

Long-Term Soil Chemistry Changes in Aggrading Forest Ecosystems

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ABSTRACT

Assessing potential long-term forest productivity requires identification of the processes regulating chemical changes in forest soils. We resampled the litter layer and upper two mineral soil horizons, A and AB/BA, in two aggrading southern Appalachian watersheds 20 yr after an earlier sampling. Soils from a mixed-hardwood watershed exhibited a small but significant decrease in soil pH. Extractable base cation content declined substantially in both mineral horizons. For example, Ca^{2+} levels in the A horizon fell from 236 kg ha^{-1} in 1970 to 80 kg ha^{-1} in 1990. Proportionally, the decline was greatest for Mg^{2+} , which dropped from 111 to 20 kg ha^{-1} . A white pine (*Pinus strobus* L.) plantation was planted in 1956, after clear-felling hardwoods and recutting sprouts for 15 yr. Soil pH and base cation concentrations declined in the A horizon from 1970 to 1990. Soil pH declined from 5.9 to 5.0 and Ca^{2+} levels from 534 to 288 kg ha^{-1} . Cation content did not change significantly in the AB/BA soil horizon. Nutrient budgets were constructed using these soil and litter data plus existing data on weathering rates, forest productivity, and hydrologic fluxes and associated chemistry. Decreases in soil base cations and soil pH are attributed to leaching and to the sequestration of nutrients in biomass.

LONG-TERM SITE PRODUCTIVITY may depend on both long- and short-term changes in soil chemical composition. In soils that have been depleted of nutrients by years of exploitative agricultural practices, reforestation

increases nutrient and organic matter content (Fisher, 1990). Planting forest species on normal production agriculture soil can decrease soil pH and base cation concentrations (Binkley et al., 1989). Only a few studies in the USA have examined long-term changes in soils that remained forested (Johnson et al., 1991). Decreases in soil pH and base cation concentrations appear common. These changes have been attributed to cation leaching and biomass accumulation.

Cation leaching can result from natural processes or acidic deposition. Leaching as a result of natural processes was reported in two N_2 -fixing red alder (*Alnus rubra* Bong.) stands in western Washington by Van Miegroet and Cole (1984, 1985) and Binkley and Sollins (1990). Large accumulations of N during a 55-yr period under alder resulted in high rates of N mineralization and nitrification. High levels of soil solution NO_3^- increased cation leaching and decreased soil pH in surface horizons. This resulted in the displacement of cations to lower soil horizons on one site but cation removal from another site.

In a long-term study, Johnson et al. (1988) attributed soil cation losses to biomass accumulation and leaching. Calcium was translocated from subsoil horizons to above-ground biomass. Decreases in soil Mg^{2+} content resulted

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Abbreviations: HDWD, mixed-hardwood watershed; WP, white pine watershed; AAS, atomic absorption spectrophotometer; CEC, cation-exchange capacity; BS, base saturation; cmol H^+ , exchangeable acidity; ANOVA, Analysis of Variance; SE, Standard error.

from leaching losses possibly caused by SO_4^{2-} deposition (Johnson and Todd, 1990).

We studied long-term changes in forest soil nutrient content in two aggrading forest ecosystems. Our study objectives were to (i) examine the 20-yr changes in surface soil and forest floor chemistry in an undisturbed mixed-oak forest and a white pine plantation and (ii) quantify biogeochemical processes underlying any chemical changes.

MATERIALS AND METHODS

The study was conducted on Watersheds 17 and 18 at the Coweeta Hydrologic Laboratory in western North Carolina. The HDWD is a 13-ha, north-facing reference watershed with mixed hardwood vegetation. In the 1920s, HDWD was selectively logged and subsequently has not been disturbed by humans. Basal area of the forest is about $26 \text{ m}^2 \text{ ha}^{-1}$, and the overstory is dominated by three *Quercus* spp.: *Acer rubrum* L., *Liriodendron tulipifera* L., and *Carya glabra* (Miller) Sweet. The understorey is dominated by *Rhododendron maximum* L. and *Kalmia latifolia* L., both evergreen species. On WP, also a north-facing watershed adjacent to HDWD, the 13-ha hardwood forest was clearcut in 1940 and regrowth was cut annually until 1955. White pine was planted in 1956, and pines were released from hardwood competition as necessary by both cutting and chemical means until 1970. Basal area of WP in 1990 averaged about $50 \text{ m}^2 \text{ ha}^{-1}$.

