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Long-term effects of commercial sawlog harvest on soil cation concentrations

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Abstract

There is increasing concern about the effects of nutrient removal associated with various forest harvesting practices on long-term site productivity. We measured exchangeable soil cation concentration responses to a commercial clearcut sawlog harvest in mixed hardwoods on a 59-ha watershed in the southern Appalachians. Soils were sampled 17 months prior to, and periodically for 17 years after, harvest. Concentrations of Ca, Mg, and K, increased significantly in the 0-10-cm soil layer for 3 years following harvest compared to pre-treatment levels. Concentrations of Mg and K were still significantly above pretreatment levels 17-20 years following harvest. Calcium concentrations did not change significantly at the 10-30 cm depth, but both Mg and K showed significantly higher concentrations in some post-treatment years. Soils in the adjacent reference watershed showed no significant changes in soil cation concentrations over the same 17-year period. Results indicate that sawlog harvest using cable-yarding techniques on these sites does not adversely impact soil cation concentrations. © 1997 Elsevier Science B.V.

Keywords: Forest management: Soil chemistry; Nutrient availability

1. Introduction

Sustained forest productivity strongly depends on the maintenance of soil nutrients. Therefore, the effects of forest management practices on soil nutrient status. including exchangeable cation concentrations. are important, Long-term trends in undisturbed forests have shown that soil cation concentrations often decrease over time (Binkley et al., 1989; Billett et al., 1990; Richter et al., 1994). These decreases result from the sequestration of nutrients in aboveground biomass and/or leaching to streams (Knoepp and Swank, 1994; Johnson et al., 1988). The sequestration of nutrients in aboveground biomass has raised questions about the long-term effects of the removal of biomass and associated nutrients on soil nutrient availability. Several studies have shown that nutrient loss through leaching, although quantitatively variable, also increases after harvest (Dahlgren and Driscoll, 1994; Mann et al., 1988; Tiedemann et al., 1988; Swank, 1988).

The responses of soil nutrient pools to forest harvest vary with harvest method and forest type. Research has shown that whole-tree harvest can decrease both total nitrogen and exchangeable base cations (Mroz et al., 198.5; J.D. Knoepp and W.T. Swank, unpublished data). While not always the case (Hendrickson et al., 1989), such losses have raised

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concerns about long-term forest productivity when whole-tree harvest methods are repeated over several rotations (Federer et al.. 1989). In contrast. studies show that commercial sawlog harvest either increases or has no effect on soil nutrient concentrations (Hendrickson et al., 1989; Kraske and Fernandez, 1993) suggesting no negative impact on long-term site productivity.

Unfortunately, studies showing the effects of harvest on soil nutrients often rely on either short-term data or the chronosequence approach to estimate long-term responses (Kraske and Femandez, 1993; Mann et al.. 1988; Hendrickson et al.. 1989: Mroz et al.. 1985). The objective of our study was to examine the long-term response (I7 years) of extractable soil cation concentrations to commercial sawlog harvest in a mixed hardwood stand on a 59-ha watershed. Responses were measured against pre-treatment soil cation concentrations. and further interpreted by comparing them with soil data collected from adjacent reference areas over a 17–20-year period.

2. Materials and methods

2.1. *Site and treatment description*

Study sites are located at the Coweeta Hydrologic Laboratory, a 2 180-ha USDA Forest Service-Southem Research Station facility in the southern Appalachians of western North Carolina. The climate is characterized by 190 cm of precipitation annually with most months receiving at least 10 cm (Swift et al., 1988). The growing season extends from early May to early October. Mean monthly temperatures are highest in June through August (20°C) and lowest in December through January (5°C).

2.2. *Commercial sawlog harvest (CSH)*

The area commercially harvested for sawlogs is on a 59-ha south-facing watershed. The elevation ranges from 720 to 1065 m with 20–80% slope. The vegetation community types were: (1) cove hardwood, at lower elevations and adjacent to the stream at intermediate elevations; (2) chestnut oak, at intermediate elevations on mesic southeast- and north-facing slopes: (3) scarlet oak-pine. at intermediate and upper elevations and ridgetops on xeric southwest and south-facing slopes (Swank and Caskey. 1982). The pre-harvest basal area was 25 $m^2 ha^{-1}$ with about 135 $Mg ha^{-1}$ biomass (Boring et al.. 1988). Logging began in January 1977 and was completed in June. Most of the logging (56%) was conducted from three contour roads across the watershed using a mobile cable system. Tractor skidding was used on areas with less than 20% slope. about 16% of the watershed. Approximately 28% of the watershed was not logged due to the poor quality of timber. Surface soil compaction was minimal and the forest floor was generally undisturbed. Site preparation was conducted in October 1977, when all stems remaining after logging were felled.

