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Changes in forest floor and soil nutrients in a mixed oak forest 33 years after stem only and whole-tree harvest

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ABSTRACT

Vegetation, forest floor, and soils were resampled at a mixed oak site in eastern Tennessee that had been subjected to stem only (SOH), whole-tree harvest (WTH), and no harvest (REF) 33 years previously. Although differences between harvest treatments were not statistically significant ($P < 0.05$), average diameter, height, basal area and biomass were 8–18% lower in the WTH than in the SOH treatment 33 years after harvest whereas they differed by 2% 15 years after harvest. In contrast to results 15 years post-harvest, total forest floor mass and nutrient contents were twofold greater in the WTH than in the SOH treatment at 33 years post-harvest, due largely to differences in Oa horizon mass. Soil total C concentrations increased significantly ($P < 0.05$) over the first 15 years post-harvest in both harvest treatments. Decreases in soil C between 15 and 33 years post-harvest were not statistically significant. Soil total N increased significantly in both harvest treatments over the first 15 years post-harvest. Consistent decreases in soil total N occurred in the WTH treatment between years 15 and 33 post-harvest that bordered on statistical significance whereas total N was stable over that time period in the SOH treatment. The increases and decreases in soil N content cannot be explained by any known processes of N inputs or outputs. Harvest treatment effects on both Ca^{2+} and Mg^{2+} observed at 15 years post-harvest are still observable and significant at 33 years post-harvest, although decreases between 15 and 33 years were found. Treatment effects and changes in soil exchangeable Ca^{2+} and Mg^{2+} are consistent with known inputs from decomposing logging residues, inputs from atmospheric deposition, and increments in forest floor and vegetation. No treatment effects were found for soil extractable P, but steady decreases over time were found. No treatment or time effects were found for soil exchangeable K^+.

1. Introduction

Concern over the effects of intensive forest harvesting on long-term productivity dates back several decades when calculations suggested that nutrient removals by whole-tree harvesting (WTH) might not be sustainable given current nutrient inputs and ecosystem nutrient capital (Boyle et al., 1973; Weetman and Weber, 1972; White, 1974). Although N was most often the limiting nutrient in forests, many early nutrient budget calculations suggested that whole-tree harvesting would cause depletion of other nutrients as well, especially Ca (Alban and Perala, 1990; Boyle et al., 1973; Johnson et al., 1982; Turner and Lambert, 1986; Weetman and Weber, 1972; see also reviews by Federer et al., 1989; Grigal, 2000). In the early 1990s, harvesting effects on forest soil C became a concern because of global C issues. A meta analysis of 73 observations from 26 publications showed that on average, whole-tree harvesting caused a slight (−6%) but significant decline in soil C while sawlog, or stem only harvesting caused a significant increase (+18%), presumably because of differences in inputs from decomposing logging residues (Johnson and Curtis, 2001). Thiffault et al. (2011) recently published a comprehensive review of studies addressing the effects of WTH compared to stem-only harvest (SOH). These authors found that WTH had mixed effects on mineral soil C compared to SOH, with approximately half the studies showing increases and half showing decreases. The effects on forest floor C were more pronounced, however, with 70% of the studies showing negative effects of WTH compared to SOH (Thiffault et al., 2011), as would be expected. The patterns for N were similar: there was a slight tendency toward lower mineral soil total N with WTH compared to SOH (58%) and a much larger negative effect on forest floor N (Thiffault et al., 2011). Of the nutrients reviewed by Thiffault et al. (2011), soil P showed the largest effects of WTH compared

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to SOH. Seventy-eight percent of the studies reviewed showed a decrease in soil P with WTH compared to SOH, which was in accordance to nutrient budgets which indicated 5–7-fold increases in P removal with WTH compared to SOH. Of the base cations reviewed (Ca, K, and Mg), nutrient budgets suggested the greatest potential for Ca depletion in most cases, although some indicated concern over K and Mg as well. Correspondingly, 70% of the studies reviewed reported a decrease in soil base cation concentrations and contents with WTH compared to SOH. In terms of post-harvest productivity, Thiffault et al. (2011) found that differences in regrowth during early years between WTH and SOH were negligible in most cases, but after 5 years most studies showed slower growth in WTH sites. In summary, Thiffault et al. (2011) noted that they could not “define universal and definitive prescriptive indices of site sensitivity to forest biomass harvesting with the data currently available.” They also noted that the data were skewed toward even-aged coniferous forests, and that more studies from uneven-aged deciduous forests, for example, were needed.

In this study, we report the results of vegetation, forest floor and mineral soil resampling 33 years after SOH and WTH in an uneven-aged, mixed deciduous forest located near Oak Ridge, Tennessee. Initial predictions from this site indicated that harvesting removals of Ca would have the most significant effect on ecosystem nutrient budgets. In particular, calculations indicated that WTH removed twice as much Ca as was initially present on the soil exchange sites (to a 45 cm depth) and accounted for 15% of total ecosystem Ca capital including total soil Ca (Johnson et al., 1982). Foliage accounted for 7%, 7%, 23%, and 5% of tree N, P, K, and Ca; thus, although harvesting took place after leaf-fall, it had little ameliorative effects on N, P, and Ca removals. A resampling of the site 15 years after harvest (in 1995) showed no difference in forest regrowth but greater foliar concentrations of K, Ca, and Mg in the SOH than in the WTH treatment (Johnson and Todd, 1998). Contrary to initial predictions, there were no changes in exchangeable Ca^{2+} contents in the WTH soils due to tree uptake. In the SOH site, soil exchangeable Ca^{2+} increased by twofold, which was attributable to Ca release from decomposing logging residues minus Ca uptake by trees. Smaller increases in exchangeable K^{+} and Mg^{2+} were also found in the SOH as compared to the WTH sites. In both WTH and SOH sites, inexplicably large increases in total soil N content were found; these increases far exceeded possible inputs from decomposing logging residues and atmospheric deposition, and no major nitrogen fixing plant species were present (Johnson and Todd, 1998).