Slopes on both watersheds average $\approx 50\%$. Two soil series were sampled on both watersheds. The Saunook series, a fine-loamy, mixed, mesic Humic Hapludult, occupies stream-side positions. Ridge positions are occupied by Cowee-Evard complex soils, fine-loamy, mixed-oxidic, mesic, Typic Hapludults.

Sampling was conducted at four positions on two sample transects established in each watershed by Yount (1975a,b) in 1970. Each transect led from a stream channel to a point 60 m upslope on both facing slopes. In HDWD, transects were at mid-watershed level, with one transect bisecting the perennial stream and one bisecting an intermittent stream. In WP, transects were across the lower and upper thirds of the single stream channel. Two plots (2 by 15 m) were established on each slope of a transect for a total of eight plots per watershed.

Methods of sample collection and preparation used in 1990 were the same as those of Yount (1975a,b). In 1990, samples were collected in March and November. Data from these 2 mo of 1970 only were used for comparison to avoid biases caused by seasonal variation in soil and forest floor cation concentration and forest floor quantity.

Following Yount's procedures, triplicate 0.25-m^2 quadrats were randomly selected for sample collection on each plot. The Oi and Oe litter layers were collected as one sample, after which composite soil samples were collected with a 1.8-cm-diam. soil probe sampler. Yount collected Oi, Oe, and Oa layers individually for WP. The Oa on HDWD was not collected but was "partly incorporated into the A1 horizon" (Yount 1975b). We quantitatively collected the Oa layer on HDWD at the November sampling date. The Oa extractable cations were determined using soil extraction methods. The A horizon cation content represents soil cation content plus Oa extractable cations. Extractable Oa cations were 20, 12, and 7% of total extractable A horizon Ca^{2+} , Mg^{2+} , and K^+ , respectively. The top two soil surface horizons were sampled, and the depth of the A horizon, which was present on all plots, was recorded. The second horizon varied from an AB to a BA and is therefore referred to as AB/BA. Average A horizon

depths were 5.4 and 5.8 cm for HDWD and WP, respectively, in 1970. The HDWD A horizon depth increased significantly ($P < 0.05$) to 7.3 cm in 1990 and, although WP A horizon depth also increased (6.4 cm), the change was not significant ($P < 0.05$).

Soil samples were air dried and sieved to $<2 \text{ mm}$. Five-gram subsamples were extracted with 20 mL 0.05 M HCl plus $0.0125 \text{ M H}_2\text{SO}_4$. Sample analyses in 1970 were performed by the Soil Testing and Plant Analyses Laboratory, Cooperative Extension Service, Athens, GA. Methods used in 1990 were the same, except AAS was used for cation determinations instead of colorimetric methods. Cation concentrations were determined by AAS, following establishment of a standard curve. All diluted samples were analyzed in duplicate. Soil pH was determined in a 1:1 soil/ H_2O slurry. The cmol H^+ was determined by pH change in a 1:2 soil/Adams and Evans buffer slurry. The cmol H^+ was calculated from the change in buffer pH (8.0), $0.8 \text{ cmol H}^+ \text{ kg}^{-1}$ soil for every 1.0 unit pH decrease. The CEC was calculated as the sum of double acid extracted cations and cmol H^+ . Percentage BS was calculated as the sum of base cations divided by total CEC $\times 100$.

Litter samples were oven dried at 50°C , weighed, and ground to pass a 1-mm sieve. Samples (0.5 g) were dry ashed at 480°C for 4 h, dissolved in 20% HNO_3 , and brought up to volume with 2% HNO_3 solution. Cation concentrations were determined by AAS.

Means of the three quadrats per plot ($n = 8 \text{ plots} \times 2 \text{ dates} = 16$) in 1970 and 1990 were used for statistical analysis. Watershed means in 1970 and 1990 were compared using the ANOVA procedure (SAS Institute, 1985).

Nutrient budgets were calculated from the 1970 and 1990 soil and litter data. Extractable soil cation contents (kilograms per hectare) were calculated using the measured depth of the A horizon and a total depth for the A plus AB/BA horizons for 20 cm (Table 1). Bulk density values ($<2\text{-mm}$ fraction) are 0.87 ($\text{SE} = 0.05$; $n = 13$) and 1.00 Mg m^{-3} (McGinty, 1976) for the A and AB/BA horizons, respectively. Total A plus AB/BA horizon depth and A horizon bulk densities were determined in soil pits in other studies in this portion of the Coweeta basin.