Sample plots were located on the following soil types: the Chandler series a coarse-loamy. micaceous, mesic Typic Dystrochrept; the Fannin series a fine-loamy, micaceous, mesic Typic Hapludult; the Cullasaja-Tuckasegee complex. loamy-skeletal or coarse-loamy, mixed. mesic Typic Haplumbrepts; the rock outcrop-Cleveland complex, loamy. mixed, mesic Lithic Dystrochrept.

2.3. *South-facing reference watershed (SREF)*

Adjacent to CSH is SREF. a 12-ha, south-south-east-facing reference watershed with mixed-hardwood vegetation. Elevation ranges from 709 to 1004 m with an average slope of 60%. The primary human disturbance on this watershed was selective logging in the 1920s. The basal area of the forest is about 26 $m^2 ha^{-1}$, with the overstory dominated by three *Quercus* spp., *Acer rubrum* L., *Liriodendron tulipifera* L., and *Carya glabra* (Mill.) Sweet. *Rhododendron maximum* L. and *Kalmia latifolia* L.. both evergreen species, are the dominant understory species, occupying 7.4% and 5.1% of the total basal area, respectively (Day et al., 1988).

Soil series on the watershed are the Fannin series (side-slope) and the Cullasaja-Tuckasegee complex (streamside) described for CSH above. All sample plots were located on the Fannin soil type, which occupies about 60% of the watershed.

2.4. *Sample collection and analysis*

CSH sample plots (100 m^2) were established before the 1977 site harvest at randomly selected points along four transects crossing the watershed (Waide et al.. 1988). Pretreatment sampling took place on 16 plots divided into two groups of eight. Beginning in 1975. each group of eight was sampled alternately every 2 weeks for 17 months. Post-treatment samples were collected on 10 plots. again divided into two groups. with alternate groups sampled every 2 weeks. Plots selected for post-treatment soil sampling were also sites of intensive vegetation inventory and physiology studies. Sampling continued for 17 months after completion of harvest. Subsequently. collection frequency decreased, but the alternate group sampling design was continued until 1985. All ten plots were resampled in 1992, 1993 and 1994. Fig. 1 shows the location of all soil sampling plots.

Four 100 m^2 sample plots on SREF were established after the CSH harvest in 1977 to serve as long-term reference plots for CSH (Fig. 1). All four plots were located in the Fannin soil type. Samples were not collected prior to CSH harvest. The four plots were divided into two groups of two. Each group was sampled alternately every 2 weeks from July 1977 through November 1978. Subsequently, collection frequency decreased, but the alternate group sampling design was continued until 1985. All four plots were resampled in 1992. 1993. and 1994.

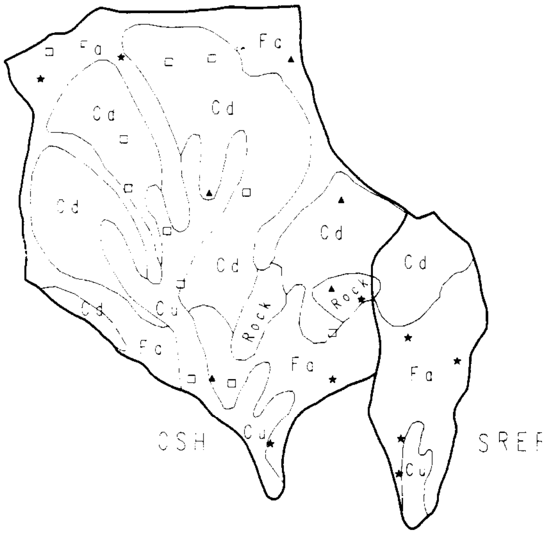

Fig 1. Commercial sawlog harvested watershed (CSH) and adjacent reference watershed (SREF). ■ represents plots sampled pretreatment only: ★ represents plots sampled post-treatment only: ▲ represents plots sampled both pre- and post-treatment. Soil type designations are: Cd, Chandler series; Fa. Fannin series; Cu. Cullasaja-Tuckasegee complex; rock, rock outcrop-Cleveland complex.

