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Long-term nitrogen dynamics of Coweeta forested watersheds in the southeastern United States of America

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Abstract. We analyzed long-term (23 years) data of inorganic N deposition and loss for an extensive network of mature mixed hardwood covered watersheds in the southern Appalachians of North Carolina to assess trends and dynamics of N in baseline ecosystems. We also assessed watershed N saturation in the context of altered N cycles and stream inorganic N responses associated with management practices (cutting prescriptions, species replacement, and prescribed burning) and with natural disturbances (drought and wet years, insect infestations, hurricane damage, and ozone events) on reference watersheds. Reference watersheds were characterized as highly conservative of inorganic N with deposition < 9.0 kg ha^{-1} yr^{-1} and stream water exports below 0.25 kg ha^{-1} yr^{-1}. However, reference watersheds appeared to be in a transition phase between stage 0 and stage 1 of watershed N saturation as evidenced by significant time trend increases in annual flow-weighted concentrations of NO_3^- in stream water and increases in the seasonal amplitude and duration of NO_3 concentrations during 1972-1994. These stream water chemistry trends were partially attributed to significant increases in NO_3^- and NH_4^+ concentrations in bulk precipitation over the same period and/or reduced biological demand due to forest maturation. Levels and annual patterns of stream NO_3^- concentrations and intra-annual seasonal patterns characteristic of latter phases of stages 1 and 2 of watershed N saturation were found for low-elevation and high-elevation clear-cut watersheds, respectively, and were related to the dynamics of microbial transformations of N and vegetation uptake. Evidence for stage 3 of N saturation, where the watershed is a net source of N rather than a N sink, was found for the most distributed watershed at Coweeta (hardwood converted to grass, fertilized, limed, treated with herbicide, and subsequently characterized by successional vegetation). Compared to other intensive management practices, prescribed burning had little effect on stream water NO_3^- concentrations, and stream NO_3^- losses associated with natural disturbances are small and short-lived.

1. Introduction

Nitrogen (N) has been the most studied nutrient in forest ecosystems because of its importance in forest growth and productivity, the role of N in aquatic ecosystems, and recent concerns about increased N emissions and deposition with consequent effects on water quality and forest health. During the past decade, there has been increased research emphasis on forest ecosystem N saturation, defined as the availability of inorganic N in excess of biological assimilation of the ecosystem [*Aber et al., 1989*]. This condition can occur in forests receiving chronically high N deposition, such as portions of Europe [*Dise and Wright*, 1995; *Nihlgard*, 1985; *Van Breeman and van Dijk*, 1988; *Schulze*, 1989] and select forest ecosystems of the eastern United States [*Nodvin et al.*, 1995; *Peterjohn et al.* 1997]. Nitrogen saturation can also be induced experimentally such as in the European NITREX project where N saturation experiments are conducted to better understand processes and environmental responses [*Hultberg et al.*, 1994; *Moldan et al.*, 1995; *Dise and Wright*, 1995] or in other catchment fertilization and deforestation experiments [*Peterjohn et al.*, 1997; *Likens and Bormann*, 1995]. There are few assessments of N saturation in the context of altered N cycles and stream inorganic N responses associated with a range of typical forest management practices (regeneration prescriptions, species replacement, and prescribed burning) or natural disturbances. In this paper, we use long-term biogeochemical cycling data from an extensive network of both reference and managed watersheds in the southern Appalachian mountains to provide such an analysis for a region of relatively low N deposition.

The N cycle has been a focus of research in both reference and disturbed watersheds for over 25 years at the Coweeta Hydrologic Laboratory, a U.S. Department of Agriculture Forest Service laboratory, located in the southeast United States of America [*Swank and Crossley*, 1988]. An extensive network of long-term climatic, hydrologic, and chemistry monitoring for mixed hardwood reference and disturbed watersheds provides the core of the research, and process level research provides interpretation of integrated catchment responses. Our objectives are to (1) synthesize the long-term trends of N deposition and loss of the reference watersheds, (2) assess alterations in N dynamics associated with both management and natural disturbances and (3) present evidence for stages of N saturation [*Aber et al.*, 1989; *Stoddard*, 1994] in the context of the magnitude and temporal patterns of nitrate (NO_3^-) in stream water.

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2. Site Description

2.1. General

Most of the research presented in this paper is derived from the Coweeta Hydrologic Laboratory which is located in the Nantahala Mountain Range of western North Carolina within the Blue Ridge Physiographic Province, latitude 35°03´N and longitude 83°25´W. In several cases, we also utilize research conducted in the same mountain range located in the Nantahala National Forest. Established in 1934, the more than 6 decades of research on Coweeta watersheds is one of the longest continuous environmental studies available.

The 2185 ha laboratory is comprised of two adjacent, east facing, bowl-shaped basins. The primary site for watershed experimentation is the 1626 ha Coweeta Basin; while some studies are conducted on the 559 ha Dryman Fork Basin, it has been held in reserve for future watershed installations. The Coweeta Basin is drained by two fourth-order streams, Ball Creek and Shope Fork, which join within the laboratory boundary to form Coweeta Creek that flows 7 km east to the Little Tennessee River. There are about 73.4 km of streams within the laboratory, and about 57% of this distance is comprised of first-order streams [*Wallace*, 1988]. Elevations range from 675 m in the administration area to 1592 m at Albert Mountain.

Climate of the region is classified as Marine, Humid Temperate [*Swift et al.*, 1988]. Mean annual precipitation ranges from 1800 mm at low elevations to 2500 mm at high elevations and is rather evenly disturbed with a range of 112 mm in October to 203 mm in March at the base climatic station. Snowfall typically comprises less than 5% of the total precipitation. At the base climatic station, mean annual temperature averages 12.6°C and ranges from 3.3°C in January to 21.6°C in July. Hydrologic response analyses show that only 10% or less of the annual discharge occurs as quick flow for low-elevation watersheds, and this increases to about 30% for high-elevation watersheds [*Swift et al.*, 1988]. Mean annual evapotranspiration decreases from about 900 mm at low elevation to 620 mm for high-elevation watersheds.

Intensive bedrock mapping within the laboratory has identified three formations within the basin [*Hatcher*, 1988]. The composition of these units includes coarse-grained quartz diorite gneiss, feldspathic to quartzose metasandstone and interlayered muscovite - biotite schist, and garnetiferous muscovite and biotite schists. Soils within the laboratory fall within two orders: immature Inceptisols and older developed Ultisols. Umbric Dystrochrepts of the Porter series are found on steep faces at high elevations on the north and south facing aspect of the laboratory, and Typic Dystrochrepts, as represented by the Chandler gravelly loam series, comprise the majority of the Inceptisols. The Ultisols are represented by Typic Hapludults and Humic Hapludults. The Typic Hapludults are the largest soil group in areal extent, and the two most common series are Cowee-Evard gravelly loam and Fannin sandy loam series.

Mixed mesophytic forests characterize the region, and four major forest types occur within the basin [*Day et al.*, 1988]: (1) northern hardwoods which occur at higher elevations and are comprised of a variety of species including yellow birch (*Betula lutea*), black cherry (*Prunus serotina*), basswood (*Tilia heterophylla*), and northern red oak (*Quercus rubra*); (2) cove hardwoods that occur in mesic coves and are dominated by yellow popular (*Liriodendron tulipifera*), eastern hemlock (*Tsuga canadensis*), red maple (*Acer rubrum*), northern red oak, and hickory (Carya spp.); (3) mixed oak which is widely distributed over the basin slopes, with chestnut oak (*Quercus prinus*) being most widespread and other important species including scarlet oak (*Q. coccinea*), white oak (*Q. alba*), and black oak (*Q. velutina*); and (4) oak-pine which is found on the ridges and drier slopes at lower elevations and is dominated by pitch pine (*Pinus rigida*) and scarlet oak. An extensive evergreen understory occurs throughout the basin and is comprised of rosebay rhododendron (*Rhododendron maximum*) and mountain laurel (*Kalmia latifolia*). Basal area averages about 30 m^2 ha^{-1} on reference watersheds, and the overstory trees are predominantly in the 80-100 year age class.

2.2. Study Watersheds

The location of watersheds within the Coweeta Basin analyzed in this paper are indicated in Figure 1. Physical characteristics, dates of stream gaging initiation, and periods for stream chemistry measurements are summarized in Table 1. Watershed areas range from 9 ha to 760 ha, maximum elevation is from 912 m to 1600 m, and aspects are represented by south, north, and east facing slopes. Both reference and disturbed watersheds span the elevational gradient and the predominant aspects found in the laboratory. Watersheds drained by first-order streams typically have a relief of about 300 m and have perennial flow even in drought years. Stream gaging on most watersheds began in the mid 1930s, and inorganic N measurements were initiated in 1971 with intermittent sampling on some watersheds (Table 1).

