NUTRIENT FLUX IN UNDISTURBED AND MANIPULATED FOREST ECOSYSTEMS IN THE SOUTHERN APPALACHIAN MOUNTAINS *

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ABSTRACT

The concentrations of nutrients in stream water were studied in western North Carolina, U. S. A., on 8 mature hardwood ecosystems and 16 forested systems that had been altered by cutting, species conversions, and changes in land use. The flux of NO_3-N, NH_4-N, PO_4-P, Cl^-, K^+, Na^+, Ca^{++}, Mg^{++}, and $SO_4^=$ through 14 of the watersheds was derived from measurements of dissolved ions in precipitation and streamflow. When compared with undisturbed watersheds, a grass-to-forest succession watershed that had been fertilized, limed, and herbicided showed larger losses of ions except for PO_4-P. Where the forests were cut and in various stages of natural revegetation, elevated NO_3-N discharge was evident at least 10 years after cutting, but appeared to return to baseline levels 20 years after treatment. Even mature deciduous forests that were partly defoliated by insects showed an increased discharge of NO_3-N. Excluding NO_3-N data, conversion of deciduous forests to white pine reduced the loss of most nutrients, and young coppice forests exhibited nutrient cycles that are as tight or closed as mature hardwood forests. The watershed manipulation most similar to commercial logging operations showed a large export of nutrients, but the interpretation of results was complicated by geologic factors. No changes in the discharge of NH_4-N and PO_4-P were observed for any of the watersheds; all ecosystems showed very large accumulations of $SO_4^=$.

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RÉSUMÉ

Les concentrations de nourriciers dans les cours d'eau étaient étudiées dans l'ouest du Caroline du Nord des Etats-Unis, sur 8 systèmes écologiques de mûr bois dur et sur 16 systèmes boisés qui avaient été modifiés en les coupant, par les conversions d'espèces, et des changements dans l'usage de la terre. Le flux de NO_3-N, NH_4-N, PO_4-P, Cl^-, K^+, Na^+, Ca^{++}, Mg^{++}, et $SO_4^=$ à travers 14 des lignes de partage des eaux était dérivé des mesurages des ions dissous dans la précipitation et dans l'écoulement de l'eau. Quand comparé avec les partages tranquilles, une succession d'herbeà-forêt partage qui avait été fertilisé, chaulé, et traité avec les herbes a montré de plus grands pertes d'ions à l'exception de PO_4-P. Quant aux bois qui étaient coupés et en divers étages de revégétation naturelle, un déchargement élevé de NO_3-N était évident 10 ans au moins après les avoir coupés, mais ils ont apparu à retourner à leurs niveaux de base 20 ans après le traitement. Eliminant l'indication de NO_3-N, la conversion des forêts caduques aux pins blancs a diminué la perte de plus de nourricier et les jeunes bois taillis ont montré des cycles nourriciers qui sont si solides ou si fermés que les mûrs bois durs. La manipulation de partage qui ressemble aux opérations de boisage commercial a montré une grande exportation des nourriciers, mais les interprétations des résultats étaient compliquées par les éléments géologiques. Aucune modification n'était observée au sujet de déchargement de NH_4-N et PO_4-P pour aucun partage; tous les systèmes écologiques ont montrés de très grandes accumulations de $SO_4^=$.

INTRODUCTION

Experimental watersheds can be ideal units for study of biogeochemical interactions in forest ecosystems (Bormann and Likens 1967), and nutrient responses to management practices on individual watersheds have been demonstrated (Aubertin et al. 1973; Pierce et al. 1972; Johnson and Swank 1973). However, in most instances, results represent only initial responses to treatment and only a small segment of the forests in a given region. Temporal and spatial stream chemistry data are needed for streams draining both undisturbed and manipulated forests. The numerous watersheds at the Coweeta Hydrologic Laboratory in North Carolina provide excellent opportunities for such studies because their hydrologic, climatological, and vegetative conditions have been well-documented over the past 40 years. Recognizing this opportunity, the Institute of Ecology at the University of Georgia and the USDA Forest Service began a cooperative study of nutrient cycling in four different vegetative ecosystems at Coweeta in 1968. Subsequently, the research became part of the U. S. International Biological Program in the Eastern Deciduous Forest Biome, and was expanded.

The long-term objective of this research is to develop models that predict nutrient circulation of forest systems so that results can be used to improve management practices. This paper summarizes the nutrient flux for 8 undisturbed watersheds and 16 watersheds that have been treated at various times in the past.