Table 1
Regression analysis output for plasma emission spectroscopy (PES) vs atomic absorption spectroscopy (AAS) analysis of double acid soil extracts. Data analyzed were 1993 CSH soil cation concentrations ($n = 24$)

	Ca^{2+}	Mg^{2+}	K^+
Slope	0.95 (< 0 001)	0.93 (< 0.001)	0.94 (< 0.001)
Intercept	32.2 (0.07)	2.16 (0.003)	2.50 (0.07)
r^2	0.99	0.99	0.99

Soil samples in both watersheds were collected at 0-10 cm and 10-30 cm. Soils were air-dried and sieved to ≤ 2 mm. Exchangeable cation concentrations were determined with the double acid extraction procedure developed by the Soil Testing and Plant Analyses Laboratory, Cooperative Extension Service. Athens, GA. Subsamples (5 g) were extracted with 20 ml 0.05 M HCl plus 0.05 M H_2SO_4. Pre- 1990 soil cation determinations were made using plasma emission spectroscopy (PES) as described by Jones (1977). Although extraction methods did not change in the 1990s, atomic absorption spectroscopy (AAS) was used for base cation concentration determinations after a standard curve was established. All diluted samples were analyzed in duplicate. Regression analysis on the 1993 samples compared PES with AAS, and the results are shown in Table 1. AAS data were transformed using these equations before statistical analysis.

2.5. *Statistical analysis*

Statistical analyses for differences between years in soil extractable Ca, Mg, and K concentrations for each watershed were tested using the GLM procedure in SAS (SAS Institute, 1985). Plot and plot-by-year interaction terms were included in the model statement. All CSH pre-treatment cation data from 1975 and 1976 were compared with annual post-treatment means. All annual means on SREF were compared. Tukey's studentized range test (SAS Institute, 1985) was used to determine significant differences among annual means, thereby minimizing the possibility of a type I experimentwise error. Analysis for significant differences between the two watersheds was conducted with data from CSH plots with soils similar to those on SREF ($n = 6$). Year-by-year examinations using the WS(PLOT) error term revealed no significant watershed differences.

3. Results and discussion

The soil base cations – Ca, Mg and K – in the O-IO cm soil depth all responded to commercial sawlog harvest. increasing for 3 years. Soil Ca increased from an average of 100 mg kg^{-1} to ≥ 200mg kg^{-1} ($P \leq 0.05$) (Fig. 2A). Surface soil Mg concentrations increased from 29mg kg^{-1} to ≥ 55 mg kg^{-1} (Fig. 3A). Pre- and post-treatment Mg levels were also significantly greater in 1992 ($P \leq 0.05$) and 1994 ($P \leq 0.1$). The extractable K response was similar, increasing from 26 to ≥ 70mg kg^{-1} for the 3 years following harvest and 1992 and 1994 (Fig. 4A).

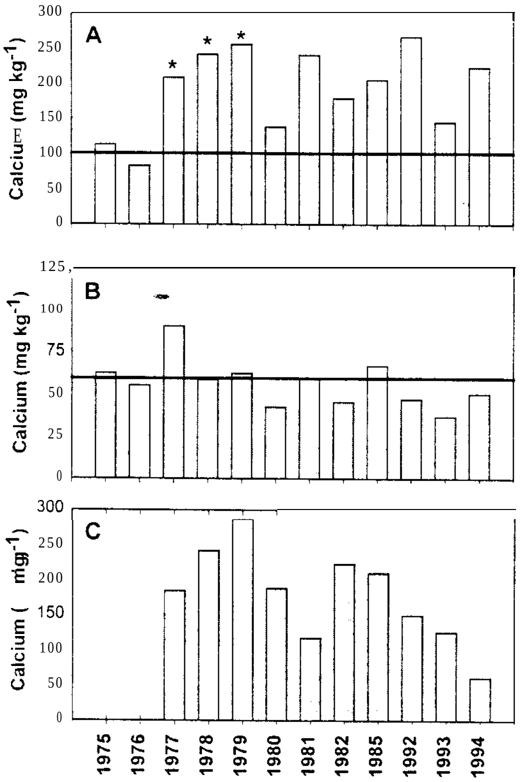

Fig. 2. Calcium concentrations from soils collected at O-IO-cm (A) and 10–30-cm (B) depth from the commercial sawlog harvest watershed before and after treatment, and O-IO-cm depth from the south-facing reference watershed (C). The horizontal line on (A) and (B) represents the mean of pre-treatment data. * and ** indicate the probability of a significant difference from the mean of pre-treatment data at $P \leq 0.05$ and $P \leq 0.1$, respectively.