Disturbance or management history for watersheds is summarized in Table 2. Stream chemistry sampling has been conducted on seven reference or control watersheds which are distributed across low, middle, and high elevations. Vegetation has remained undisturbed by management since 1927 with a prior logging history of selective cutting in 1924 [*Douglass and Hoover*, 1988]. Natural disturbances include the loss of American chestnut (*Castanea dentata*) to the chestnut blight fungus [Endothin parasitica (Murr.)P.] in the 1920-1930s, defoliation by fall cankerworm (Lepidoptera: Geometridae) infestations on watershed (WS) 27 and 36 during the 1970s, a record drought during the period 1985-1988, and patchy but widespread windthrow associated with hurricane Opal in October 1995. The latter three natural disturbances coincide with the record of stream chemistry. Management disturbances include clear-cuts and selection cuts of various ages with and without logging (WS 7, 13, 28, 37, and 40), replacement of mixed hardwoods with white pine (*Pinus strobus*) (WS 1 and 17), and old field succession (WS 6) following hardwood to grass conversion with lime, fertilizer, and herbicide applications (Table 2). The other major management prescription we will consider is the use of fire to maintain or restore mixed pine-oak communities located on National Forest lands. Two separate studies are in progress on watersheds in proximity to Coweeta. The first involves broadcast burning as a site preparation tool following clear-felling [*Vose and Swank*, 1993], and the second study is assessing the use of fire as a method for stand replacement

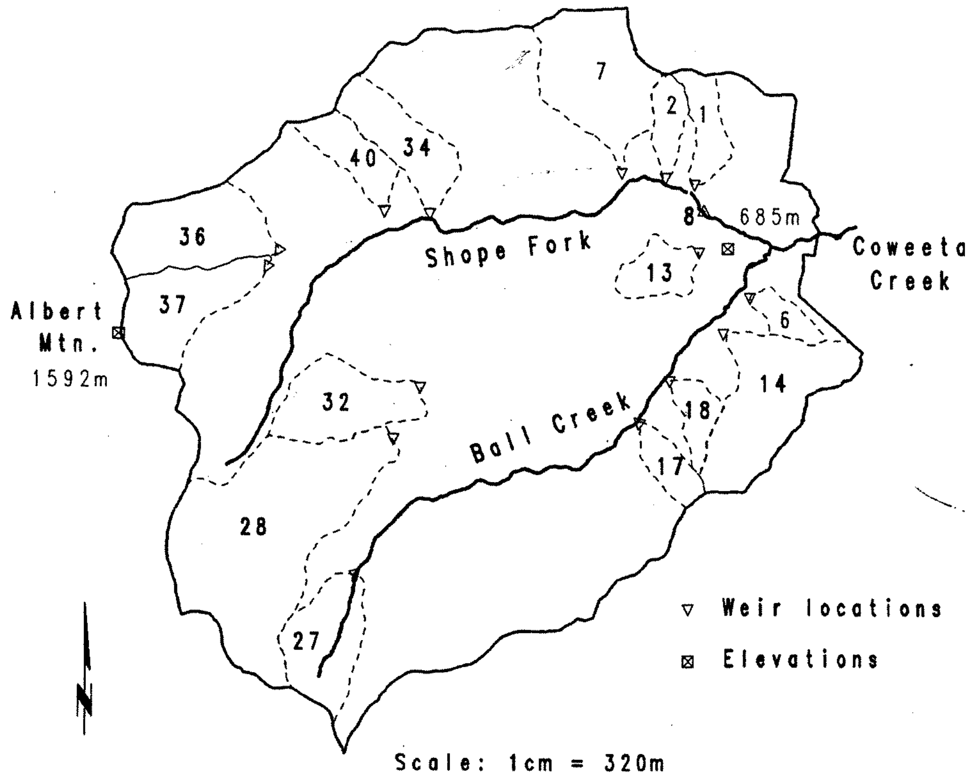

Figure 1. Locations of reference and experimental watersheds within the Coweeta Basin used in this paper. See Table 2 for a description of treatments corresponding to the watershed numbers.

which is part of an ecosystem management project [*Swank et al.*, 1994]. In this paper we will summarize and evaluate N responses to these prescriptions.

3. Sampling Network and Methods

Bulk precipitation samples are collected weekly using 16 cm diameter plastic funnels connected to buried two L polyproplyene bottles at eight extant precipitation stations located over the 1626 ha Coweeta Basin. These stations were selected to be representative for estimating individual watershed precipitation based on more than 2000 gage years of record [*Swift et al.*, 1988]. Samples are not collected unless weekly precipitation is > 1.3 cm to ensure that adequate sample amounts are available for all chemical analyses. When rainfall is insufficient, samples remain in the field until precipitation

Table 1. Summary of Watershed Characteristics at Coweeta Hydrologic Laboratory

Watershed	Stream Name	Area ha	Maximum Elevation, m	Aspect	Date of First Hydrologic Record	Period of Stream Solute Record
1	Copper Branch	16	988	S	June 6, 1934	1973-1974; 1982-present
2	Shope Branch	12	1004	SSE	June 22, 1934	1972-present
6	Sawmill Branch	9	905	NW	June 10, 1934	1972-present
7	Big Hurricane	59	1077	S	July 31, 1934	1972-present
8	Shope Fork	760	1600	NA	Oct. 6, 1934	1972-present
13	Carpenter Branch	16	912	ENE	March 12, 1936	1973-1974; 1982-present
14	Hugh White Branch	61	992	NW	May 26, 1936	1972-1974; 1982-present
17	Hertzler Branch	13	1021	NW	June 6, 1936	1972-present
18	Grady Branch	13	993	NW	July 3, 1936	1972-present
27	Hard Luck Creek	39	1454	NNE	Nov. 2, 1946	1972-present
28[a]	Henson Creek Number 2	144	1551	E	May 31, 1937	1973-1974
32	Cunningham Creek Number 2	41	1236	ESE	Oct. 25, 1941	1973-1974; 1982-present
34	Bee Branch	33	1184	SE	Oct. 31, 1938	1972-1974; 1982-present
36	Pinnacle Branch	49	1542	ESE	Apri 29, 1943	1972-present
37	Albert Branch	44	1592	ENE	April 15, 1942	1973-1974; 1983-present
40[a]	Wolf Rock Branch	29	1298	SSE	Dec. 4, 1938	1972-1973; 1986-1988

[a]Weirs are inactive or have been removed from service.

Table 2. Historical Descriptions of Coweeta Watershed Treatments

Watershed	Treatment Description
2, 14, 18, 32, 34	Controls with mixed hardwoods stand remaining undisturbed since 1927.
27	Control but partially defoliated by fall cankerworm infestation from 1972 to 1979.
36	Control but partially defoliated by fall cankerworm infestation from 1975 to 1979.
1	Entire watershed prescribed burned in April 1942. All trees and shrubs within the cove-hardwood type (areas adjacent to stream) deadened with chemicals in 1954. This treatment represented 25% of both land area and total watershed basal area. Retreated as necessary for three consecutive growing seasons. All trees and shrubs cut and burned in 1956-1957, no products removed; white pine planted in 1957. In subsequent years, pine released from hardwood competition by cutting and chemicals as necessary.
6	All woody vegetation cut and scattered in the zone 5 m vertically above the stream; reduced total watershed basal area 12%. Clear-cut in 1958, products removed and remaining residue piled and burned. Surface soil scarified, watershed planted to grass, limed, and fertilized in 1959; fertilized again in 1965. Grass herbicided in 1966 and 1967; watershed subsequently reverted to successional vegetation.
7	Lower portion of watershed grazed by an average of six cattle during a 5 month period each year from 1941 to 1952. Commercially clear-cut and cable logged in 1977.
8	Combination watershed containing both control and treated watersheds.
13	All woody vegetation cut in 1939 and allowed to regrow until 1962 when the watershed was again clear-cut; no products removed in either treatment.
17	All woody vegetation cut in 1940 and regrowth cut annually thereafter in most years until 1955; no products removed. White pine planted in 1956 and released from hardwood competition as required with cutting or chemicals.
28	Multiple use demonstration comprised of commercial harvest with clear-cutting on 77 ha, thinning on 39 ha of the cove forest, and no cutting on 28 ha; products removed.
37	All woody vegetation cut in 1963; no products removed.
40	Commercial selection cut with 22% of basal area removed in 1955.

is ≥ 1.3 cm. However, owing to the magnitude and frequency of precipitation events at Coweeta, this is infrequent, and on average there are about 38 weekly collections per year. Funnels and tubing are routinely inspected and replaced, and preservative is added to sample bottles in the field to inhibit sample degradation [*Swank and Henderson*, 1976]. In an earlier study, we examined homogeneity of gage means for all solutes analyzed at Coweeta [*Swank and Waide*, 1988]. Individual gage means were not significantly different (analysis of variance; $p \leq 0.05$) for NO_3^- and NH_4^+; thus all eight gages are used to calculate a weekly arithmetic mean concentration for the basin which is used along with specific watershed precipitation amounts to estimate watershed nutrient inputs.

Samples for estimating dry deposition inputs of nutrients to the Coweeta Basin have been collected since 1971 in dry fall samplers located at two low-elevation sites near the administration area. Both collectors close automatically to exclude rain and snow. Samples are recovered weekly from each collector in 500 mL of deionized water and analyzed for inorganic constituents.

Coweeta has also participated as a site for monitoring precipitation chemistry in the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) since July 1978. Additionally, the laboratory was one of the sites in the Integrated Forest Study (IFS), which evaluated the effects of atmospheric deposition on nutrient cycling in forest ecosystems [*Johnson and Lindberg*, 1992]. Data from these projects will be used in the results sections to further interpret N deposition data from the long-term Coweeta sampling network.

Stream discharge is measured continuously on each watershed using primarily 90° or 120° V-notched weirs, and flow summaries are routinely conducted using methods developed at Coweeta [*Hibbert and Cunningham*, 1966]. Stream water is sampled weekly by collecting a 250 mL sample in the flowing stream above the weir. Water samples are returned to the laboratory and refrigerated immediately; samples are typically analyzed within 7 days following collection. Nitrate was determined by the automated cadmium reduction method prior to July 1990 and thereafter by ion chromatograph, and NH_4^+ was determined by the automated phenate method [*Standard Methods*, 1985; *Deal et al.*, 1996] Quality control protocols include routine analyses of standards, from an independent laboratory, that represent the range of values typically found in precipitation and stream water samples. For some studies, flow proportional stream water samples have been collected and either composited or retained as discrete samples over storm hydrographs. Inorganic N shows small and inconsistent concentration changes during storm events. In a previous assessment of the reliability of weekly grab samples to estimate annual exports of NO_3^- values were compared to flow proportional calculated exports [*Swank and Waide*, 1988]. On the basis of a comparison over a 3 year period, the average annual export was only 9% higher for the estimates derived from the weekly grab sample compared to proportional sampling.