In 2013, we sampled vegetation, forest floor, and mineral soils of this site using the same procedures as in the past with the exception of large woody debris inventory. Soil samples from the 1980 and 1995 samplings were available and re-analyzed to avoid the possibility of laboratory bias.

2. Materials and methods

2.1. Site

The study site is located on Dept. of Energy’s Oak Ridge Reservation near Oak Ridge, Tennessee. Mean annual precipitation is approximately 1500 mm, and mean annual temperature is approximately 14.4 °C (Johnson et al., 1982). The site was a woodland pasture prior to 1942 when it became part of the Oak Ridge Reservation. Since that time, it has converted to a mixed oak forest. Major species prior to harvest (and currently on the reference watershed) included chestnut oak (*Quercus prinus* L.), black oak (*Quercus velutina* Lam.), northern red oak (*Quercus rubra* L.), white oak (*Quercus alba* L.), tulip-poplar (*Liriodendron tulipifera* L.), red maple (*Acer rubrum* L.), black gum (*Nyssa sylvatica* Marsh.), sourwood (*Oxydendrum arboreum* L.), and hickory (*Carya ovata* L. and *Carya tomentosa* Nutt.). There were also occasional shortleaf pine (*Pinus echinata* Mill.) and sugar maple (*Acer saccharum* Marsh.) in the overstory and occasional sassafras (*Sassafras albidum* Nutt.) and dogwood (*Cornus florida* L.) in the understory. Non-tree understory vegetation (grasses, forbs, etc.) was negligible in this closed canopy forest. Ages of overstory trees ranged from 50 to 120 years at the time of harvest (Johnson et al., 1982).

In 2013, thirty-three years after harvest, chestnut oak, red maple, scarlet oak (*Quercus coccinea* Münchh.), and black cherry (*Prunus serotina* Ehrh.) accounted for approximately 70% of the overstory in both harvested treatments (Fig. 1). Other overstory species included southern red oak (*Quercus falcata* Michx.), white oak, tulip-poplar, loblolly pine (*Pinus taeda* L.), hickory (*Carya* spp.), sugar maple, sourwood, and northern red oak. Understory species included occasional dogwood, sweetgum (*Liquidambar styraciflua* L.), black gum, eastern red cedar (*Juniperus virginiana* L.), white ash (*Fraxinus americana* L.).

Soils are highly-weathered Ultisols derived from dolomite. Soil from ridgetops on nearby Walker Branch Watershed, which lie on the same ridge and soil type as this study, have been shown to reach 30 m in depth (Johnson and Henderson, 1979) and presumably such extremely deep soils are also present on ridgetops of the current study as well. The two dominant series on the site are highly eroded phases of the Fullerton and Bodine series, both Typic Paleudults. Fullerton soils occupy ridgetop and upper slope positions whereas Bodine occupy steeper side slopes and have a greater coarse fragment component. There are also minor inclusions of the Dewey and Dunmore series (Typic Paleudults) in the lowest slope positions (Johnson et al., 1982).

2.2. Treatments

In the spring of 1979 (prior to harvest), five contiguous watersheds ranging in size from 0.25 to 0.54 ha were surveyed and assigned treatments: watersheds 1 and 2 were whole-tree harvested, watersheds 3 and 4 were harvested for sawlogs only, leaving logging residues on site, and watershed 5 was left as an unharvested reference. In the fall of 1980, watersheds 1–4 were clearcut. All above-stump material was removed from watersheds 1 and 2, while only sawlogs (>28 cm dib) were removed from watershed 3 and 4. Each harvested log and tops and non-commercial trees from watersheds 1 and 2 were weighed at the time of harvest (Johnson et al., 1982).

2.3. Sampling

In the spring of 1979, two 10 × 10 m plots were established in each watershed ($n = 4$ for each harvested treatment, $n = 2$ for the reference watershed) for detritus and soil sampling, as per the protocols used for detritus and soil sampling on nearby Walker Branch Watershed (Johnson et al., 2007). Within each 10 × 10 m plot, three 2 × 2 m randomly selected subplots were sampled for forest floor and soil sampling ($n = 12$ for each harvest treatment and $n = 6$ for the reference treatment). Forest floor was sampled by horizon within a 0.25 m^2 circular ring at each sample point. After removal of the forest floor, a 5 cm diameter core was taken at one point within the 0.25 m^2 area for bulk density and soil samples were taken at 0–15, 15–30, and 30–45 cm depths using a bucket auger at another point in the 0.25 m^2 area. In the 1979 sampling, total soil bulk density measurements were obtained by quantitative pit excavations (Johnson et al., 1982), and these data were used to calculate total soil C and other nutrient contents. In both the 1995 and 2013 samplings, the originally established 10 × 10 m plots were relocated and sampled at different randomly-located