Poster paper

WATERSHED-SCALE RESPONSES TO OZONE EVENTS IN A *PINUS STROBUS* L. PLANTATION

Wayne T. Swank[1] and James M. Vose

USDA, Forest Service
Southeastern Forest Experiment Station
Coweeta Hydrologic Laboratory
999 Coweeta Lab Road
Otto, North Carolina, USA 28763

Abstract. High O_3 levels during the 1984 growing season in the southern Appalachian Mountains ca extensive damage to a 28 yr old white pine plantation on a 13.4 ha watershed at the Coweeta Hydrol Laboratory. Ozone stress effects included premature senescence and loss of foliage, stimulatio pine seedling germination, reduced basal area increment, and small but measurable increases in NC and K^+ concentrations in stream water. There were no observable effects of O_3 damage on nutr concentrations of stemwood and foliage but net nutrient accumulation was reduced due to lower sten production. Ozone injury did not predispose trees to root pathogens or bark beetle infestations.

1. Introduction

According to a critical review of the literature by McLaughlin (198 laboratory and field research provides circumstantial evidence for role of atmospheric pollution in reducing vigor or increasing mortal of forest tree species in Europe and the United States. Recent empha has been placed on gaseous pollutants such as NO_x and a photochemi product, O_3, as a possible cause of forest decline. Ozone is particul ly significant because it occurs in phytotoxic concentrations over br geographic regions.

Recent reviews have specifically examined the role of O_3 in t decline in North America (Chevone and Linzon, 1988); the impact of O_3 assimilate partitioning in plants (Cooley and Manning, 1987); and effects on vegetation (Krupa and Manning, 1988), forest hea (Hakkarinen, 1987; Linzon, 1986), and growth and yield of trees (F 1988). A common theme of these reviews is the difficulty in conclusiv linking forest decline to a single stress factor such as O_3. The effe of O_3 on physiological processes are reasonably well understood (Winr 1989; McLaughlin *et al.*, 1988), and a unifying theory for quantify plant response to O_3 has been developed (Reich, 1987). However, studies in the greenhouse or open-top chamber studies on seedlings saplings are difficult to extrapolate to mature trees and for ecosystems. Similarly, under natural conditions forest ecosystems frequently subjected to multiple concurrent stresses, or trees may exposed to cumulative impacts of a single or multiple stress. Both these situations preclude a conclusive interpretation of causal impa on forests.

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1 Author for all correspondence.

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In this paper we examine the effects of episodic O_3 events, wh occurred during the growing season of 1984, on the health and function a 28 yr old white pine (*Pinus strobus* L.) plantation. The analy represents a unique opportunity to measure the responses of a natur mature forest ecosystem to a single pollutant.

2. Site Description

The study site is within the Coweeta Hydrologic Laboratory, a 2185 research area in the Nantahala Mountain Range of western North Caroli USA (Figure 1). The Laboratory is a site of long-term hydrology ecology research with a focus on biogeochemical cycles of for ecosystems. Annual precipitation varies from 180 cm at lower elevati (690 m) to 250 cm on the upper slopes (1550 m). Mean monthly tempe tures range from 3.3°C in January to 21.6°C in July (Swift *et al.*, 198 Coweeta is located in a rural, predominantly forested setting and farn is an important land use. Regional air mass movement is typically f the south and is strongly influenced by high and low pressure syst over the Gulf of Mexico. The nearest large city is Atlanta, Georg which is 160 km to the southwest (Figure 1). Long-term records of and dry deposition chemistry measurements in the Coweeta basin show influence of local land use disturbance such as plowing and burn (Swank and Henderson, 1976), the importance of sea-salt aerosols anthropogenic emissions on deposition chemistry (Swank and Waide, 198 and the effect of long-range transport of particulates on deposit chemistry in the basin (Swank, 1984).

The primary site of this study is Watershed 17 (WS 17), a 13.4 north-facing catchment with side slopes averaging 50%. Elevations ra from 760 m at the weir to 1021 m on the ridge. The treatment history the watershed includes cutting all hardwood vegetation in 1940 and ann cutting of regrowth in most years until 1955. White pines were plan in 1956 and released from hardwood competition as required by cutting applying herbicides. In 1985, stocking was 890 trees ha^{-1} with a ba area of 46 m^2 ha^{-1}. Stream gaging was initiated in 1936 and hydrologic and biogeochemical cycles of the ecosystem have been int sively studied for over 50 yr (Swank and Crossley, 1988).

A secondary site utilized in this study is Coweeta Watershed 1 (WS a 16.1 ha south-facing catchment 1.5 km from WS 17 on the opposite s of the Coweeta Basin. The mixed hardwood forest on WS 1 was clear cut 1956 and planted with white pine in 1957. Subsequently, the treatn history has been identical to WS 17 and in 1985 stocking was 1165 t ha^{-1} with a basal area of 47 m^2 ha^{-1}. Hydrological and ecolog processes have also been closely monitored for many years on WS 1.