4. Long-Term Baseline Chemistry Trends

4.1. Precipitation Chemistry

The long-term mean monthly bulk precipitation concentrations and deposition for NO_3^- and NH_4^+ (Figures 2a and 2b) are based on 23 years of data. NO_3^- concentrations show some seasonality with highest values in spring and early summer months and lowest concentrations during the winter months (Figure 2a). Owing to the seasonality of precipitation, NO_3^- deposition shifts, with highest inputs during the wetter late winter-early spring periods and lowest inputs in the

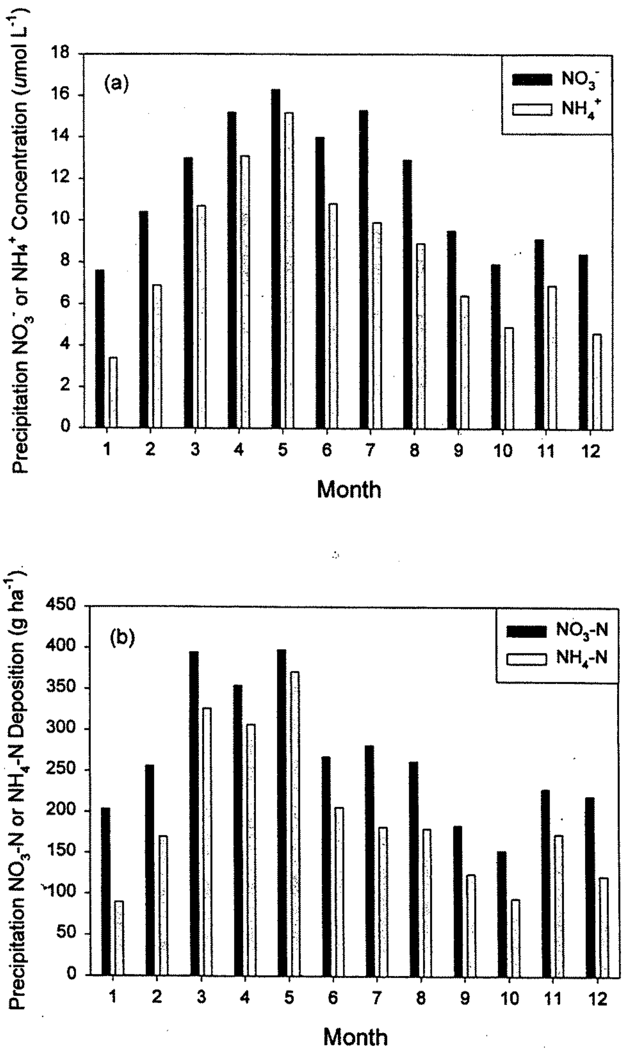

Figure 2. Long-term mean monthly NO_3^- and NH_4^+ (a) concentrations and (b) deposition in bulk precipitation. Data were averaged across eight collectors distributed throughout the Coweeta Basin.

fall season (Figure 2b). Long-term seasonal patterns of NH_4^+ concentrations and deposition track NO_3^- patterns, but intra-annual variation is greater for NH_4^+ (Figures 2a and 2b).

Although there is substantial interannual variability in volume-weighted NO_3^- and NH_4^+ precipitation concentrations, both ions show concentration increases over the period of 1972-1994 (Figure 3a). Linear regression analysis of concentrations versus time show weak, ($r^2 = 0.09$) but significant ($p < 0.10$) time trend (slope = 0.13 μmol L^{-1} yr^{-1}) for NO_3^- and a strong ($r^2 = 0.51$) time trend (slope = 0.27 μmol L^{-1} yr^{-1}) for NH_4^+ which has doubled in concentration over the past 23 years. Previous trend analysis of NO_3^- and NH_4^+ concentrations using NADP/NTN data for Coweeta showed decreasing concentrations over time [*Lynch et al.*, 1995]. However, only 13 years of data were available, and the data also excluded dry deposition. Part of the inter-annual variability in ion concentrations is related to variation in precipitation amounts where annual concentrations are inversely related to precipitation [NO_3^- $r^2 = 0.45$ ($p < 0.01$) and NH_4^+ $r^2 = 0.11$ ($p < 0.10$)] (Figure 3b). Multiple linear regressions of ion concentrations versus time and precipitation indicated that both time and precipitation were significantly related to NO_3^- and NH_4^+. For NO_3^-, precipitation was significant at the $p < 0.01$ level and time was significant at the $p < 0.10$ level (adjusted $r^2 = 0.52$) (model: $NO_3^- = 18.95 - 0.04 * \text{precipitation} + 0.11 * \text{year}$). For NH_4^+, time was significant at the $p < .01$ level and precipitation at the $p < .05$ level (adjusted $r^2 = 0.60$) (model: $NH_4^+ = 9.70 - 0.03 * \text{precipitation} + 0.25 * \text{year}$). For NO_3^-, partial r^2 values were 0.44 for precipitation and 0.08 for time, indicating that precipitation amount was the primary factor influencing intra-annual variation in NO_3^- concentration. For NH_4^+, partial r^2 values were 0.50 for time and 0.10 for precipitation, indicating the importance of increased contributions from external atmospheric sources over time.

We postulate that these temporal trends are primarily due to increased dry deposition. Dry deposition includes sedimentation, aerosol impaction, and vapor absorption processes. The

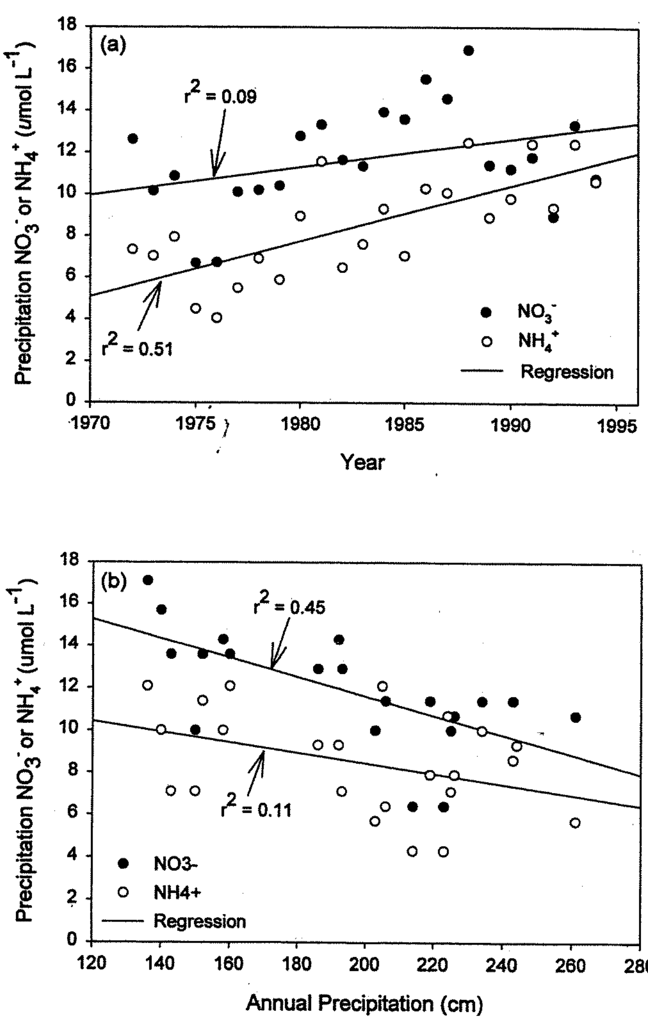

Figure 3. Trends in average annual bulk precipitation NO_3^- and NH_4^+ concentrations in relation to (a) time and (b) total annual precipitation. For Figure 3a, regression lines are significant at $p < 0.10$ and $p < 0.01$ for NO_3^- and NH_4^+, respectively. For Figure 3b, regression lines are significant at $p < 0.01$ and $p < 0.10$ for NO_3^- and NH_4^+, respectively.

open bucket samplers used at Coweeta primarily collect coarse particles during nonprecipitation events. Previous analysis of atmospheric chemistry in the Coweeta Basin has shown the influence of spring plowing and burning plus fall burning on inter-annual precipitation chemistry [*Swank and Henderson*, 1976]. More recent research at Coweeta provides a unique opportunity to interpret atmospheric deposition estimates of the standard sampling network with alternative methods for estimating deposition. Using data from April 1, 1986, to March 31, 1989, we compared NO_3^- and NH_4^+ deposition estimates derived from the IFS study [*Johnson and Lindberg*, 1992], the NADP/NTN network data, and Coweeta bulk precipitation data. Over the 3 year period, annual NO_3^- and NH_4^+ deposition was 25% to 30% higher for the Coweeta network compared to NADP/NTN estimates. These results are not unexpected since the latter estimates are for "wet" deposition only. Methods used in the IFS study sampled all forms of dry deposition (i.e., sedimentation, vapors, and aerosols). Comparison of Coweeta bulk versus IFS precipitation plus coarse particles deposition showed differences of only 10% for both NO_3^- and NH_4^+. However, IFS estimates of total annual deposition were 20% higher for NH_4^+ because of fine particulate contributions that are largely unmeasured in open buckets and were 40% higher for NO_3^- due to HNO_3 vapor deposition which also is not measured by bucket sampling. Thus, for the following discussion it is important to recognize that the dry fall estimates of NO_3^- and NH_4^+ reported in this paper underestimate total deposition to forested watersheds by 20-40%. Moreover, the patterns of dry fall primarily represent coarse particulate deposition, and trends for other forms of dry deposition are unknown.