Deposition inputs were calculated from the bulk precipitation chemistry sampling network at Coweeta (Swank and Henderson, 1976). Chemistry and precipitation amounts have been measured weekly since 1972 and thus provide a high degree of precision for estimating inputs of most dissolved solutes (Swank and Waide, 1988). Geochemical weathering rates were calculated by the hydrologic balance method (Berry, 1977, unpublished data; Velbel, 1988). This method combines geochemical mass balance data with empirically determined min-

Table 1. Characteristic soil profiles showing horizon depths and NH_4OAc extractable base cations for Saunook and Cowee-Evard soil series. Values represent means of four soil pits located in sites in the Coweeta basin similar to the location of sample plots within the mixed-hardwood and white pine watersheds.

Horizon	Depth	Ca^{2+}	K^+	Mg^{2+}
	cm	kg ha ⁻¹		
Saunook: fine-loamy, mixed, mesic Humic Hapludult				
A	0-12	79	108	42
AB	12-25	54	121	36
BC	25-45 +	291	296	239
Cowee-Evard: fine-loamy, mixed, mesic Typic Hapludult				
A	0-9	49	117	32
E	9-19	6	48	6
EB/AB	19-33	24	151	22
Bt/Bw	33-54	64	230	151
BC	54-74 +	29	460	270

Table 2. Analysis of variance showing effects of year, month, year \times month, and soil type on total Ca^{2+} , K^+ , and Mg^{2+} to a 20-cm depth for mixed-hardwood (HDWD) and white pine watersheds (WP). Degrees of freedom for each effect equals one.

	HDWD			WP		
	MS	F	P < F	MS	F	P < F
Ca^{2+}						
Year	359669	42.82	0.00	314170	5.57	0.02
Month	3269	0.39	0.54	60163	1.07	0.31
Year \times month	10247	1.22	0.28	968	0.02	0.90
Soil type	198386	23.62	0.00	453460	8.05	0.01
K^+						
Year	35482	20.05	0.00	1650	0.73	0.40
Month	137	0.08	0.78	79	0.04	0.85
Year \times month	368	0.21	0.65	613	0.27	0.61
Soil type	955	0.54	0.47	1275	0.56	0.46
Mg^{2+}						
Year	137574	44.45	0.00	160655	14.28	0.01
Month	10660	3.44	0.07	75056	6.67	0.01
Year \times month	8941	2.89	0.10	66384	5.90	0.02
Soil type	43090	13.92	0.00	271	0.02	0.88

eral weathering reactions specific to the primary minerals at Coweeta. Estimates of mineral weathering rates at Coweeta compare favorably with mineral weathering rates determined in laboratory experiments under similar hydrogeochemical conditions (Velbel, 1988).

Outputs from the watersheds include dissolved exports calculated from continuous weir discharge measurements combined with chemical analyses of weekly grab samples of stream water since 1972 (Swank and Waide, 1988). Analysis of Coweeta

streams has shown that grab sample estimates of export for most constituents are within 1 to 5% of values calculated from flow-proportional stream samples (Swank and Waide, 1988); thus, export estimates are considered to be highly reliable. Other components of output are also based on long-term data and include sediment export (Swank and Waide, 1988) and biomass accumulation above ground (Monk and Day, 1988; Swank and Schreuder, 1973; Swank, 1988, unpublished data) and below ground (McGinty, 1976; Vose, 1992, unpublished