EXPERIMENTAL SITE DESCRIPTION

The study site is the 1,625-ha Coweeta Basin which is in the Blue Ridge Province of the southern Appalachian Mountains of North Carolina. The Region has undergone uplift, repeated and complex folding, and erosion. Three distinct rock types dating from the late Precambrian--early Palezoic period are present and are tentatively classified as the Coweeta Group (Hatcher 1974). Basin relief is about 1,000 meters. Individual watersheds have well-defined topographic boundaries, a relief of about 300 m with slopes that average about 45 percent.

Summers are cool and winters are mild. Rainfall is abundant and distributed rather uniformly throughout the year with at least 7 cm falling each month. Mean annual temperature is 12.8° C, and mean annual precipitation varies from 250 cm on the upper slopes to 170 cm at the lower elevations. Snow comprises less than 5 percent of the annual precipitation.

Soils include Dystrochrept (Typic Fluvaquentic and Umbric) and Haludult (Typic and Humic) classifications. The regolith is characteristically deep, averaging about 7 m in depth. Profiles are well-developed at lower elevations, and surface horizons are low in density and highly permeable.

The indigenous vegetation is multistoried and is dominated by *Quercus* and *Carya* species interspersed with many associated species. Early use of the forest has been described elsewhere (Johnson and Swank 1973). Since 1924, there have been no fires or timber cutting in the basin except for experimental purposes.

Streamflow is perennial on the small watersheds, and the range of flow is rather narrow for all months. Discharge is highest and most variable in late winter and lowest and most stable in fall. Quickflow (or direct runoff) typically averages less than 10 percent of precipitation, and overland flow rarely occurs.

A summary of treatments and the vegetation types for the 24 subwatersheds used in this study are given in table 1, and additional details on treatments, physical characteristics, and vegetation are contained elsewhere (Hewlett and Hibbert 1961; Douglass and Swank 1972). Eight watersheds are controls or relatively undisturbed forests covered with mixed, mature hardwoods. They range in size from 12 to 61 ha. Vegetation on 13 watersheds which range from 9 to 144 ha in size has been altered by past experiments (table 1). Three stream gaging sites are on third-order streams (fig. 1), and these Watersheds (8, 9, and 16) include a combination of control and treated watersheds.

The most severe, recent disturbance was to Watershed 6 where the forest was harvested in 1958; the watershed was heavily fertilized and limed and converted to grass in 1959, and fertilized again in 1965. In 1966 through 1968, the grass cover was killed with herbicides; subsequently, the watershed has reverted to successional vegetation (Johnson and Swank 1973). The unregulated agriculture treatment on Watershed 3 was also a severe disturbance, but the area was rehabilitated 20 years ago by planting grasses and establishing eastern white pine (*Pinus strobus* L.) and yellow-poplar (*Liriodendron tulipfera* L.). This watershed was also heavily fertilized and limed at the time grasses were planted. The least disturbance was to Watershed 7 where a small number of cattle were allowed to graze the woodlands.

Table 1.--Summary of Coweeta watershed treatments, size, and vegetation types corresponding to chemistry data

Watershed No.	Treatment	Area (ha)	Vegetation Corresponding to Chemistry Data
1	All trees and shrubs cut in 1956-57, no products removed; white pine planted in 1957	16.2	White pine at ages 15 and 16 years
2, 14, 18, 21, 32, 34, & 36	All control	12.1, 61.1, 12.5, 24.3, 41.3, 32.8, & 48.6 respectively	All mixed mature hardwoods
3	Unregulated agriculture 1940-52 followed by planting yellow poplar and white pine	9.3	3 ha in 18-yr.-old poplar; 2 ha in 18-yr.-old white pine; 4 ha in 32-yr.-old coppice
6	Cut in 1958 and products removed; limed, fertilized, and grassed in 1959; refertilized in 1965; herbicided in 1966 and 1967	8.9	Grass-to-forest succession from 2nd through 6th year
7	Woodland grazed by six cattle 4 months each year from 1941 to 1952	58.7	Mixed mature hardwoods
8, 9, & 16	Combination watersheds; contain control and treated watersheds	759.6, 723.6, & 381.6 respectively	Mixture of mature hardwoods and regrowth
10	Commercial timber cut with 30 percent basal area removed in 1942-56	85.8	Mostly mature hardwoods with some regrowth
13	All trees and shrubs cut in 1939, recut in 1962; no products removed	16.2	Coppice at ages 7 through 11 years
17	All trees and shrubs cut in 1942, recut annually through 1955, no products removed; white pine planted in 1956	13.4	White pine at ages 13 through 17 years
19	Laurel and rhododendron understory cut in 1948-49; about 22 percent basal area	28.3	Mixed mature hardwoods
22	All trees and shrubs in alternate 33-ft. strips deadened by chemicals in 1955; no products removed	24.3	50 percent mature hardwoods; 50 percent 20-yr.-old regrowth
27	Control, but partially defoliated by fall cankerworm infestation	38.8	Partially defoliated mature hardwoods
28	All trees and shrubs cut on 77 ha, cove forest of 39 ha thinned, no cutting on 28 ha; products removed	144.1	77 ha of 11- to 12-yr.-old coppice; 39 ha of regrowth and poplar; 27 ha mature hardwoods
37	All trees and shrubs cut in 1963; no products removed	43.7	Coppice at ages 9 and 10 years
40	Commercial timber cut with 22 percent basal area removed in 1955	20.2	Mostly mature hardwoods
41	Commercial timber cut with 35 percent basal area removed in 1955	28.7	Mostly mature hardwoods