Mean annual (1972-1994) dry fall inputs of both NO_3^--N and NH4$^+$-N are 0.21 kg ha^{-1} y^{r-1} which represents 7% and 9% of the mean annual bulk deposition for NO_3^- and NH_4^+, respectively. A time trend analysis of dryfall deposition indicates that both NO_3^- ($r^2 = 0.42, p < 0.01$) and NH_4^+ ($r^2 = 0.26, p < 0.01$) have nearly tripled (0.1 to 0.3 kg ha^{-1}) over the past 2 decades (Figure 4) which partially contributes to the inter-annual bulk precipitation trends (Figure 3a). Additional analysis of time trends revealed significant increases in NO_3^-

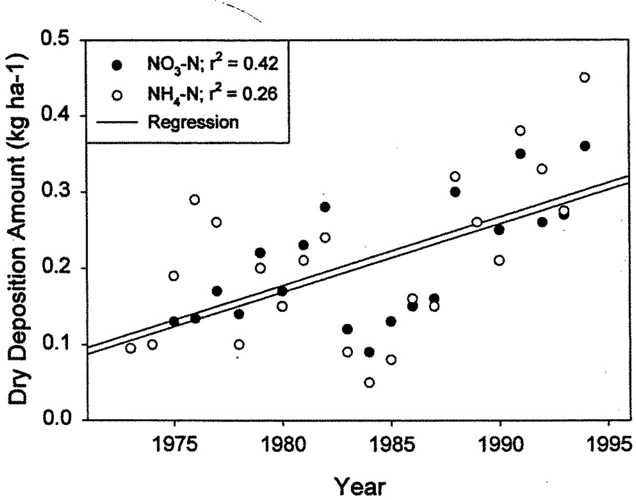

Figure 4. Trends in annual dry deposition totals for NO_3-N and NH_4^+N. Regression lines are significant at $p < 0.05$.

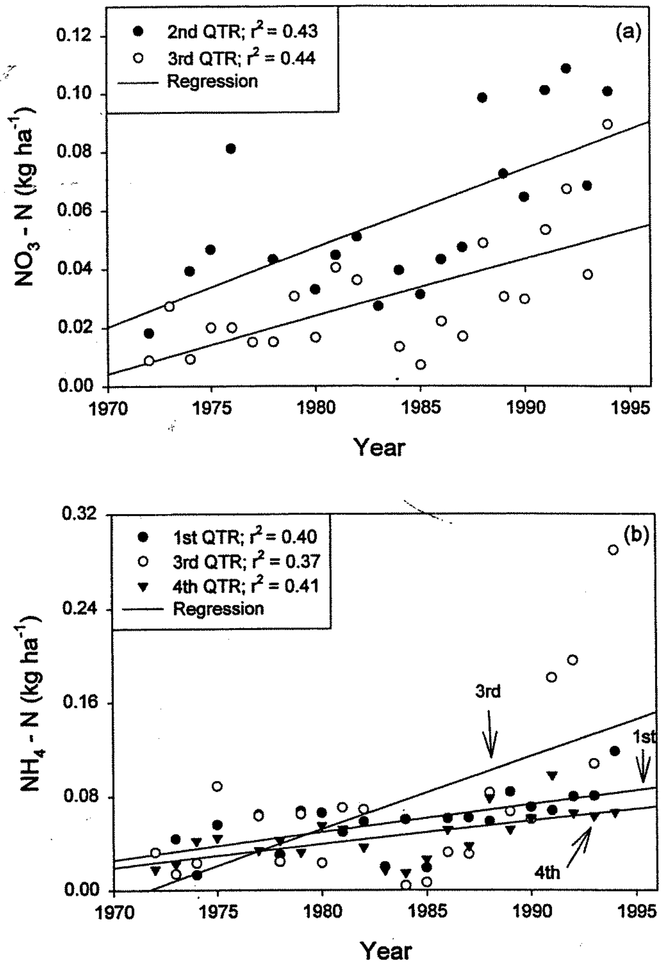

Figure 5. Trends in dry deposition of (a) NO_3-N and (b) NH_4^+N in relation to time. Data are summarized as quarterly means (first is January - March, second is April - June, etc.), and only quarters with significant regressions are presented.

deposition in the second and third quarters of the calendar year (Figure 5a) and in the first, third, and fourth quarters for NH_4^+ dryfall deposition (Figure 5b). Thus it appears that regional sources of particulate forms of inorganic N have increased over time, especially during the spring and summer months.

4.2. Stream Chemistry

Concentrations of NO_3^- and NH_4^+ in stream water of Coweeta reference watersheds are very low and frequently near detection limits (0.15 μmol L^{-1}). As previously discussed in the methods section, during storm events, NO_3^- concentrations remain rather stable and show little dilution or concentrating effects with flow. Storm event sampling for streams draining disturbed watersheds with higher NO_3^- levels exhibit less stability in concentration/flow relationships and frequently show some dilution during a storm.

The intra-annual and interannual time trends for NO_3^- and NH_4^+ concentrations are similar for all reference watersheds, and data for only a subset (i.e., WS 18 and 36) are shown for illustrative purposes. Stream NH_4^+ concentrations were consistently low and showed little variation among watersheds or with time; thus NH_4^+ is excluded from further discussion.

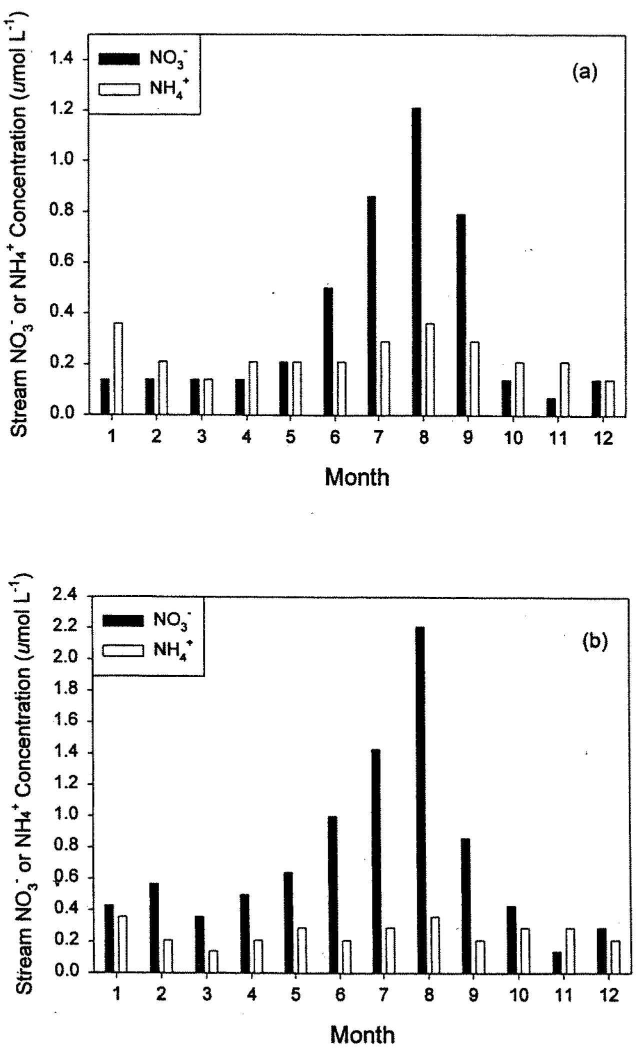

Figure 6. Intra-annual variation in stream water NO_3^- and NH_4^+ concentrations for (a) low-elevation (WS 18) and (b) high-elevation (WS 36) watersheds. Data are mean monthly values from 1972 to 1984.

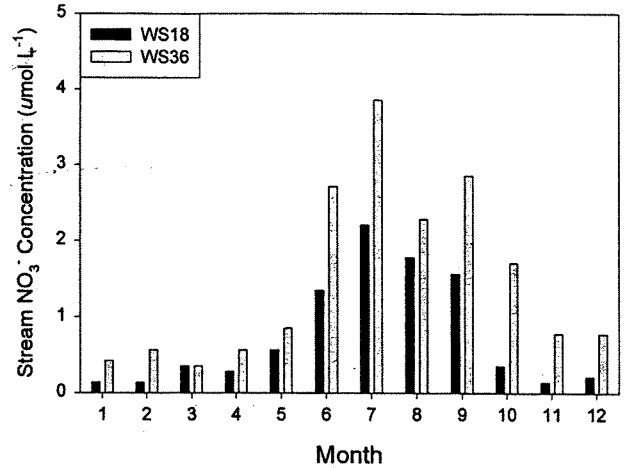

Figure 7. Intra-annual variation in stream water NO_3^- concentrations for low-elevation (WS 18) and high-elevation (WS 36) watersheds in 1991.