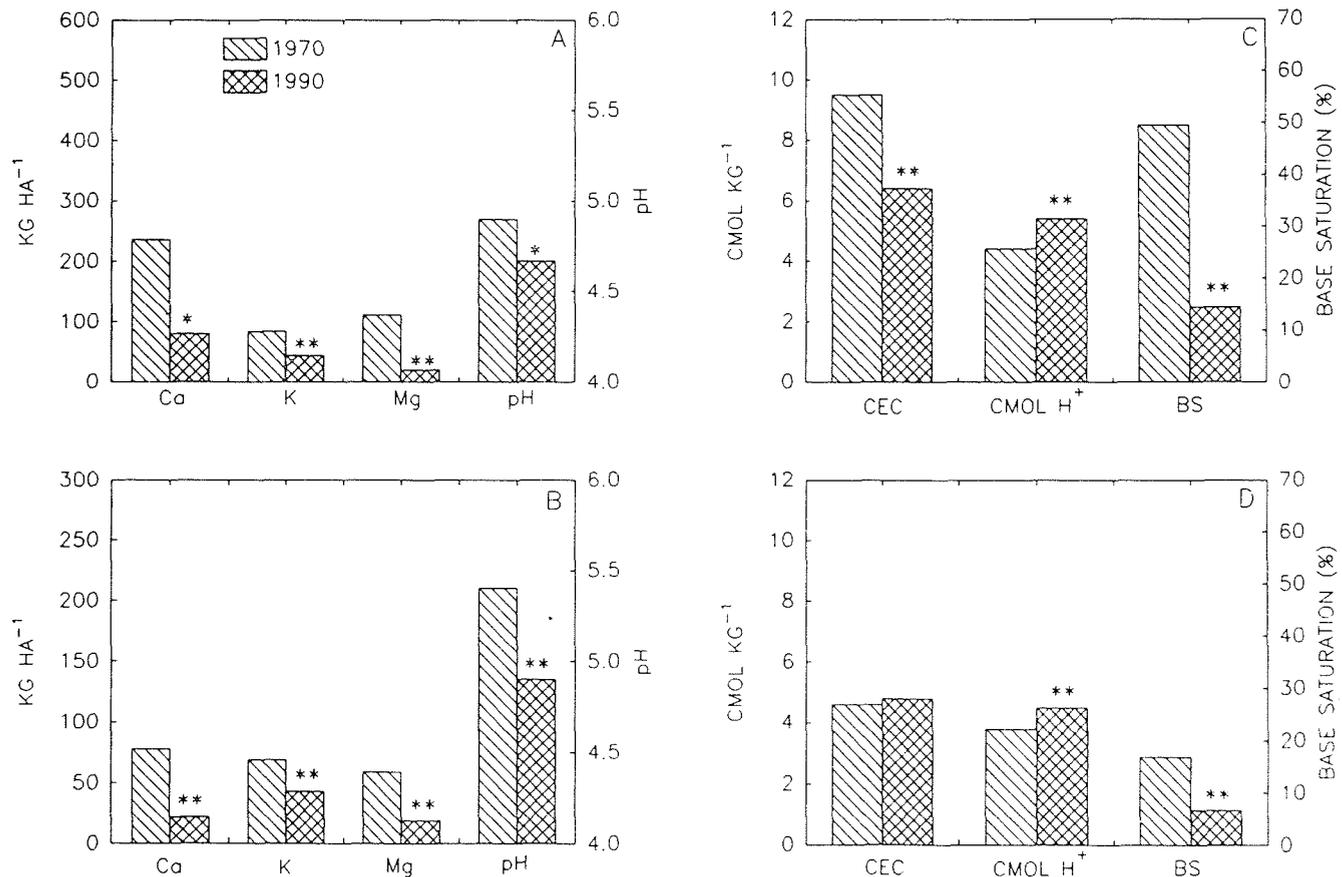


Fig. 1. Double acid extractable Ca^{2+} , K^+ , and Mg^{2+} contents, soil pH, cation-exchange capacity, exchangeable acidity, and base saturation for (a and c) A horizon and (b and d) AB/BA horizon soils for a mixed-hardwood watershed (HDWD). Values represent means of eight sample plots at two sample dates. *, ** Significant difference between 1970 and 1990 means at $P \leq 0.05$ and 0.01, respectively.

data). Aboveground biomass accumulation was calculated from remeasurement of permanent vegetation plots in both watersheds in combination with allometric equations for estimating biomass (Monk and Day, 1988; Swank and Schreuder, 1973; Swank, 1988, unpublished data). Belowground biomass increment for WP was calculated from measurement of coarse root biomass in 1975 (McGinty, 1976) and 1991 (Vose, 1992, unpublished data) on another white pine watershed at Coweeta. Initial belowground biomass for HDWD was measured in 1974 (McGinty, 1976); biomass accumulation was estimated using the ratio of aboveground/belowground biomass accumulation measured for WP. Fine root biomass was assumed to be in steady state. Estimates of woody litter accumulation measured at Walker Branch Watershed (Johnson et al., 1990) were used in the nutrient budget because these data were not available for Coweeta.

RESULTS AND DISCUSSION

Soil and Litter Chemical Composition

Characteristic soil profiles for the Saunook and Cowee-Evard soil series are shown in Table 1. Data included are horizon depth and Ca^{2+} , K^+ , and Mg^{2+} contents. Profile descriptions represent the means of four soil pits for each series located in the same area as HDWD and WP in the Coweeta basin.

Table 2 shows ANOVA for total kilograms per hectare Ca^{2+} , K^+ , and Mg^{2+} (20-cm depth), including mean

square, F statistics, and probability of values greater than F . Year is significant for Ca^{2+} and Mg^{2+} on both HDWD and WP and for K^+ on HDWD only. Soil type has a significant effect on changes in Ca^{2+} content for both HDWD and WP and in Mg^{2+} content only on HDWD, indicating some spatial variability. However, spatial variability in bulk density was slight. Bulk density was determined in 13 soil pits in HDWD and an adjacent watershed. A horizon bulk density was 0.87 Mg m^{-3} with $\pm 6\%$ SE. The B horizon was less variable; bulk density mean was 1.27 Mg m^{-3} with $\pm 4\%$ SE.