Grazing was concentrated on about 15 percent of the watershed, and the forest h remained undisturbed for about 25 years since termination of the experiment. E periments between these two extremes include light selection cuttings, clearcut without roads and no products removed, commercial logging operations, and conversion of mixed hardwoods to white pine.

PROCEDURES AND METHODS

The chemical responses of the different ecosystems are documented by measuring n trient concentrations of stream water or by calculating the mass flux of nutrien for the watersheds. The mass flux is estimated by monitoring the input and loss nutrients in precipitation and streamflow. Streamflow monitoring was suspended c some watersheds after experiments were terminated and, for these watersheds, average nutrient concentrations of stream water are used in evaluating responses. Water samples are routinely analyzed for pH, nitrate and ammonium nitrogen, phosphorus, chloride, calcium, sodium, potassium, magnesium, and sulfate.

Areal precipitation received by each experimental watershed is estimated using an isohyetal weighting system based on 35 years of rainfall data (Swift 1970). Th precipitation network consists of 12 standard raingages, and a separate gage at each site is used to collect samples for analysis of bulk precipitation chemistry. All gages are measured weekly. Bulk precipitation chemistry includes nutrients received as particulate fallout and in solution. Swank and Henderson (1974) provide a more complete description of methods used to monitor precipitation chemistry.

Concentration of ions and pH vary widely among samples for a given storm. To determine if concentration varied by location, an analysis of variance and Scheffe's Test (Freeze 1967) were performed on 13 months of precipitation data. For all ions studied, only Ca^{++} for one gage differed significantly (0.10 probability level) from most other gages. Therefore, concentrations for all gages were averaged, and input of ions to a watershed was obtained by multiplying mean concentrations by the weighted precipitation for each watershed.

Streamflow is measured continuously at weirs at the base of each watershed. Most weirs are sharp-crested 90° or 120° V-notch blades, but for large streams, 6-foot rectangle and 12-foot Cipolletti weirs are used. Samples for stream chemistry are collected weekly in polypropylene bottles from the stream directly above each weir. Details of stream sampling procedures are given elsewhere (Johnson and Swank 1973).

Water samples are analyzed at the Laboratory soon after collection. Analytical methods used for chemical analyses have been described by McSwain (1973) and McSwain et al. (1974).

RESULTS AND DISCUSSION

Hydrology

Because only several years of nutrient data are available for some watersheds, hydrologic factors must be considered during the interpretation of results. Average annual precipitation for the 2-year period of June 1972 through May 1974 exceeded the long-term average of the basin. For example, precipitation on Watershed 18 for this period averaged 236 cm/year, 30 percent greater than the 30-year average. Streamflow from individual watersheds was also substantially greater than long-term average flows, and the annual difference between total precipitation (P) and total runoff (RO) on Watershed 18 averaged 91 cm, only about 5 percent above the 30-year average P-RO value. Thus, although the hydrologic component of the nutrient influx and efflux are above average, the net differences are close to long-term means.