Nitrate concentrations in some months are typically higher for streams draining high elevation watersheds (WS 27 and 36) compared to low-elevation watersheds (Figures 6a and 6b). Although NO_3^- concentrations of all reference streams are generally low, there are some consistent intra-annual patterns. Characterization of mean monthly concentrations is based on the period 1972-1984, prior to a record drought during 1985-1988 that occurred throughout the southeast. During winter, early spring, and fall seasons, NO_3^- concentrations are at detection limits, and only during the summer months are small (1-2 μmol L^{-1}) increases in concentration observed. In the drought years, peak NO_3^- concentrations increased to > 5 μmol L^{-1} and persisted into the fall in response to concentrating effects of reduced streamflow. Subsequently, during average precipitation years, (e.g., 1991) the expanded seasonality and magnitude of peak concentrations were still present (Figure 7). Stream NO_3^- fluxes (g ha^{-1}) for reference watersheds follow the same seasonal patterns as concentrations (Figure 8a) where the largest fluxes occur in the growing season. This pattern

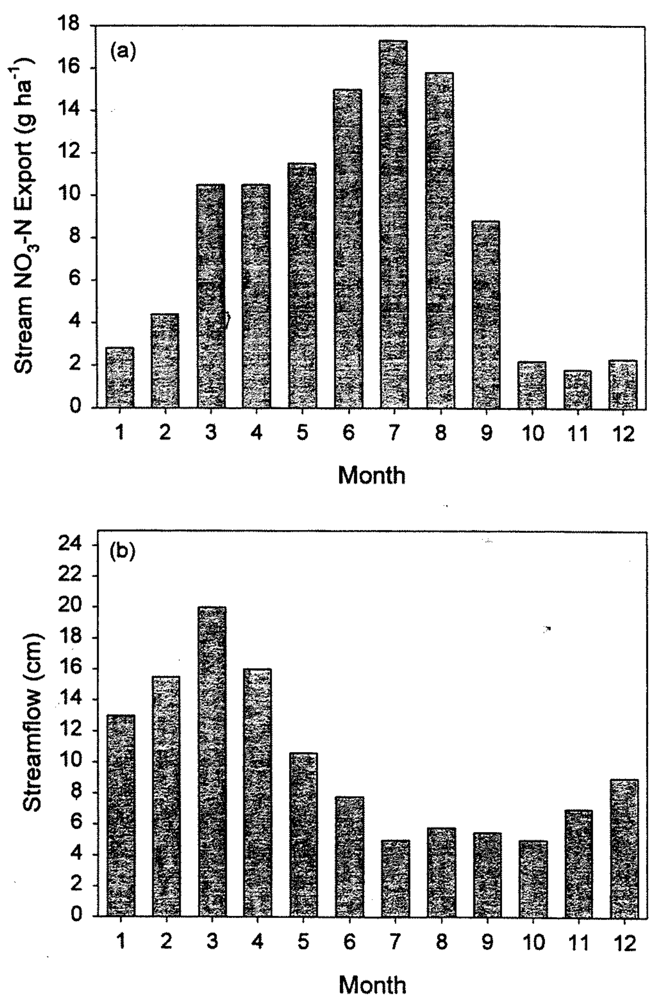

Figure 8. Intra-annual variation in (a) stream water NO_3-N export and (b) streamflow for WS 18. Data are mean monthly values for 1990-1994.

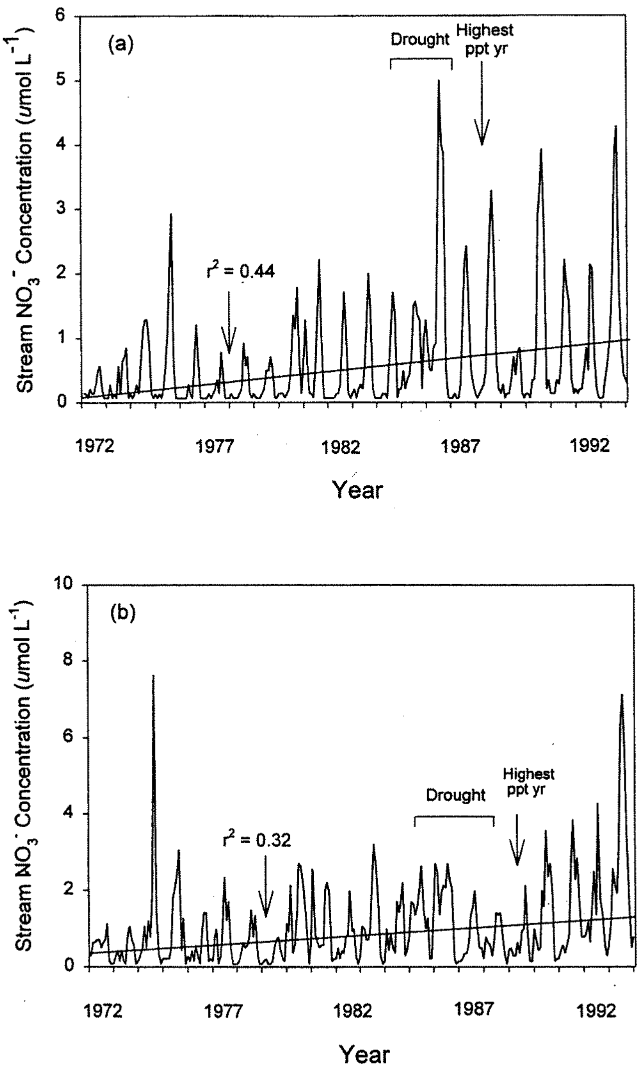

Figure 9. Trends in stream water NO_3^- for (a) low- and (b) high-elevation (WS 36) watersheds. The regression line ($p < 0.01$) was fit to annual means across the sampling period.

persists even though highest flows occur in early spring and then decrease during the summer months (Figure 8b).

The long-term (1972-1994) monthly time series of NO_3^- concentrations on reference WS 18 shows that the seasonal amplitude and duration of NO_3^- concentrations have increased, and annual concentrations, when regressed against time, show a significant ($r^2 = 0.44$ $p < 0.01$) increase over time (Figure 9a). Reference WS 36, a high elevation watershed, also showed a similar time trend ($r^2 = 0.32$ $p < 0.01$), but the rate of increase was about double WS 18 (Figure 9b). Annual discharge was not related to time, and when added as a second variable in multiple regression analysis, discharge did not explain additional temporal variation in NO_3 concentrations on WS 36 and WS 18.

The seasonal and monthly time series data indicate that the mixed hardwood watersheds at Coweeta may be in a transition phase between stage 0 and stage 1 of watershed N saturation proposed by *Aber et al.* [1989] and expanded upon by *Stoddard* [1994]. The important stream water characteristics of stage 0 watersheds are very low NO_3^- concentrations during most of the year and maximum spring or other seasonal concentrations that are below typical deposition concentrations. At stage 1, the seasonal pattern typical of stage 0 is amplified; that is, seasonal concentrations are higher, persist over a longer period of time, and may exceed deposition concentrations. At Coweeta the early record shows very low or detection limit NO_3^- concentrations during most of the year. Thus vegetation and microbial demands utilize most of the available NO_3^-, and there is a very small seasonal signal. Over time, as the successional forest becomes more mature, the seasonal pattern of NO_3^- is amplified; that is, peak concentrations increase, and there is an expanded seasonality of NO_3^- losses. This small, but measurable, alteration in the seasonal dynamics of NO_3^- is evident for all reference watersheds at Coweeta and may be related to the time trends of increased NO_3^- concentrations in precipitation and/or reduced biological demands associated with forest maturation.

4.3. Annual Budgets

Both precipitation and runoff increase with watershed elevation over the basin, but evapotranspiration (Et) decreases in response to differences in driving climate variables, soil depth, length of growing season, and vegetation structure between high and low elevations (Table 3). On average, annual Et for low- versus high-elevation watersheds is 90 cm and 60, cm respectively. Forested watersheds at Coweeta are highly conservative of inorganic N as previously shown by low stream solute concentrations and hence have positive net budgets of 2.9 - 3.6 kg ha^{-1} yr^{-1} for NO_3^--N and 2.1- 2.8 kg ha^{-1} yr^{-1} for NH_4-N (Table 3). Temporal trends of inputs mimic concentration trends; that is, the deposition of NH_4^+ has doubled over the last 2 decades.

5. Responses To Disturbance

The effects of management and experimental disturbances on water quality, and specifically, stream chemistry have been a central, integral theme of the long-term biogeochemical cycling research at Coweeta [*Swank and Crossley*, 1988]. Moreover, the time period of biogeochemical cycling research has encompassed important natural disturbances; for example, insect infestations, record drought and flood years, ozone events, and extensive hurricane damage. Our objective in this section is to summarize the impacts of these disturbances from a perspective of alterations in inorganic stream chemistry and budgets which, in turn, provide insights into factors regulating internal N retention and loss. Emphasis is placed on assessing responses in the context of watershed N saturation.

5.1. Effects of Cutting and Species Conversions

Disturbances at Coweeta have had little effect on stream NH_4^+ concentrations; thus only NO_3^- will be discussed. Nitrate serves as a sensitive indicator of ecosystem disturbance at Coweeta since values of reference streams are consistently low. Thus relatively small changes in stream NO_3 are indicative of large alterations in internal N cycling.

The long-term mean flow-weighted concentrations for streams draining managed watersheds exhibit several patterns

Table 3. Average Annual Water and Inorganic N Budgets for Coweeta Reference Watersheds (1972-1994)

	Water			NO_3-N			NH_4-N		
Watershed	Input	Output	Net[a] Difference	Input	Output	Net Difference	Input	Output	Net Difference
2	181	86	+95	2.93	0.04	+2.89	2.13	0.02	+2.11
14	187	101	+86	3.25	0.07	+3.17	2.51	0.03	+2.48
18	196	109	+87	3.19	0.06	+3.13	2.34	0.03	+2.31
27	239	174	+65	3.87	0.03	+3.15	2.82	0.07	+2.76
32[b]	222	152	+70	3.60	0.04	+3.56	2.36	0.06	+2.30
34	191	111	+80	3.34	0.05	+3.29	2.53	0.03	+2.50
36	216	172	+44	3.50	0.18	+3.32	2.55	0.06	2.49

Average annual water is measured in centimeters; N is measured in kilograms per hectare.
[a] Input - output provides an estimate of annual evapotranspiration.
[b] Based on data for 1972-1982.

(Table 4). On watersheds where the hardwood vegetation was clear-cut (WS 7, 13, 28, and 37), mean NO_3^- concentrations 18 to 34 years after treatment range from 2 to 13 μmol L^{-1}, which substantially exceeds concentrations of reference streams (0.2 - 0.5 μmol L^{-1}). Watersheds converted from hardwoods to white pine (WS 1 and 17) also show elevated NO_3^- concentrations 39 years after treatment. The light selection cut (22% basal area) on WS 40 had no long-lasting effect on NO_3^-, and the low value on WS 8, fourth-order Shope Fork, reflects a mixture of water from undisturbed and disturbed watersheds. The highest NO_3^- concentrations (56 μmol L^{-1}) found in the basin occur on WS 6 which was converted from hardwoods to grass along with fertilization and liming in 1959, was treated with herbicide in 1966-1967, and subsequently reverted to successional vegetation.