In HDWD A horizon soils, extractable Ca^{2+} , K^+ , and Mg^{2+} and soil pH declined substantially and significantly ($P \leq 0.05$) between 1970 and 1990 (Fig. 1a). Soil Mg^{2+} declined 82% from 111 kg ha^{-1} in 1970 to 20 kg ha^{-1} in 1990. Soil K^+ showed the least decline, dropping from 84 to 44 kg ha^{-1} . Soil pH decreased from 4.9 to 4.7. In the AB/BA horizon, all three cations and soil pH also decreased significantly ($P \leq 0.05$) (Fig. 1b). Extractable Ca^{2+} decreased most, from 78 to 22 kg ha^{-1} . Soil K^+ again showed the smallest proportional decrease in pool size, from 69 to 43 kg ha^{-1} . Soil pH decreased from 5.4 to 4.9.

The CEC and BS decreased in HDWD A horizon soils from 9.5 to 6.4 cmol kg^{-1} and 49 to 14% in 1970 and 1990, respectively (Fig. 1c). The cmol H^+ increased from 4.4 to 5.4 cmol kg^{-1} . The AB/BA horizon also

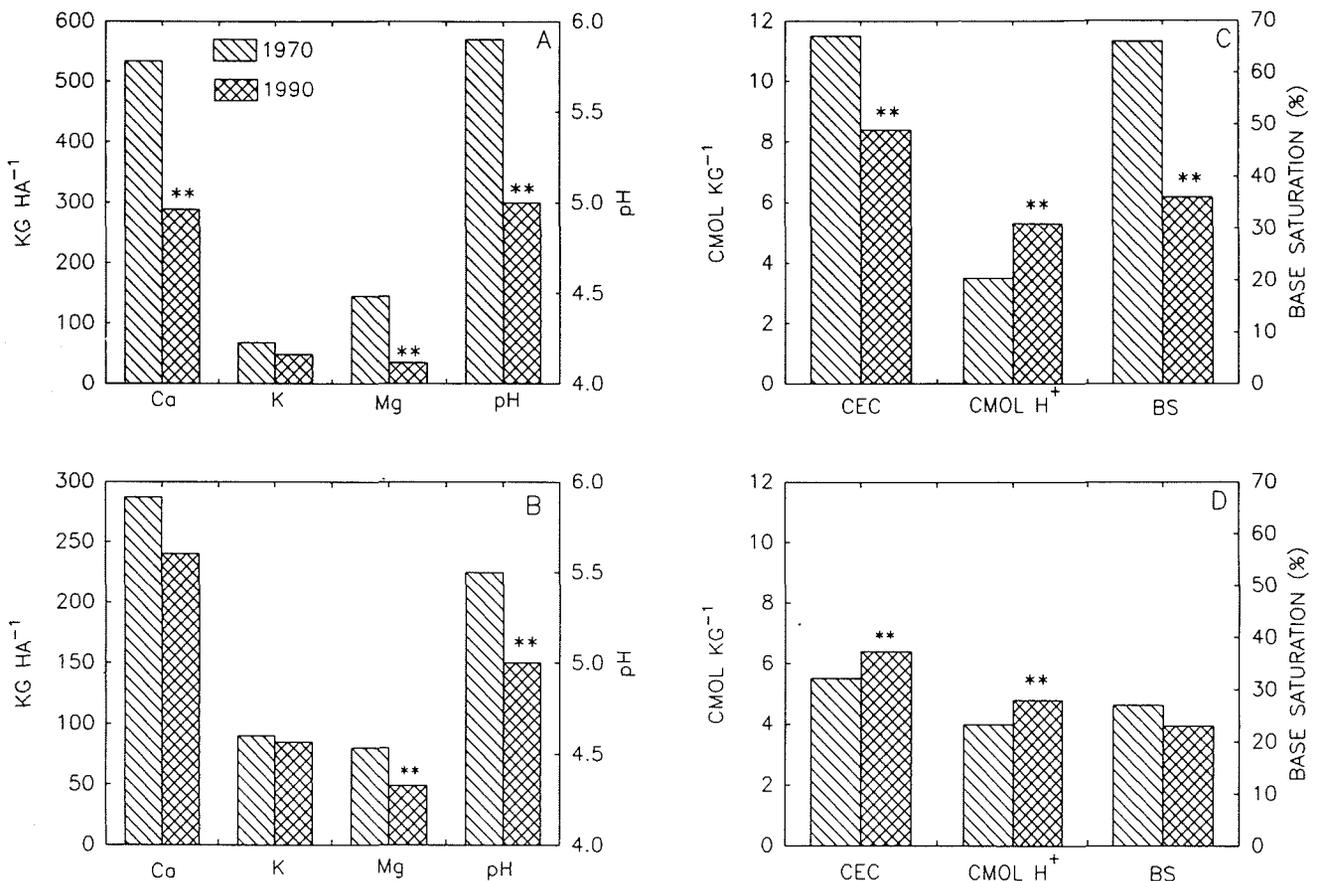


Fig. 2. Double acid extractable Ca^{2+} , K^+ , and Mg^{2+} contents, soil pH, cation-exchange capacity, exchangeable acidity, and base saturation for (a and c) A horizon and (b and d) AB/BA horizon soils for a white pine watershed (WP). Values represent means of eight sample plots at two sample dates. *, ** Significant difference between 1970 and 1990 means at $P \leq 0.05$ and 0.01, respectively.

showed a decrease in BS along with an increase in cmol H^+ , but CEC did not change (Fig. 1d).

In WP A horizon soils, extractable Ca^{2+} , K^+ , and Mg^{2+} and soil pH decreased between 1970 and 1990 (Fig. 2a). Soil Mg^{2+} levels fell from 145 to 35 kg ha^{-1} , and K^+ content declined the least, from 68 to 48 kg ha^{-1} ($P = 0.06$). In the AB/BA horizon, only Mg^{2+} decreases were significant (Fig. 2b). Soil pH decreased in both A and AB/BA horizons from 5.9 to 5.0 and 5.5 to 5.0, respectively.

In the A horizon soils of WP (Fig. 2c), BS decreased from 66 to 36%, CEC decreased, and cmol H^+ increased. The AB/BA horizon soils had an increase in CEC and cmol H^+ but no change in BS (Fig. 2d).

The total weight of Oi plus Oe layers increased on both HDWD and WP (Fig. 3a and 3b). On HDWD, total litter weight increased 28% from 7200 to 9300 kg ha^{-1} , and on WP, it increased 45%, from 12 200 to 17 800 kg ha^{-1} . On HDWD and WP, Ca^{2+} , K^+ , and Mg^{2+} concentrations decreased ($P \leq 0.05$) in the combined Oi and Oe layers (Fig. 3a and 3b).

Nutrient Budgets