Evapotranspiration and streamflow have been altered on some watersheds by vegetative treatments, and these alterations must be considered when evaluating nutrient budgets. The paired-watershed method of analysis is used to determine the effect of treatments on water yield. Of the treated watersheds, flow records coincident with nutrient data are available for Watersheds 1, 6, 7, 13, 17, 28, and 37. Annual flows on Watersheds 7, 28, and 37 are all at pretreatment levels; i.e., flow from 1972-1974 was not statistically different from that expected from the original hardwood cover. For the 5 years of chemistry data (1969-1974) on Watersheds 6 and 13, annual flows averaged 4.4 cm (6 percent) and 10.0 cm (10 percent) above pretreatment levels. On Watersheds 1 and 17, evapotranspiration from the young pine forests is much greater than from the original hardwood forests, and during 1969-1974, average annual streamflow on each watershed was reduced by 18 cm (19 percent).

Precipitation and Stream Chemistry

Concentrations of most ions in both precipitation and stream water at Coweeta were low, usually less than 1 mg/l. The relative input of ions was $SO_4^{=} > Cl^{-} > Na^{+} > Ca^{++} > NO_3\text{-}N > NH_4\text{-}N > K^{+} > Mg^{++} > PO_4\text{-}P$. The pH of precipitation averaged 4.6 and ranged from 3.2 to 5.9. A previous summary of precipitation chemistry data showed that Ca^{++}, Mg^{++}, and K^{+} exhibit seasonal trends with peak concentrations occurring during spring and fall (Swank and Henderson 1974). Peak values are associated with local land use activities such as plowing and burning. Sea-salt aerosols appear to be the primary source of Na^{+} and Cl^{-}; for other ions, the period of record was insufficient to establish input patterns and sources.

Although ion concentrations in streams were generally low, there were clearly some significant differences in stream chemistry among watersheds (table 2). Concentrations of NO_3-N on undisturbed control watersheds averaged about 0.003 mg/l, but concentrations for treated watersheds are at two distinct response levels. Fo watersheds where vegetation was cut (Watersheds 13, 28, and 37), NO_3-N concentrations 10 years after treatment range between 0.050 and 0.182 mg/l, values which ar substantially above control streams. On watersheds where 20 or more years have elapsed since treatment (Watersheds 7, 10, 19, 22, 40, and 41), levels of NO_3-N ar similar in value to control streams. Watershed 3, one of the more drastically altered forest ecosystems, still shows slightly higher values (0.011 mg/l) than control streams. Watersheds converted to pine (Watersheds 1 and 17) also show elevated concentrations, and the highest values found on the Basin occur on Watershed ((.672 mg/l), which is the most recent severely manipulated system. Concentration of NO_3-N in the larger streams (Watersheds 8, 9, and 16) reflect the mixture of w ter from control and treated streams.

Concentration of NO_3-N on control Watershed 27 is about fivefold higher than other controls. This low, but obviously elevated, NO_3-N level is associated with the partial defoliation of vegetation by a fall cankerworm infestation. Supporti evidence of NO_3-N release to stream water by natural defoliation is available on control Watershed 36, although data are not included in table 2. During the spri of 1974, variable but elevated concentrations of NO_3-N were observed for Watersh 36. A ground survey of cankerworm egg masses in the winter of 1975 indicated th a moderate-to-heavy defoliation on parts of the watershed was to be expected. Tl spring, the expected defoliation occurred and was accompanied by a sixfold incre in NO_3-N in streamflow, a response similar to that shown for Watershed 27 in tab 2.

Studies of nitrifying bacteria populations in soils on some of the watersheds Coweeta show a positive correlation between NO_3-N content of streams and the qua tity of nitrifying populations (Todd 1974). The results indicate that nitrifyi activity is dependent on vegetation type and successional stage. Although addi-

Table 2.--Average annual concentration[1] (mg/l) of ions and pH of streams draining control, combination, and treated watersheds[2] at Coweeta Hydrologic Laboratory