Mean annual inorganic N budgets (Table 5) provide another level for evaluating the effects of management practices on ecosystem N retention and loss because they integrate the influence of hydrologic processes on biogeochemical cycles. For example, by age 10, evapotranspiration (Et) from the white pine stands exceeded Et expected from mature hardwoods and at present, annual stream discharge is about 25% lower for the pine [*Swank and Vose*, 1994]. Thus net NO_3^- fluxes from the pine ecosystems are similar to reference watersheds even though conversion increased stream NO_3^- concentrations. The long-term NO_3^- inputs and outputs on clear-cut WS 37 are almost in balance, and WS 6 shows the most striking contrast to other disturbed ecosystems with a net loss of 4.0 kg ha^{-1} yr^{-1} (Table 5).

Table 4. Mean Annual Flow-Weighted NO_3 Concentrations of Streams Draining Treated Watersheds at Coweeta

Treatment[a]	Watershed	NO_3 Concentration, μmol L^{-1}	Period of Treatment Record
Clear-cut	7	5	1977-present
	13	2	1973-1974; 1982-present
	28	9	1973-1974
	37	13	1973-1974; 1983-present
Hardwood to pine conversion	1	2	1973-1974; 1982-present
	17	10	1972-present
Selection cut	40	<1	1972-1973; 1986-1988
Combined treated and undisturbed	8	1	1972-present
Hardwood to grass conversion; successional vegetation	6	56	1972-present

[a]Mean annual flow weighted NO_3 Concentrations of reference streams were < 0.3 μmol L^{-1} for all watersheds (WS) except WS 37 (reference < 0.6 μmol L^{-1}).

Disturbance regimes that increased annual streamflow subsequently declined to pretreatment annual streamflow levels in the early stages of stream chemistry measurements at Coweeta. Therefore current elevated N losses reflect alteration of internal N transformations rather than increased streamflow.

5.2. Evidence for Stages of Watershed N Saturation

5.2.1. Stage 1. Intra-annual and interannual patterns and levels of NO_3^- concentrations in streams draining cut watersheds are very relevant to stages of forest N saturation since internal N processes can be substantially altered with disturbance. The NO_3^- dynamics on WS 7 provide strong evidence for conditions that support stage 1 of watershed N saturation and the influence of vegetation uptake on stream NO_3 concentrations. WS 7 has been the focus of intensive biogeochemical cycling research along with comparative process level studies on control WS 2 and represents the most precise quantification of effects of clear-cutting and logging on biogeochemical cycles and stream chemistry conducted at Coweeta. Processes regulating internal N cycling have been a major emphasis of the research. Increases in NO_3^- concentrations began about 9 months after cutting and harvest. Subsequently, concentrations increased to > 6 μmol L^{-1} in the next 2 years (Figure 10). When combined with reduced Et and increased discharge due to cutting, NO_3^-N export was increased an average of 1.2 kg^{-1} ha^{-1} yr^{-1} in the second and third years after treatment [*Swank*, 1988]. Thereafter, NO_3^- concentrations declined to < 4 μmol L^{-1} for the next 9 years, even in drought years (1985-1988) when the concentrating effects of low flow are maximal (Figure 10). Then, beginning in 1990, NO_3^- concentrations increased to levels observed in the early years following cutting (6-7 μmol L^{-1}) and subsequently were elevated to 10 μmol L^{-1} in the next 2 years. We attribute this pattern of stream water NO_3^- to successional vegetation

Table 5. Average Annual Water and Inorganic N Budgets for Treated Watersheds at Coweeta Hydrologic Laboratory

Treatment	Watershed	Water			NO_3-N			NH_4-N		
		Input	Output	Net Difference	Input	Output	Net Difference	Input	Output	Net Difference
Clear-cut	7	181	106	75	2.95	0.61	+2.34	2.18	0.03	+2.15
	13	187	103	84	3.21	0.31	+2.91	2.51	0.03	+2.48
	28	241	174	67	3.74	2.14	+1.61	2.54	0.08	+2.46
	37	218	156	62	3.81	2.89	+0.93	2.87	0.05	+2.81
Hardwood to pine conversion	1	171	56	115	2.98	0.13	+2.85	2.31	0.02	+2.29
	17	201	70	131	3.26	0.97	+2.29	2.39	0.03	+2.37
Selection cut	40	214	124	90	3.32	0.07	+3.25	2.16	0.06	+2.10
Combined treated and undisturbed	8	203	123	80	3.31	0.23	+3.08	2.44	0.04	+2.40
Hardwood to grass conversion; successional vegetation	6	187	91	96	3.05	7.05	-4.00	2.26	0.04	+2.22

See Table 4 for period of record included in analysis. Average annual water is measured in centimeters; N is measured in kilograms per hectare.

dynamics which is also revealed by changes in water yield responses (Figure 11). Increased water yield is highest the first year after cutting and then exhibits an exponential decline with time, appearing to return to pretreatment levels in 6-10 years following disturbance. However, a second period of significantly increased flow is observed 14-15 years during succession. The long-term changes in streamflow on WS 7 are consistent with water yield responses of previous watershed clear-cutting experiments at Coweeta [*Douglass and Swank*, 1975], and the second, short-lived pulse of increased water yield has been related to reduced Et because of tree mortality associated with canopy closure and tree competition [*Swank and Helvey*, 1970; *Swift and Swank*, 1981). Apparently the same vegetation - Et - water yield responses occurred on WS 7. Remeasurement of the successional forest indicates that by 1993, woody stem density was reduced by 80% from 1984 density values [*Elliott et al.*, 1997], and field observation confirms that much of this mortality occurred early in the 1990s.

The first several years after clear-cutting on WS 7, rates of N mineralization and nitrification were substantially elevated, and soil NO_3^- and NH_4^+ increased [*Waide et al.*, 1988]. The initial, rapid recovery of N losses to baseline levels are related to high rates of net primary production (NPP) and incorporation and storage of nutrients in successional vegetation [*Boring et al.*, 1988]. In the first year after cutting, the N pool in NPP was already 29% of the NPP of the mature forest, and by the third year NPP was 60% of precutting values. The second stream NO_3^- pulse was probably due to tree mortality and decline in herbaceous vegetation [*Elliott et al.*, 1997] with consequent reductions in N uptake. We postulate that stream NO_3^- concentrations will again decline toward baseline values with the characteristic rapid recovery of Coweeta forest vegetation. The levels and annual patterns of stream NO_3^-

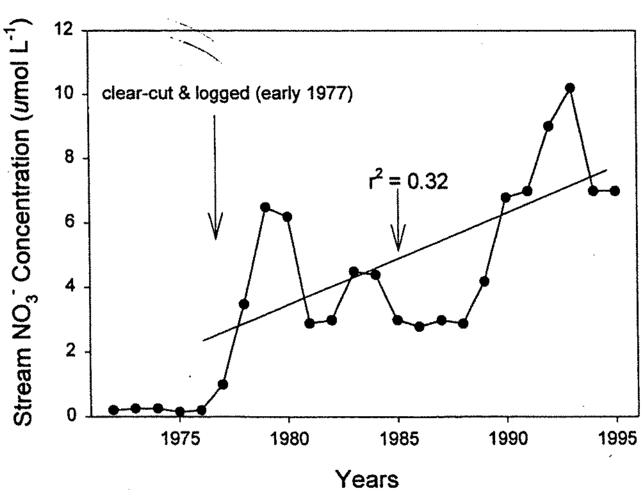

Figure 10. Trends in average annual stream water NO_3^- concentration on WS 7. The regression line ($p < 0.05$) was fit to the postcutting period of 1978-1995.

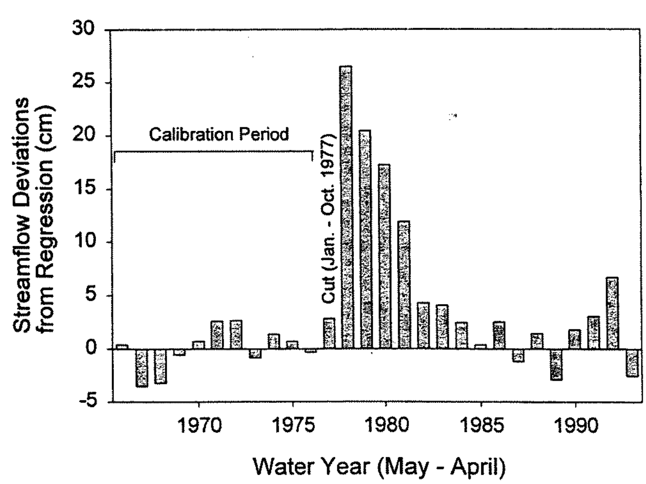

Figure 11. Annual streamflow deviations from regression predictions during precutting (1966-1976) and postcutting periods (1977-1993) for WS 7.