3. Characterization of Ozone Events

In mid-July 1984, pronounced discoloration of white pine foliage clearly visible from an overlook with a 400 m direct view into WS Canopy discoloration was initially most obvious on the upper third of watershed, but in the ensuing 2 wk about 75% of the 13 ha planta showed foliar discoloration. The initial, general appearance fro distant view was of a stand severely infested with bark beetles.

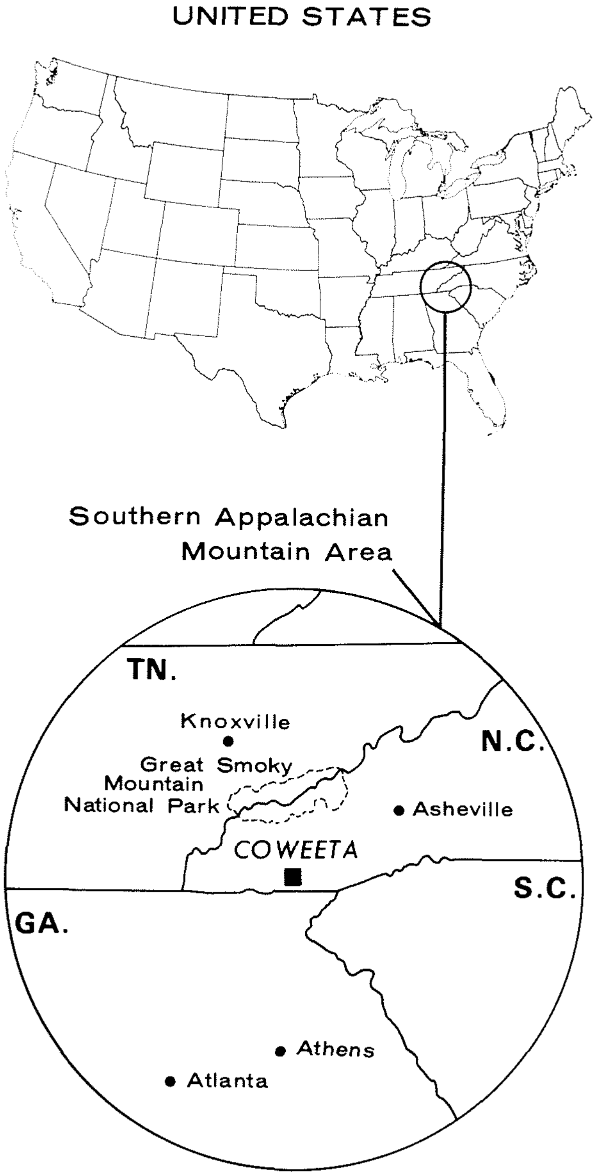

Figure 1. The Coweeta Hydrologic Laboratory is in the southern Appalachian Mountains of North Carolina. The Great Smoky Mountains National Park, another site of atmospheric pollution research is 65 km north of Coweeta.

Initial examination of fascicles revealed symptoms of foliar inj distinctive for O_3 damage. Chlorotic mottling was prevalent on need of most affected fascicles and tipburn was also common. The prelimin diagnosis was confirmed by Dr. Charles Berry, a pioneer in research on and SO_2 damage to white pine (Berry, 1961). His visual examination the stand in mid-August indicated that damage occurred from at le three separate O_3 episodes. In September it appeared that anot damaging O_3 event occurred. Typically, foliar damage was most severe dominant and codominant trees with the entire upper two-thirds of th crowns usually exhibiting visual symptoms. Other mature white pines the nearby (within 1 km) valley showed no visible symptoms of damage the white pine on WS 1 (1.5 km) also lacked significant visible dama Ozone monitoring was not in place within the Coweeta Basin in 1984, measurements were initiated in 1986. Ozone concentrations monito across an elevational gradient in the basin during the past 4 yr provi evidence for different diurnal patterns and levels of O_3 concentrati over relatively short distances. These patterns may partially expl the variable response of white pine in the Coweeta Basin to the 1984 events.

