-and-effect relationships often are inferred from rigorous, systematic treatment sampling (Milliken and Johnson 1989), with attention to the formative processes under which the soil was created (Daniels and Hammer 1992). Soil carbon has been shown to fluctuate significantly temporally and spatially by topographic position in response to changes in parent material, biotic respiration, temperature, moisture and pH (Hammer and others 1987, Hanson and others 1993). Therefore, it was essential to assess the significance of treatment responses by controlling as many of these potentially confounding factors as possible. Soil density and compressibility between the control areas of both study sites were not controllable, but patterns of SOC concentrations across trail types did facilitate the monitoring of SOC quantity changes.

The increase in the quantity of carbon in the skid trails on the mechanized skidder site was not a direct result of increased soil density from compaction. Rather, a combination of compaction, rock contents in control versus skid trail areas and a minimal decrease in SOC concentration best explain the measured trends. The absence of a measurable decrease in SOC is attributed to the short time lapse between harvesting and soil measurements. Debris from skidded logs still was present in both primary and secondary skid trails, and the decomposition of this debris would be expected to mitigate SOC losses due to perturbation in the short term. The removal of rock fragments from the skid trails due to skidding also contributed to the observed increase in carbon content compared to the undisturbed control areas.

Bulk density determination in rocky soils has long been known to be problematic, so accurate estimation of soil compaction from skidding was difficult. With the adjustments to sample volume measurements, soil density responses to skidding disturbance were improved and trends across control and skid trail areas were discernable, but considerable "noise" still persisted. Contrary to expectations, carbon content did not decrease significantly in the skid trails of either site. This observation is expected to be a transient effect due to the decomposition of slash debris within the skid trails. Similarly, carbon concentrations did not change or decrease measurably in the skid trails of either site, so the observed increases in carbon content were likely due to both increased soil density and decreased near-surface rock content in the skid trails. As a result of displacing rocks from the skid trails during skidding, the mass of soil per unit of sample volume increased. Higher carbon contents in the subsurface horizons of control samples within the animal-skidded site make comparisons of carbon change to a 30 cm depth difficult. Additional measurements to quantify soil carbon changes over a period of years instead of months are needed to determine true trends in SOC quantities following harvesting operations with either mechanized or animal-skidding systems. The plots used in this study still are marked, so follow-up measurements would be possible.

The comparison of animal skidding with rubber-tired skidding revealed some advantages to using mules to minimize the impact of logging operations on Ozark forest sites. The advantages observed were not related to the magnitude of disturbance. Rather, the extent of disturbance was reduced by nearly one-third with the use of animal skidding-- even when a greater number of stems, a greater basal area, and a higher volume were removed on the animal-skidded site which resulted in more log-turns. An additional benefit observed on the animal-skidded site was a reduction in the extent and severity of damage to residual trees (Ficklin and others 1997). This study does not provide evidence that animal skidding improves the retention of SOC in forest soils following harvesting, but the data on short term changes in SOC dynamics following soil compaction and scarification do provide evidence of benefits from mule skidding. Given the reduced area of soil scarification, it is reasonable to hypothesize that rapid fluxes of CO_2 from forest soils following selection harvests would be reduced when animal skidding techniques are employed. As long as a niche market exists for low productivity harvest systems employing animal skidding, forest landowners have an option for timber management even when fiber production is not a primary management objective. If future studies support the hypothesis that reduced site scarification also reduces CO_2 efflux, then the prospects for forest landowners to earn more carbon credits with the use of animal skidding would be an incentive to adopt such low intensity harvesting operations.

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