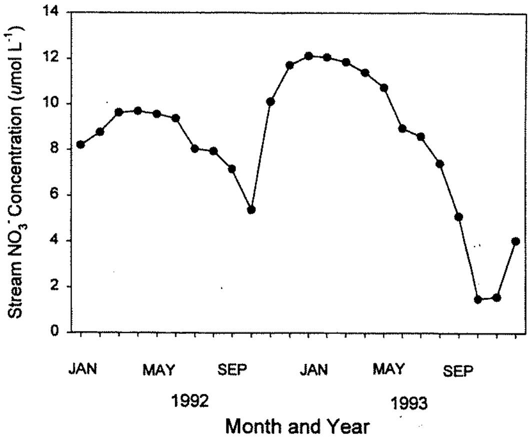

Figure 12. Intra-annual variation in stream water NO_3^- concentration for WS 7 in 1992 and 1993.

concentrations and intra-annual seasonal patterns (Figure 12) are characteristic of the latter phases in stage 1 of N saturation described by *Stoddard* [1994]. There is still net watershed N retention, but some losses occur in concert with the dynamics of microbial transformations and vegetation uptake. There is pronounced seasonality in NO_3^- concentrations with higher values in the winter during peak-flow months and declining, minimum concentrations during the growing season with minimum concentration in the low flow autumn months (Figure 12). Intra-annual precipitation patterns, in combination with deep soils at Coweeta, produce a lag in stream responses; that is, part of the increased soil NO_3^- does not reach the stream until the soils are fully recharged by winter precipitation. Evidence for this hydrologic lag between cause and effect has previously been described in the numerous water yield studies at Coweeta [*Douglass and Swank*, 1972].

5.2.2. Stage 2. WS 37 appears to be in the stage 2 of watershed N saturation. This high-elevation (1592 m) watershed, originally covered by a northern hardwood forest on the upper half and a mixed oak community on the lower half, was clear-cut in 1963, and no products were removed. Since 1972, when stream chemistry measurements began, annual flow-weighted concentrations have remained relatively stable (Figure 13a), and inputs are in near balance with outputs (Table 5). Representative monthly flow-weighted NO_3 concentrations over a 2 year period (1992-1993) show elevated NO_3^- concentrations in all months (Figure 13b) compared to concentrations of the adjacent control WS 36. The seasonality of NO_3^- levels are substantially damped, and highest concentrations tend to occur in late summer. The highest concentrations in 1993 are largely due to very low flows in that particular year. Patterns of both NO_3^- concentrations and budgets are indicative of late conditions for stage 2 in watershed N saturation described by *Stoddard* [1994]. The primary characteristics of this stage are elevated base flow concentrations of NO_3^- and damped seasonal patterns with surface water concentrations equivalent to those in deposition. In some years on WS 37, the catchment is a net source of N rather than a sink; however, we hypothesize that the elevated NO_3 source is associated more with alteration of mineralization, nitrification, and vegetation uptake than with increased atmospheric deposition. Watershed 37 was clear-cut and no products were removed thus providing a large input of organic matter for decomposition. Moreover, other research in northern hardwood forests at Coweeta has shown that these high-elevation ecosystems have much higher rates of mineralization and nitrification than other forest types in the basin (J.D. Knoepp, unpublished data, 1997). Additionally, a short growing season, low primary production, and low leaf area index of these forests combine to produce a low N demand and accelerated NO_3^- leaching.

5.2.3. Stage 3. The long-term NO_3^- dynamics of WS 6, the most severely disturbed watershed (conversion to grass, fertilized, limed, treated with herbicide, and characterized successional vegetation) at Coweeta, represent stage 3 of watershed N saturation. Stage 3 is characterized by extremely high stream NO_3^- concentrations, and the watershed becomes a net source of N rather that a sink [*Stoddard*, 1994]. WS 6 is a net source of N rather than a sink with net N losses in excess of 4 kg ha^{-1} yr^{-1} 29 years after the last treatment (Table 5). Mean annual flow-weighted stream NO_3^- concentrations (Figure 14a) show a strong relationship with changes in vegetation

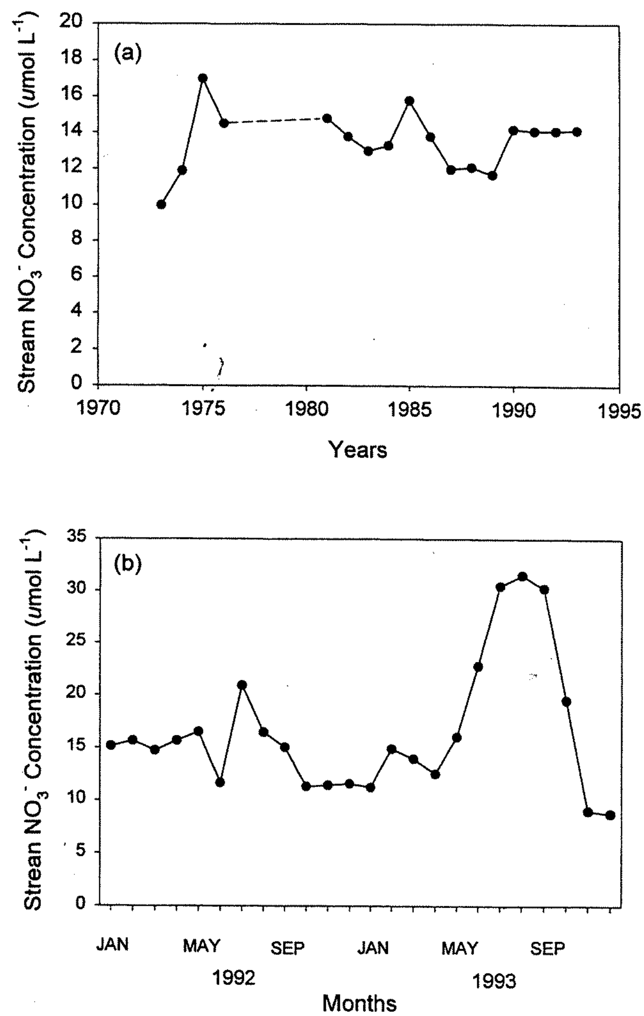

Figure 13. (a) Interannual and (b) intra-annual variation in stream water NO_3^- concentration for WS 37. The dashed line in Figure 13a represents a period when stream samples were not taken.

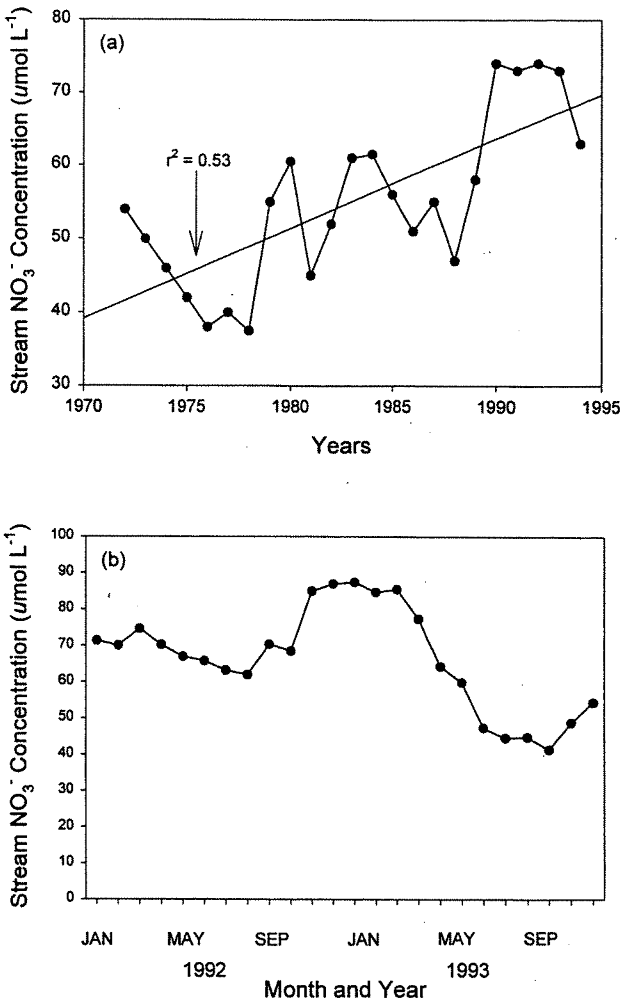

Figure 14. (a) Interannual and (b) intra-annual variation in stream water NO_3^- concentration for WS 6. The regression line in Figure 14a is significant at $p < 0.05$.

structure and composition. In the period from 1972 to 1978, during early succession from herbaceous to woody vegetation, NO_3^- declined from 55 μmol L^{-1} to 35 μmol L^{-1}. Subsequently, in 1979, NO_3^- abruptly increased to 55 μmol L^{-1} concurrent with a heavy infestation of the locust stem borer (*Megacyllene robiniaeiae*). Black locust was the dominant woody species on the watershed, and by 1982, 21% of the trees were dead, 18% were severely injured and many of the remaining trees showed evidence of decline. Elevated NO_3^- leaching is attributed to reduced vegetation uptake and alteration of soil N transformation processes [*Montagnini et al.*, 1986, 1991]. Thereafter, NO_3^- concentrations fluctuated around values observed in the early 1970s (45-60 μmol L^{-1}) and then dramatically increased to > 75 μmol L^{-1} in 1990-1993. The elevated levels coincide with further reductions in the density of black locust (> 75%) and biomass of ground flora (76%) which had previously provided a vegetation sink for N retention within the watershed. The seasonality of stream NO_3^- concentrations provides further evidence for stage 3 saturation (Figure 14b). Concentrations of NO_3^- exceed deposition in all months, and although lowest values occur in the growing season when vegetation demand is highest, mineralization and nitrification greatly exceed demands, and there is a chronic leaching of NO_3^- throughout the year with largest losses occurring in the high-flow winter months. A forest nutrient cycling model (NUCM), has been used to simulate and further elucidate interactions among vegetation, soils, and nutrients associated with the treatments imposed on WS 6 [*Johnson et al.*, 1995]. Simulated BC horizon soil solution concentrations mimicked the general patterns in stream water NO_3^- during the early stages of succession, but NUCM simulations did not capture the dynamics of stream NO_3 concentrations associated with insect infestation.