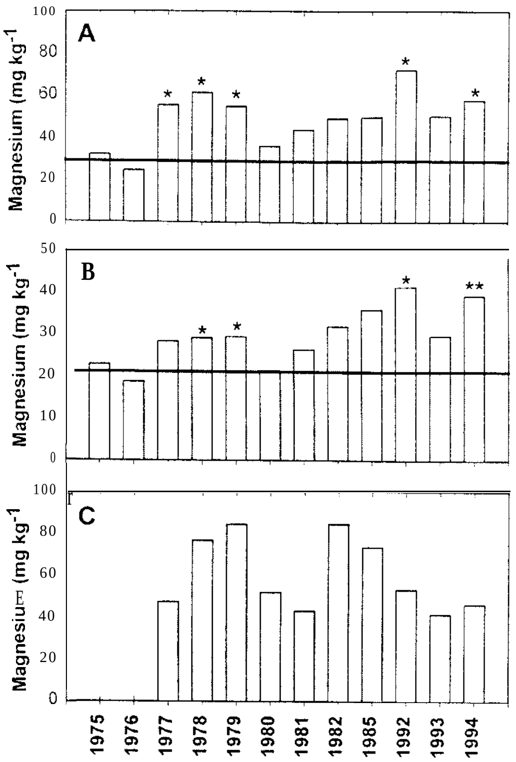

Fig. 3. Magnesium concentrations from soils collected at O-IO-cm (A) and 10–30-cm depth (B) from the commercial sawlog harvest watershed before and after treatment. and O-IO-cm depth from the south-facing reference watershed (C). The horizontal line on 4 and B represents the mean of pre-treatment data. * and ** Indicate the probability of a significant difference from the mean of pre-treatment data at $P \leq 0.05$ and $P \leq 0.1$. respectively.

Responses at the 10–30 cm depth varied considerably among the three base cations. Subsoil Ca did not respond significantly to site harvest (Fig. 2B). However, subsoil Mg concentrations increased ($P \leq 0.05$) in 2 of the 3 years following site harvest, and in 1992 ($P \leq 0.05$) and 1994 ($P \leq 0.1$) (Fig. 3B). All but two post-treatment years had K concentrations significantly greater than pre-treatment levels (Fig. 4B).

Lack of significant differences between pre-treatment and some post-treatment years may be due to the high variability among plots and decreased sampling frequency. Table 7 shows that differences among plots are significant for both Ca and Mg concentrations. Plot mean square values are only slightly less than Year mean square values. Pre-treatment annual means represent values from $n > 100$ plots. Plots sampled in post-treatment years decrease from $n = 122$ in 1978. the first full year after harvest. to n = IO for years 1982 through 1994.

Several authors have reported short-lived increases in soil cation concentrations following sawlog harvest (Snyder and Harter. 1984: Kraske and Fernandez, 1993; Hendrickson et al., 1989). Snyder and Harter (1984) attributed these increases to the influx of organic materials following harvest. The CSH harvest removed only about 10% of the total aboveground biomass (Boring et al., 1988) and left 12 I Mg ha^{-1} of logging residue (Mattson and Swank. 1987). An immediate source of cations to the soil was the throughfall beneath the harvest slash. A study of slash throughfall chemistry on CSH showed substantially elevated concentrations of cations leached from bark and woody materials (W.T. Swank, unpublished data). Leaves and small twigs, which decompose rapidly, provide another immediate source of exchangeable cations and soil organic matter (Abbott and Crossley, 1982; J.D. Knoepp and W.T. Swank, unpublished data). Small branches, boles, and roots represent a longer lived source of nutrients and organic matter. They initially immobilize some nutrients. such as Ca, and later release them (Abbott and Crossley, 1982; Fahey et al., 1988). This process may limit the loss of dissolved material to streams that occurs following harvest (Dahlgren and Driscoll, 1994; Mann et al.. 1988; Tiedemann et al., 1988; Swank, 1988).

Understanding the long-term response of a site to harvest is essential to estimate impacts on site productivity. This requires not only measuring changes over a long period of time but also comparing the harvest site with a control or reference area. Monitoring the reference area incorporates changes in physi-

Table 2
Analysis of variance table for soil Ca. Mg. and K concentrations from the 0–10 cm soil from CSH. Shown are degrees of freedom (DF). mean square. F value. and the probability of values greater than F (Prob $>F$) Source\ of variance included in the analysis are year. plot and plot hy year interaction

Source	DF	Mean square	F	Proh $>F$
Calcium				
Year	11	238 172	7.56	0.0001
Plot	23	214771	6.82	0.0001
Year × Plot	97	31 929	1.01	0.4521
Magnesium				
Year	11	10928	14.42	0.0001
Plot	23	6183	8.55	9.0001
Year × Plot	97	863	1.14	0.1938
Potassium				
Year	11	58225	12.81	0.0001
Plot	23	3543	0.78	0.7575
Year * Plot	97	‘637	0.58	0.9993