Watershed No.	pH	NO_3-N	NH_4-N	PO_4-P	Cl	K	Na	Ca	Mg	SO
Control:										
2	6.85	.003	.003	.002	.700	.533	1.158	.636	.346	.3
14	6.61	.004	.004	.002	.540	.350	.739	.460	.280	.3
18	6.67	.003	.004	.002	.538	.461	.883	.626	.296	.2
21	6.62	.003	.004	.002	.495	.392	.716	.524	.227	N
27	6.51	.017	.004	.001	.538	.250	.511	.365	.208	1.0
32	6.58	.003	.004	.001	.499	.305	.665	.493	.285	.4
34	6.65	.003	.004	.001	.560	.394	.893	.692	.345	.2
36	6.63	.005	.004	.002	.567	.326	.784	.609	.267	.74
Combination Control and Disturbed:										
8	6.72	.009	.003	.002	.533	.386	.790	.804	.323	.48
9	6.68	.028	.005	.001	.533	.400	.817	.710	.344	.46
16	6.65	.016	.005	.002	.530	.400	.830	.728	.327	.55
Treated:										
1 ✓	6.61	.019	.006	.002	.714	.551	1.152	.724	.398	.51
3 ✓	6.84	.011	.005	.002	.554	.406	1.001	5.671	.460	.56
6	6.58	.672	.005	.002	1.296	.602	1.102	1.074	.649	.35
7	6.80	.003	.004	.002	.774	.495	.939	.876	.376	.42
10 ✓	6.77	.003	.004	.002	.543	.494	.931	1.343	.418	NA
13	6.61	.050	.004	.001	.500	.415	.640	.460	.262	.255
17	6.63	.127	.004	.002	.503	.458	.784	.516	.227	.336
19	6.67	.002	.004	.002	.504	.350	.679	.415	.240	NA
22	6.62	.006	.004	.002	.476	.343	.718	.559	.233	NA
28	6.68	.128	.004	.002	.509	.428	.850	.964	.442	.471
37 ✓	6.57	.182	.006	.001	.472	.402	.648	.744	.317	1.019
40 ✓	6.75	.005	.004	.003	.609	.538	1.116	1.038	.400	NA
41 ✓	6.72	.006	.004	.002	.582	.519	.997	1.030	.424	NA

0157
0336-0393

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[1] Concentration weighted by flow volume for Watersheds 1, 2, 6, 7, 8, 13, 14, 17, 18, 27, 28, 32, 34, 36, and 37; concentrations unweighted for all others.

[2] Period of record: $SO_4^=$ for all watersheds, June 1973 through May 1974; Ion concentration for Watersheds 10, 19, 21, 22, 40, and 41, June 1972 through May 1973; remaining watersheds, June 1972 through May 1974 except for Na^+, K^+, Ca^{++}, and Mg^{++} on Watersheds 6, 13, 17, and 18 which are for June 1969 through May 1974.

tional data are needed to clarify transformations within the systems, it is clear from the data in table 2 that NO_3-N provides a sensitive indicator of natural and man-induced disturbances of forest ecosystems. Moreover, an accelerated release of NO_3-N to streams is detectable at least 10 years after cutting forest vegetation, but levels approach baseline values in about 20 years.

Concentrations of NH_4-N and PO_4-P are very low and essentially the same for control, treated, and combination watersheds (table 2). These results are consistent with other studies that have shown that P is relatively immobile and strongly conserved by forest ecosystems (Hobbie and Likens 1973) and that NH_4-N is rapidly immobilized by soil biota or taken up by the root-mycorrhiza complex (Mitchell et al., in press).

With a few exceptions, other differences among watersheds are difficult to resolve from concentration data alone. Chloride, K^+, Na^+, Ca^{++}, and Mg^{++} concentrations on Watershed 6 usually exceed values shown for all other watersheds. However, nutrient levels are low considering past applications of heavy fertilizer, lime, and herbicides. Apparently, the deep soil of the watershed acts as a "buffer" which provides a gradual release of ions to the stream. The highest Ca^{++} concentrations are found on Watershed 3 and are partially due to past lime applications. Sulfate levels for Watersheds 27, 36, and 37 are substantially higher than for other watersheds, but reasons for the divergence are not clear. Compared to other watersheds, there is a general pattern of higher Na^+ and Ca^{++} concentrations in streams draining southerly facing watersheds (Watersheds 1, 2, 3, 7, 10, 34, 40, and 41) on Shope Fork (fig. 1). The basin geology is currently being mapped, and preliminary indications are that this pattern may reflect differences in bedrock composition.

Concentrations of some ions vary seasonally. Earlier, Johnson and Swank (1973) reported that concentrations of Ca^{++}, Mg^+, K^+, and Na^+ on undisturbed hardwood (Watershed 18), coppice (Watershed 13), and pine (Watershed 17) were highest in the summer and lowest in the winter. The seasonal pattern of K^+ and Mg^+ for grass-to-forest succession appeared to be 6 months out of phase with the forested watersheds.