5.3. Forest Ecosystem N Responses to Prescribed Burning

Another management prescription of strong interest in the United States of America is the use of fire to achieve silvicultural and ecological goals. Specifically, the use of prescribed fire to maintain mixed pine-hardwood forests in the southern Appalachians has become increasingly important as this forest type has declined in areal extent. For example, *Smith* [1991] estimated that 98% of the pine-hardwood stands present in 1934 in the Coweeta basin have little or no remaining live pine. The loss of pine is due to a reduction of disturbances, such as fire, needed to regenerate pine, and mortality from southern pine beetle infestations during a drought period in 1985-1998. One silvicultural prescription used in the past several decades to regenerate degraded stands is to clear fall all vegetation, remove merchantable timber if present, and burn the residual slash (cut and burn). A more recent alternative under investigation is to use prescribed stand replacement fires to restore degraded stands, which, if successful, provides an attractive economic alternative.

5.3.1. Cut and burn prescription. We are conducting research on both burning prescriptions to assess environmental and resource responses on the Nantahala National Forest near Coweeta [*Vose et al.*, 1997; *Vose*, 1994; *Swift et al.*, 1993]. The cut and burn treatment was applied to three sites (≈4 ha each) paired with controls. The preburn and postburn N status was evaluated for aboveground wood, foliage, forest floor [*Vose and Swank*, 1993], streams (only one site), soil, and soil water [*Knoepp and Swank*, 1993]. Total mass consumed by burning ranged from 47% to 61% of preburn totals due to differences in fire intensity across sites, and N losses from woody material ranged from 129 to 305 kg ha^{-1}. Foliage, herbs, and sprouts were completely consumed on all sites, and the Oi layer of the forest floor was reduced > 90% on two sites and 50% on the third site. However, N pools were not significantly reduced in the Oe plus Oa layer on any of the burn sites, and this layer contains a major portion of the aboveground N pool. Taken collectively, total N losses ranged from 193 kg ha^{-1} to 480 kg ha^{-1} across the sites which represented 60% of the total aboveground preburn pools on two sites and 30% on the third site. The primary response in soil N [*Knoepp and Swank*, 1993] was an immediate (48 hours) pulse of NH_4^+ at all three sites following burning, and during the first 3 months, content change increased from < 1 to 3.5 kg N ha^{-1}. There were no consistent responses in rates of N mineralization, in situ net nitrification, and soil NO_3^- content. There were small, but measurable increases in NO_3^- concentrations of

Table 6. Summary of N Pools in Aboveground Components in Southern Appalachian Pine-Hardwood Ecosystems and N Losses Following Two Prescribed Burning Prescriptions

	Fell and Burn[a]				Stand Replacement			
Aboveground	Preburn N Pool	Postburn N Pool	Loss (Percent of Preburn)		Preburn N Pool	Postburn N Pool	Loss (Percent of Preburn)	
Standing wood	0	0	0	(0)	...	...	...	
Downed wood (large and small combined)	296	90	206	(70)	51	20	31	(70)
Litter	96	17	79	(82)	52	28	24	(46)
Humus	223	216	7	(3)	437	417	20	(5)
Totals	615	323	292	(47)	540	465	75	(14)

N is measured in kilograms per hectare. Elipses indicate N in standing vegetation was not measured; qualitative observations indicate that these losses were negligible.

[a]N losses are the average of three treatment areas.

soil solutions and a small NO_3^- pulse (from <1 to 5 μmol L^{-1}) over a 7 month period in the stream draining the one burn site [*Knoepp and Swank*, 1993]. There were no treatment responses for NH_4^+ in soil and stream water. Additionally, there was little evidence of erosion or soil loss from the sites [*Swift et al.*, 1993]. Taken together, it is apparent that the effects of high intensity, but low-severity burning on N dynamics of these ecosystems are minimal off site (erosion and NO_3^- leaching to streams), and the main impact is on site, that is, N lost from consumed aboveground vegetation. Thus it would appear that fire effects (as applied in this study) are of less concern than cutting effects from watershed N saturation and water quality perspectives. However, N combustion losses may have long-term productivity implications which is the subject of our current research on these sites.

5.3.2. Stand replacement burning prescription. The stand replacement fire was conducted as part of an Ecosystem Management Project on Wine Spring Creek, a third-order watershed in the Nantahala National Forest about 50 km from Coweeta [*Swank*, 1995]. In April 1995, ≈140 ha in two separate subdrainages were ignited by helicopter with strip head fires applied on the lower slope and midslope positions. The fire was most intense on the ridge position (peak flame temperatures > 800°C), the target area for pine-hardwood restoration. The riparian area did not burn because of high fuel moisture, and there was a mosaic of fire intensities over the midslope. Preburn fuel loadings in the ridge position were 5, 31, and 7 Mg ha^{-1} for litter, humus, and downed small wood (< 7.5 cm diameter), respectively (Table 6). Mass consumption by the fire was 65% for litter, 7.1% for humus, and 80% for downed small wood with a total aboveground N loss of 75 kg ha^{-1} or about 25% of the N loss estimated for the fell and burn prescription (Table 6). In contrast to the fell and burn treatment, large downed wood pools were about 11 Mg ha^{-1}, with very little consumption or N loss postfire.

The effects of burning on stream chemistry were assessed for both streams draining the two burned sites. Preburn and postburn NO_3^- concentration regression analyses with reference stream NO_3^- concentrations showed no change in concentrations over the 15 months following burning (Figure 15). Slopes and intercepts of the regressions were nearly identical, as indicated by overlapping 95% confidence intervals of the parameter estimates.

Thus, as with the cut and burn prescription, it appears that fire disturbance has little relevance to questions of watershed N saturation of these ecosystems. However, it is clear that stand replacement burning has less impact on ecosystem N losses than the cut and burn prescription. The ultimate goal of sustaining mixed pine-hardwood stands remains to be evaluated for the two methods. Prior research has shown that pines successfully regenerate after cut and burn treatments [*Clinton et al.*, 1993], while current research is evaluating regeneration and forest succession of stand restoration burning. Indeed, the trade-offs between achieving vegetation management goals and maintenance of total site productivity may reside with our ability to evaluate the consequences of site N losses. Such complex issues must utilize detailed N cycling models that are combined with long-term field research.

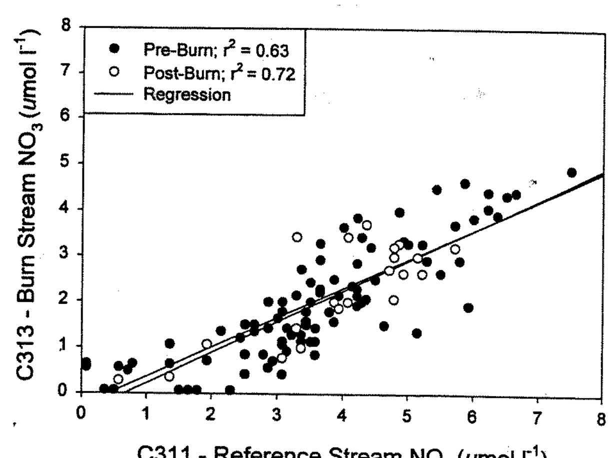

Figure 15. Comparison of stream chemistry of preburn and postburn stream water NO_3^- concentration in a control stream (C311) and a stream draining a prescribed burned watershed (C313). Regressions through preburn and postburn data were significant (p < 1.05), but they did not differ from each other (i.e., slopes and intercepts are equal).

5.4. Effects of Natural Disturbances

The period of biogeochemical cycling research at Coweeta has encompassed a wide range of natural disturbances to forest ecosystems. Some effects of these disturbances on the N dynamics of watersheds have been discussed in sections 4.2 and 5.2 of this paper, for example, the concentrating and diluting effects of precipitation on stream NO_3^- concentrations during drought and very wet periods, elevated stream water NO_3^- concentrations associated with locust stem borer infestations on WS 6, and NO_3^- responses related to stand structure dynamics of successional forests (WS 6, 7, and 37). Other research has described in detail small but measurable increases in stream water NO_3^- concentrations during chronic infestations of a spring defoliator on WS 27 and 36 [*Swank et al.*, 1981] and episodic ozone damage to white pine on WS 17 [*Swank and Vose*, 1990]. We are currently studying the effects of hurricane Opal damage (October 1995) on forest ecosystem processes in the Coweeta Basin, including potential responses in biogeochemical cycles. Reference WS 34 sustained extensive windfall damage over the upper 25% of the catchment; beginning in May 1996, stream NO_3^- concentrations began to rise from background levels of <0.5 μmol L^{-1} to >2 μmol L^{-1}. Generally, stream NO_3^- losses associated with natural disturbances are small compared to some intensive management prescriptions, but even low-level responses are indicative of large alterations of the internal N cycle because the baseline systems are highly conservative of N.

6. Conclusions

The long-term data set at Coweeta on both reference and experimental watersheds offers a unique opportunity to examine temporal patterns in N dynamics of forested watersheds. It is particularly important that we understand the role of natural and man-made disturbances on N dynamics, because disturbance is a major force shaping southern Appalachian forests. Our analyses of long-term inorganic N data for reference and disturbed southern Appalachian forested watersheds provide evidence for the following trends and dynamics: (1) Net N budgets for mature hardwood forests show these ecosystems are highly conservative of N, (2) Time trend analysis of bulk precipitation reveals increases in annual volume-weighted concentrations of NO_3^- and NH_4^+ that are partially attributed to time trend increases in dry deposition of both ions, (3) Annual flow-weighted NO_3^- concentrations of streams draining reference watersheds have increased over time and, along with increases in the intra-annual seasonal amplitude and duration of NO_3 concentrations, are indicative of a transition from stage 0 to stage 1 of watershed N saturation, (4) Forest management activities such as clear-cutting can alter microbial N transformations and vegetation uptake and, along with stream NO_3^- dynamics provide evidence for stages 1 and 2 of watershed N saturation, (5) The multiple treatments applied in a forest to grass conversion experiment produced conditions typical for stage 3 of N saturation, (6) Other management and natural disturbances examined showed measurable but small responses in stream NO_3^- losses from watersheds.

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