Complete nutrient budgets were constructed for each watershed using soil and litter chemistry, nutrient inputs and outputs, leaching, and biomass accumulation. This allowed us to identify the biogeochemical processes responsible for cation losses (Table 3). On HDWD, cation outputs to streamflow were equal to, or slightly greater than, biomass accumulation. Ratios of biomass accumulation/leaching were 3:4 for Ca^{2+} , 1:1 for K^+ , and 2:3 for Mg^{2+} . In contrast, on WP, large proportions of base cations depleted from the surface soils were sequestered in the vegetation rather than lost through leaching. Ratios of biomass accumulation to leaching were 2:1 for Ca^{2+} , 3:1 for K^+ , and 2:1 for Mg^{2+} .

Net nutrient balance values were about the same on HDWD and WP but varied for individual cations. The small discrepancies for Ca^{2+} budgets, +17 kg ha^{-1} on HDWD and +27 kg ha^{-1} on WP, indicate that most losses from surface soils are accounted for by vegetation increment and leaching. The negative Mg^{2+} budget balances indicate unmonitored losses on both watersheds. In contrast, balances for K^+ in both watersheds are positive. Apparently, an unmonitored source of K^+ is available for vegetative uptake and leaching loss.

Eleven-year changes in B horizon cation concentrations were measured in soils from Walker Branch, a mixed-deciduous forested watershed in Tennessee (Johnson et al., 1988). Exchangeable Ca^{2+} and Mg^{2+} both decreased. Changes in Ca^{2+} corresponded with accumulation in forest biomass. However, Mg^{2+} losses did not agree with calculated amounts sequestered in biomass. Later studies indicated that Mg^{2+} losses were the result of leaching by SO_4^{2-} from atmospheric inputs (Johnson and Todd, 1990).

Leaching was also an important loss mechanism for Mg^{2+} from HDWD in our study. The biomass accumulation/leaching ratio was 2:3. However, biomass accumulation and leaching as streamflow do not account for all

the Mg^{2+} lost. It is possible that Mg^{2+} was leached out of the A and AB/BA horizons and retained in the deeper subsurface horizons. Displacement of cations from surface to subsurface soils was found by Van Miegroet and Cole (1985). Rates of cation leaching from surface soils of the alder stand they studied were high because of high rates of NO_3^- formation. In that case, base cations moved to the B horizons at 15 to 45 cm.