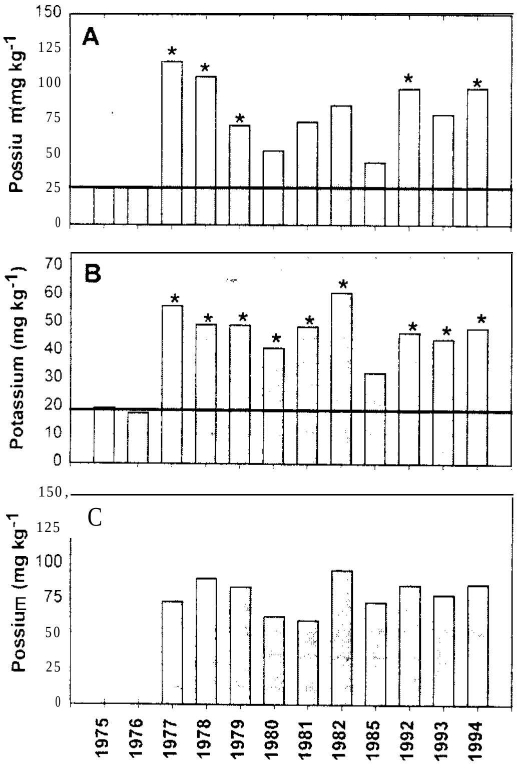

Fig. 4. Potassium concentration5 from soils collected at A) 0 to IO-cm. B) IO to 30-cm depth from the commercial sawlog harvest watershed before and after treatment and C) 0 to 10 -cm depth from the south-facing reference watershed. The horizontal line on A and B represents the mean of pre-treatment data. The ∗'and '∗∗' Indicates probability of a significant difference from the mean of pre-treatment data at $P \leq 0.05$ and $P \leq 0.1$, respectively.

cal. chemical. and biological factors that affect nutrient cycling but are unrelated to treatment. For example. in previous work we showed that the sequestration of nutrients in biomass and leaching losses in an aggrading forest at Coweeta reduced soil cation concentrations over a 20-year period (Knoepp and Swank. 1994). In contrast to our previous findings. data from SREF show no significant changes in cation concentrations over the 17-year sampling period (Fig. 2C. Fig. 3C and Fig. 4C). Lack of pretreatment data for SREF precludes direct comparison of cation concentrations for SREF and CSH. The only appropriate comparison showed no significant differences between watersheds for any post treatment year. However, we can assume that trends in cation concentration changes would be similar because the two sites have comparable soils. aspect and slope. Mean separation tests showed no significant differences among years on either CSH or SREF over the 17-year post-harvest sample period, 1979 to 1994. This suggests that the increase in cation concentration on CSH will be fairly long-lived and harvest did not adversely affect site nutrient availability.

The relatively constant cation concentration in SREF over time vs soil cation decreases observed on a north-facing Coweeta reference watershed is probably due to a combination of factors. Loss of cations was attributed to the sequestration of nutrients in the biomass and leaching of cations to stream water. While the vegetation of two reference watersheds has similar composition, there may be differences in net primary production and nutrient sequestration in biomass. Swank and Waide (1988) showed the two watersheds differ in leaching losses. Net annual losses of Ca are 1.82 kg ha^{-1} for SREF and 3.03 kg ha^{-1} for the north-facing watershed. Two factors may contribute to stream export differences, soil type and differences in rainfall and water use. (1) *Soil type differences*. All plots on SREF are located in side slope position Inceptisols with micaceous mineralogy. Soils sampled on the north-facing watershed were Ultisols in both side slope and riparian positions with mixed mineralogy. (2) *Rainfall and water use differences*. The north-facing watershed receives 20 cm more rainfall than SREF. The south-facing SREF watershed receives greater solar inputs than the north-facing watershed, especially in the winter. This difference in insolation results in less total rainfall leaving as streamflow on SREF compared to the north-facing reference watershed (Swift and Knoerr. 1973; Douglass and Swank. 1975). These results emphasize the need to have reference sites that provide maximum normalization of factors (climate. hydrology and soils) that influence biogeochemical cycles and hence facilitate the interpretation of treatment effects.

In summary, our data show large initial increases in soil exchangeable cations following commercial sawlog harvest by clearcutting with cable yarding when compared to pre-treatment levels. Indirect comparison of treatment data with changes in soil chemistry on an adjacent reference watersheds suggest that increases may be long-lived. However, these findings must be considered in the context of specific harvest practices and timber utilization. We also found that long-term impacts on soil chemistry are site specific and may vary with factors affecting the biogeochemical cycling of nutrients.

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