Ozone concentrations during the summer of 1984 were generally high the region. Lacking O_3 data for our specific location in 1984, selected nearby rural O_3 monitoring stations whose records were availa for the period of interest. Look Rock, a monitoring station for Great Smoky Mountains National Park (GSMNP) (Figure 1), is on Chilho Mountain in east Tennessee at an elevation of 792 m and about 65 km f Coweeta. The diurnal patterns of O_3 concentrations at Look R (Reisinger and Valente, 1985) are similar to patterns at the top Coweeta WS 17 and another high-elevation monitoring site (data collected in 1984) in the GSMNP (Figure 2). In spring and summer, diurnal cycle is characterized by a small amplitude with mini concentrations at midmorning, followed by a broad, flat maximum in afternoon which is maintained throughout the night. Average hourly concentrations at Coweeta are about 15% lower than average values this GSMNP station. During the growing season in 1984, O_3 concentrati at Look Rock frequently averaged over 80 ppb for periods of over consecutive hours with maximum hourly concentrations of 90 ppb (Table Taken together, diurnal patterns and concentrations of O_3 in 1 indicate that white pine on WS 17 were exposed to relatively high le of O_3 for extended periods. Moreover, stomatal conductance to diffusion was probably optimal because precipitation was abun throughout the growing season and trees were not subject to water str Other evidence, although indirect, for O_3 damage to the pine available. Clones propagated from trees visibly damaged on WS 17 in 1 have been used in dose-response experiments and also outplanted bioindicator plots colocated with O_3 monitoring stations at Cowee Exposure of the clones to O_3 concentrations of 80 ppb for 8 hr or lo has caused foliar damage symptomatic of O_3.

Our characterization of the visible and physical evidence for damage in 1984 does not provide unequivocal proof that other oxidi pollutants or factors of air pollution did not contribute to the obse damage. However, rainfall acidity during the growing season at Cow over the past 17 yr is typically in a pH range of 3.7 to 5.3; during 1 all precipitation events were above pH 4.2. Furthermore, over the pa yr, measurements of SO_2 and HNO_3 acid vapor at Coweeta have shown con

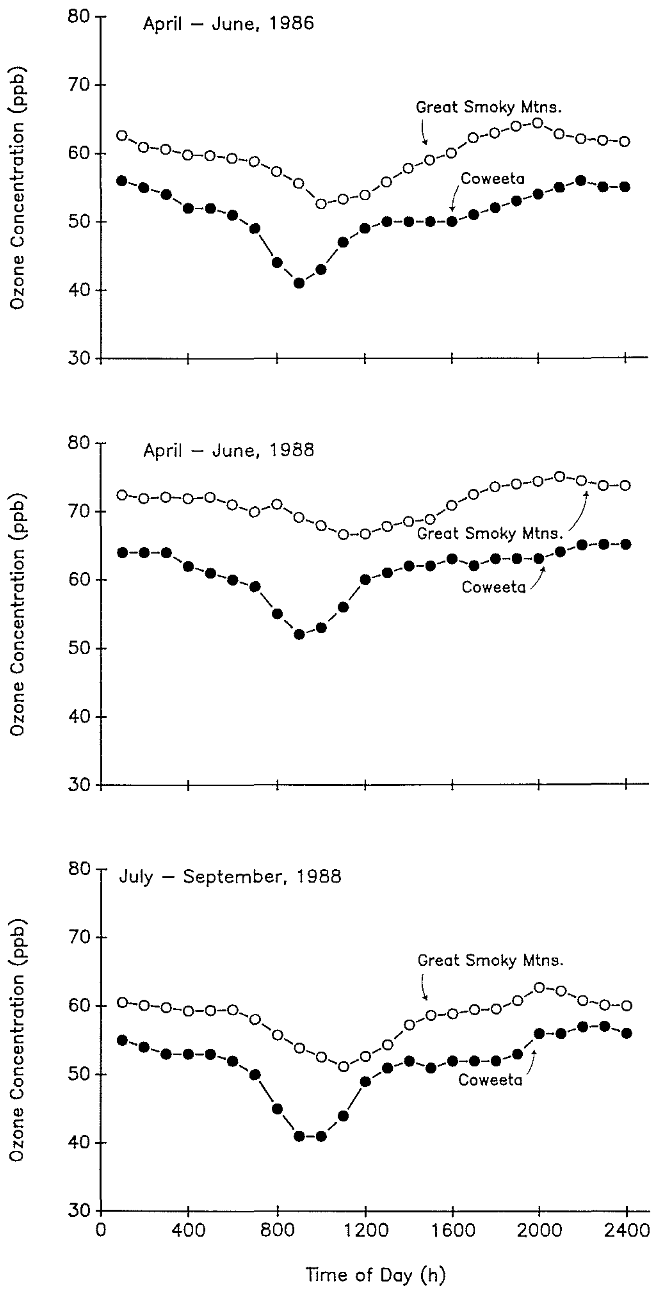

Figure 2. Diurnal O_3 concentrations at two high-elevation sites, Coweeta (1010 m) and GSMNP (Cove Mountain 1262 m), in the southern Appalachian Mountains for the second and third quarters of 1988 and the second quarter of 1986.