The subsurface soil horizons can act not only as a potential cation sink, as in the case of Mg^{2+} , but also as a potential source. Nutrient budgets indicate that there was a source of K^+ that was not included in our budgets. Examination of soil chemical profiles characteristic of study site soils showed substantial amounts of all base cations, and particularly K^+ , available below the A and AB/BA horizons (Table 1). Cations at depths between 20 and 65 cm are readily available to plants. Approximately 30% of the root biomass of hardwood tree species at Coweeta is at depths of 20 to 80 cm (McGinty, 1976). Subsoil fertility was also found to be important to the nutrition of trees and other deep-rooted plants by Comerford et al. (1984) and Nowak et al. (1991).

Direct mineral weathering by roots may be another source of nutrients available to plants that is not included in standard nutrient budgets. April and Keller (1990) investigated the effects of roots on soil minerals and the

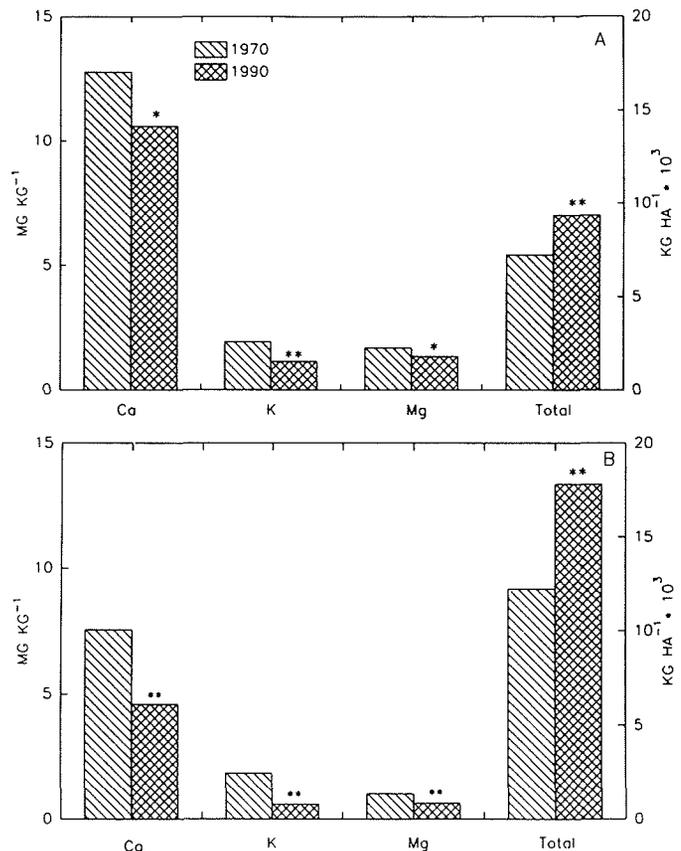


Fig. 3. Total weight and cation concentration of Oi plus Oe litter layers for (a) mixed-hardwood and (b) white pine watersheds. Values represent means of eight sample plots at two sample dates. * and ** represent significant difference between 1970 and 1990 means at $P = 0.05$ and 0.01 , respectively.

Table 3. Nutrient budgets for mixed-hardwood (HDWD) and white pine watersheds (WP). Budget is balanced in respect to the surface soil (20 cm) cation concentration differences between 1970 and 1990. Inputs and outputs represent 20-yr totals based on annual averages. '+' and '-' balance values indicate unmonitored additions and removals of cations to the watershed, respectively.

	HDWD			WP		
	Ca ²⁺	K ⁺	Mg ²⁺	Ca ²⁺	K ⁺	Mg ²⁺
	kg ha ⁻¹					
1970 pools						
Soil†	314	153	170	774	153	225
Litter‡	99	15	13	92	22	12
Inputs						
Depositions§	80	40	17	82	40	17
Bedrock weathering¶	82	76	56	82	76	56
Total	575	284	256	1030	291	310
Outputs						
Vegetation						
Aboveground#,††	90	100	20	215	200	56
Belowground‡‡	59	36	19	55	44	15
Stream§,§§						
Sediment	3	0.1	0.2	3	0.1	0.2
Dissolved	189	134	60	117	91	31
1990 pools						
Soil	102	86	39	575	138	83
Litter	93	11	13	81	11	11
Woody litter¶¶	56	16	4	11	10	10
Losses or additions	+ 17	+ 99	- 101	- 27	+ 203	- 104

† Yount, 1975a.