Nutrient Budgets

Average annual nutrient budgets (inputs vs. outputs) for dissolved ions were determined for seven control and seven treated watersheds (table 3). Perhaps the most striking results are for nitrogen. Control watersheds accumulated about 3.5 and 2.5 kg/ha/year of NO_3-N and NH_4-N, respectively. Since Todd et al. (in press) have shown that gaseous transformations of nitrogen must be quantified to obtain total nitrogen budgets for forest ecosystems, we must emphasize that nitrogen values in table 3 represent the inorganic fractions in solution. Treated watersheds also show accumulations of NO_3-N, but net differences are less than for controls. Unlik other ecosystems, Watershed 6 shows a large (5.4 kg) net loss of NO_3-N. Net budget of NH_4-N varied little among treated and control watersheds, and all ecosystems shc an average annual accumulation of about 0.10 kg/ha of PO_4-P.

The net budgets of other ions for control watersheds also show some trends. On controls, chloride inputs and outputs appear to be in balance. The net budgets fo K^+ and Mg^{++} are reasonably consistent between controls, with an average annual net loss of 3.4 and 3.6 kg/ha, respectively. Budgets for Na^+ and Ca^{++} are more variable, possibly in response to differences in bedrock mineralogy and weathering rate On both control and treated watersheds, $SO_4^=$ appears to be accumulating at a net a nual rate of 25 to 39 kg/ha. Sulfate inputs are in reasonable agreement with valu reported for other forest ecosystems, but outputs are much lower (Likens and Borma 1972). Following deforestation of a hardwood-covered watershed at Hubbard Brook i New Hampshire, Likens et al. (1970) observed a 45-percent reduction in $SO_4^=$ concen trations of stream water. Several possible explanations were given for the

Table 3.--Average annual[1/] nutrient budgets for control and treated watersheds at Coweeta Hydrologic Laboratory. Values are expressed in kg/ha.

Watershed Number	Input	Output	Net difference	Input	Output	Net difference	Input	Output	Net difference	Input	Output	Net difference	Input	Output	Net difference
	NO_3-N			NH_4-N			PO_4-P			Cl			SO_4		
Control:															
2	3.18	0.03	+3.15	2.42	0.03	+2.39	0.11	0.02	+0.09	7.88	7.98	-0.10	35.88	3.91	+33.97
14	3.33	0.06	+3.27	2.55	0.05	+2.50	0.11	0.02	+0.09	8.24	7.56	+0.68	36.18	4.90	+31.28
18	3.52	0.04	+3.48	2.65	0.05	+2.60	0.11	0.02	+0.09	8.70	8.07	+0.63	38.03	4.48	+33.55
27	4.30	0.36	+3.94	3.19	0.10	+3.09	0.14	0.03	+0.11	10.90	11.82	-0.92	50.36	29.76	+29.60
32	3.86	0.05	+3.81	2.90	0.07	+2.83	0.13	0.02	+0.11	9.82	9.04	+0.78	43.90	7.57	+36.33
34	3.49	0.05	+3.44	2.61	0.06	+2.55	0.12	0.02	+0.10	8.63	8.50	+0.13	39.49	4.53	+34.96
36	3.86	0.11	+3.75	2.89	0.08	+2.81	0.13	0.03	+0.10	9.67	12.42	-2.75	44.60	15.44	+29.16
Treated:															
1	3.09	0.15	+2.94	2.36	0.04	+2.32	0.10	0.02	+0.08	7.63	5.85	+1.78	34.95	4.11	+30.84
6	2.66	8.06	-5.40	2.51	0.06	+2.45	0.10	0.02	+0.08	8.15	15.54	-7.39	35.59	4.17	+31.42
7	3.22	0.03	+3.19	2.45	0.05	+2.40	0.10	0.02	+0.08	7.96	10.48	-2.52	36.42	6.02	+30.40
13	3.47	0.71	+2.76	2.64	0.05	+2.59	0.11	0.02	+0.09	8.39	7.12	+1.27	37.69	3.58	+34.11
17	3.60	1.33	+2.27	2.71	0.04	+2.67	0.12	0.02	+0.10	8.90	5.25	+3.65	38.85	3.35	+35.50
28	4.10	2.50	+1.60	3.06	0.08	+2.98	0.14	0.03	+0.11	10.43	9.98	+0.45	48.02	8.92	+39.10
37	3.88	3.74	+0.14	2.90	0.11	+2.79	0.13	0.03	+0.10	9.73	9.79	-0.06	45.17	19.99	+25.18