‡ Yount, 1975b.

§ Swank and Waide, 1988; Swank, 1988, unpublished data.

¶ Berry, 1977, unpublished data.

Monk and Day, 1988.

†† Swank and Schreuder, 1973; Swank, 1988, unpublished data.

‡‡ McGinty, 1976; Vose, 1992, unpublished data.

§§ Swank, 1988.

¶¶ Johnson et al., 1990.

potential for nutrient uptake at several sites, including Coweeta. They found evidence for differential weathering of biotite, a source of K⁺, adjacent to root surfaces.

Watershed History and Species Effects

Effects of the older mixed-hardwood forest and younger white pine plantation, on both soils and biomass, differed during the 20-yr period. All cation concentrations in the HDWD AB/BA horizon decreased significantly, but changes in soil cation concentrations in the WP AB/BA horizon were not significant. In 1970, beneath the pine, Ca²⁺ pools in the A plus AB/BA horizons were more than two times greater than in HDWD (Table 3). The higher initial cation content on WP results from the treatment before and during white pine establishment. The watershed was clear-cut in 1940 with no wood removal from the site. The vegetation was recut annually from 1940 through 1955 as part of a water yield experiment. After planting, the pines were released through manual and chemical means. The continued addition of vegetation material may have acted as a slow-release fertilizer treatment for the surface soils. The greater quantity of soil Ca²⁺ available in 1970 under the pine resulted in a smaller proportional change in soil Ca²⁺ during the 20-yr period, i.e., 25 and 75% decreases for WP and HDWD, respectively.

Biomass accumulation/leaching ratios of all three cations were greater for WP than for HDWD. This dissimilarity is due to both lower cation leaching rates and greater

rates of biomass accumulation in WP. Two processes are responsible for reduced leaching rates in WP. First, 25% greater evapotranspiration in WP (Swank et al., 1988) decreases total water movement through the watershed. Second, net primary production of woody material is much greater in the white pine than the hardwood forest, 9.0 vs. 4.0 Mg ha⁻¹ yr⁻¹. Thus, the younger, more vigorous white pine stand accumulated about 80% more Ca²⁺, K⁺, and Mg²⁺ than the mixed hardwood forest.

Components of the K⁺ budgets for these ecosystems also differ. For example, there was little or no decrease in K⁺ pools in the upper 20 cm of soil during the 20-yr period for WP. It appears that a greater amount of K⁺ was accumulated from subsurface soils in WP than in HDWD (204 vs. 99 kg ha⁻¹). This difference is approximately equal to the increased sequestration of K⁺ in the white pine plantation (108 kg ha⁻¹).

Alban (1982) and Binkley and Valentine (1991) found that many tree species change soil pH and cation concentrations, especially in the surface horizons. Species differed in their effects on soil acidity. Binkley and Valentine (1991) found more acidic soils under white pine and Norway spruce [*Picea abies* (L.) karsten] than under green ash (*Fraxinus pennsylvanica* Marshall var. *pennsylvanica*). Alban (1982), on the other hand, found that the acidifying effect of aspen (*Populus tremuloides* Michaux) was greater than red pine (*Pinus resinosa* Aiton) or jack pine (*Pinus banksiana* Lambert) and about equal to white spruce [*Picea glauca* (Moench) Voss]. In our study, soil pH of A horizon soils in WP decreased

from 5.9 to 5.0 whereas, in HDWD, it fell from 4.9 to 4.7. The decrease in BS indicates that accumulation of cations in biomass is largely responsible for the pH decrease. The decline in CEC indicates that the exchange complex may have changed (Binkley, 1992). This can result from changes in pH-dependent exchange sites on organic compounds, in organic matter quality, or in secondary minerals. Soil pH also decreased in AB/BA horizons in both watersheds. Decreases in HDWD soil pH resulted from cation losses. This is evident because of the decrease in BS with no change in CEC (Fig. 1d). The WP shows a different pattern where AB/BA soil pH decreased but CEC increased and BS did not change. This suggests a change in the exchange complex (Binkley, 1992).

Our results show the importance of monitoring biomass accumulation and cation leaching as well as changes in soil chemical composition. Without this information, it would be impossible to attribute changes in soil nutrient content to the appropriate regulating processes. This understanding is essential to assessments of long-term productivity and interpretations of anthropogenic influences on forest ecosystems. The compilation of nutrient budgets shows that each base cation cycles differently and each watershed reacts distinctively.

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