Watershed Number	Input	Output	Net difference	Input	Output	Net difference	Input	Output	Net difference	Input	Output	Net difference
	K			Na			Ca			Mg		
Control:												
2	2.08	6.08	-4.00	5.55	13.18	-7.63	4.20	7.26	-3.06	0.88	3.94	-3.06
14	2.14	4.90	-2.76	5.78	10.34	-4.56	4.30	6.45	-2.15	0.92	3.93	-3.01
18	2.36	5.61	-3.25	4.90	10.75	-5.85	4.93	7.62	-2.69	1.10	3.61	-2.51
27	2.96	5.50	-2.54	7.67	11.24	-3.57	5.70	8.05	-2.35	1.21	4.57	-3.36
32	2.67	5.54	-2.87	6.89	12.06	-5.17	5.11	8.94	-3.83	1.09	5.16	-4.07
34	2.33	5.96	-3.63	6.06	13.56	-7.50	4.61	10.49	-5.88	0.97	5.23	-4.26
36	2.68	7.17	-4.49	6.77	17.22	-10.45	5.11	13.40	-8.29	1.09	5.86	-4.77
Treated:												
1	2.04	4.53	-2.49	5.37	9.45	-4.08	4.09	5.94	-1.85	0.85	3.26	-2.41
6	2.23	6.32	-4.09	4.63	11.57	-6.94	4.61	11.28	-6.67	1.00	6.81	-5.81
7	2.12	6.74	-4.62	5.60	12.80	-7.20	4.26	11.92	-7.66	0.89	5.12	-4.23
13	2.39	5.00	-2.61	4.85	7.71	-2.86	4.77	5.55	-0.78	1.11	3.16	-2.05
17	2.45	4.01	-1.56	5.02	6.87	-1.85	5.14	4.52	+0.62	1.14	1.99	-0.85
28	2.87	8.40	-5.53	7.34	16.67	-9.33	5.45	18.92	-13.47	1.17	8.66	-7.49
37	2.72	8.40	-5.68	6.84	13.48	-6.64	5.15	15.49	-10.34	1.10	6.60	-5.50

[1/] Period of record: $SO_4^=$ for all watersheds, June 1973 through May 1974; K^+, Na^+, Ca^{++}, and Mg^{++} values for Watersheds 6, 13, 17, and 18, June 1969 through May 1974; all other response; one suggestion was increased sulfate reduction by bacteria due to increased anaerobic conditions in the deep soil layers. Reasons for low $SO_4^=$ concentrations in Coweeta streams and, hence, ecosystem accumulations are not known.

Net budgets for treated watersheds are highly variable for some ions. To draw more conclusive inferences of treatment effects on nutrient budgets, data in table 3 for control ecosystems were compared with adjacent treated watersheds to minimize differences in geology and weathering rates between watersheds. The treated watersheds were grouped by vegetative cover or treatment history (table 4). Compared to controls, the young white pine plantations show small losses of NO_3-N, no differences in NH_4-N, PO_4-P, and $SO_4^=$, but accumulations of 1.5 to 3.5 kg/ha/year for other ions. Total loss of ions is dependent on total water flow, and the net gain of ions in the pine ecosystem is partly attributable to greater evapotranspiration and, consequently, reduced flow from pine compared to mature hardwoods. The rapid accumulation of biomass for pine (Swank and Schreuder 1973) is also a factor in nutrient retention by the pine ecosystems. The young coppice forests show a net loss of 2 kg/ha/year for NO_3-N and no change in NH_4-N, PO_4-P, and Mg^{++} compared to mature hardwoods. Both gains and losses are shown for other ions, and it appears that the biogeochemical cycles for the young coppice are as tight or closed as cycles for mature hardwoods on the control watersheds. Average annual losses of 8.8 kg/ha for NO_3-N are shown for the grass-to-forest succession ecosystem, and smaller net losses are consistently indicated for most other nutrients. Reasons for this response have already been recounted. The commercially logged ecosystem (Watershed 28) contains a mixture of young coppice (54 percent), thinned forest with regrowth (27 percent), and uncut forest (19 percent). A net loss of 2.2 kg/ha/year is shown for NO_3-N, with little or no change for NH_4-N, PO_4-P, and Cl^-. However, net losses are large for K^+, Na^+, Ca^{++}, and Mg^{++}, while $SO_4^=$ shows a net gain. This is a relatively large ecosystem (144 ha), and geology may differ from the control watersheds used in the comparison (Watersheds 27 and 32), even though they bracket the boundaries of the treated watershed (fig. 1). On the other hand, site disturbance from skidding operations and roads is a primary treatment difference compared to the other coppice ecosystems in table 4 and could contribute to accelerated nutrient losses. Additional data are clearly needed to assess the impacts of commercial logging operations on nutrient flux in hardwood forests of the southern Appalachian Mountains.

Table 4.--Net loss or gain of ions for treated watersheds using the net budgets of the adjacent undisturbed hardwood-covered watersheds as baseline values (kg/ha/year)

Vegetation Type and Watershed No.	NO_3-N	NH_4-N	PO_4-P	Cl	K	Na	Ca	Mg	SO_4
Eastern white pine (1, 17)	-0.66	+0.05	0.00	+2.44	+1.48	+3.46	+2.12	+1.78	-0.05
Coppice (13, 37)	-2.12	+0.02	0.00	+1.66	-0.40	+3.08	-0.20	-0.01	-1.14
Grass-to-forest succession (6)	-8.78	-0.10	0.00	-8.04	-1.08	-1.74	-3.91	-3.05	-1.00
Commercial logging (28)	-2.21	+0.02	0.00	+0.59	-2.83	-4.96	-10.38	-3.78	+6.14

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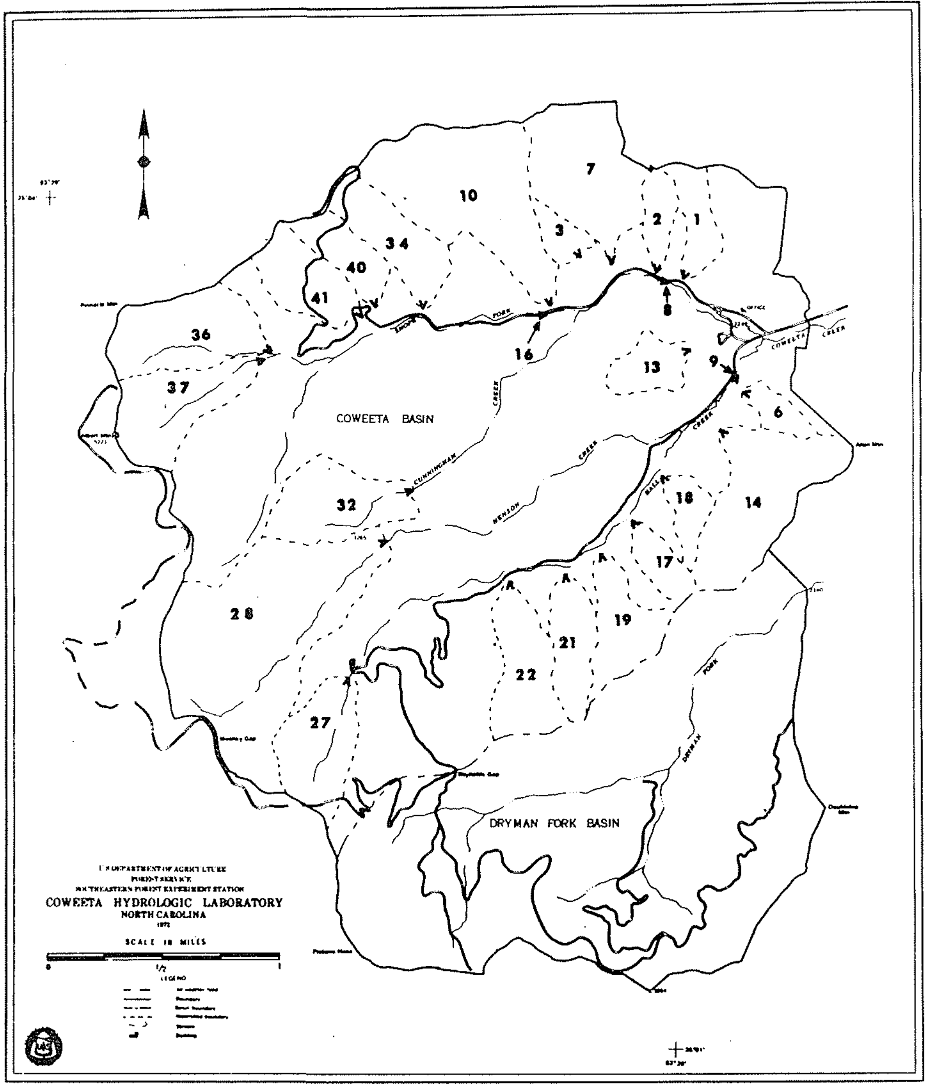

Fig. 1. The 1,625-ha Coweeta Basin is located in the mountains of western North Carolina. Experimental watersheds are indicated by number, and boundaries and steam gaging sites are shown for each watershed.