Table I

Ambient O_3 concentrations at Look Rock, TN,* near the GSMNP during sele periods in 1984.

Date	Time period (hr)	Mean O_3 concentrations (ppb)	Maximum hourly O_3 concentration (ppb)
May 12	1000-2400	80	93
May 19	1000-2400	81	93
May 20	0100-2400	87	93
June 4	1000-2400	89	98
June 5	0100-2400	73	93
June 7	1000-2400	83	98
June 24	1000-2400	76	88
June 27	1000-2400	78	93
July 9	1000-2400	73	91
August 18-19	1000-0700	84	93
September 17-18	1300-0800	83	98
September 20-21	1500-0900	78	83
September 21-22	1500-0900	86	119
September 23	0100-0900	78	78
October 6-7	1300-0900	85	108

* In 1984 the monitoring station was operated by the Air Polluti Control Division of the State of Tennessee.

trations to be low with maximum concentrations of 7.8 and 8.0 $\mu g\ m^-$ respectively. Likewise, analyses have shown very low concentrations trace metals in precipitation at Coweeta (Lindberg and Turner, 198{ Thus, it is highly unlikely that a pollutant other than O_3 was t primary cause of damage to the pine on WS 17.

4. Results and Discussion

4.1 Growth responses

The most conspicuous impact of O_3 damage to white pine on WS 17 was 1 premature senescence and loss of foliage, particularly past year (> 1 ; foliage. Damaged needles were abundant on the forest floor in Augu: although litterfall traps were not installed until September 15, 1984 WS 17 and WS 1, the effects of O_3 on needle loss were still obvio Over a 5 mo period (September to February), foliage litterfall on WS was 299 g m^{-2} (SE = 27) compared to 190 g m^{-2} (SE = 18) on WS 1.

subsequent years, foliage litterfall for the two populations was a the same. Leaf area on WS 17 was so markedly reduced that l intensities at the forest floor were sufficiently increased to stimu widespread pine seedling germination, a process not previously obse in the stand.

The effect of O_3 damage on tree growth was examined by measu radial growth of trees sampled in both WS 17 and WS 1. Twelve domi and codominant trees were sampled on each watershed. Sample trees o 17 were from the upper third of the catchment where visible foliar da was most prevalent. Two cores were taken on opposite sides of sa trees at DBH and parallel to the slope. Extracted cores were store drinking straws, transported to the laboratory, mounted in a jig, shaved to provide a clean, flat surface for measurement. Annual widths were measured to 0.01 mm under a microscope (375x) usin incremental measuring instrument coupled to a microcomputer. Meas ments from the two cores were averaged and annual growth expresse basal area increment (BAI in cm^2).

During the period of 1979 to 1983, BAI of trees in both plantat varied widely from year-to-year and growth rates of sample trees higher on WS 17 compared to WS 1 (Figure 3). These differences probably due to site quality from which sample trees were selec However, growth patterns over this period were similar for the populations. In 1984, BAI of trees on WS 17 decreased dramatica whereas BAI of trees on WS 1 was unchanged. In fact, growth rate trees from the O_3 damaged plantation dropped below those of trees o 1. In the following year, growth on WS 17 continued to decline, there was also a similar decline on WS 1 which may be partly associ with below average precipitation during several months of the gro season. Statistical analysis of growth response on WS 17 was perfo by comparing BAI in 1984 to the average BAI of the preceding 5 yr (to 1983). Data were analyzed by analysis of variance, with sample t included as a block factor in the analysis. Sample tree blocking necessary because there was a positive relationship between BAI initial tree size (block effects were highly significant [$p < 0.0001$ the analysis). The 18% reduction in BAI in 1984 was significa different ($p < 0.05$) from the previous 5 yr period (Table II).

Analysis of tree growth within the O_3 impacted population and bet O_3 symptomatic and O_3 asymptomatic populations provides strong evid for a significant growth reduction of larger trees due to O_3 damage more intensive study is in progress to assess impacts across the en range of tree sizes. For example, it is plausible that intermed canopy trees, which showed much less visible O_3 damage, could positive growth responses to increased light availability resulting the reduction in leaf area of larger competing trees.

Dose-response O_3 experiments were conducted on three clones sele from dominant trees visually damaged in 1984 on WS 17. In 1985, s material was selected from the upper crown (about 25 m) of parent t and 30 ramets were grafted from each clone. Ramets were maintained u an open, lathe covered structure at Coweeta, and by 1988 clonal mate was typically 0.7 to 1.0 m tall. In July 1988, nine ramets of each c were exposed to concentrations of 0, 100, and 200 ppb of O_3 over a period in stirred chambers operated by the U.S. Agricultural Rese Experiment Station, Raleigh, North Carolina. Plants were exposed to

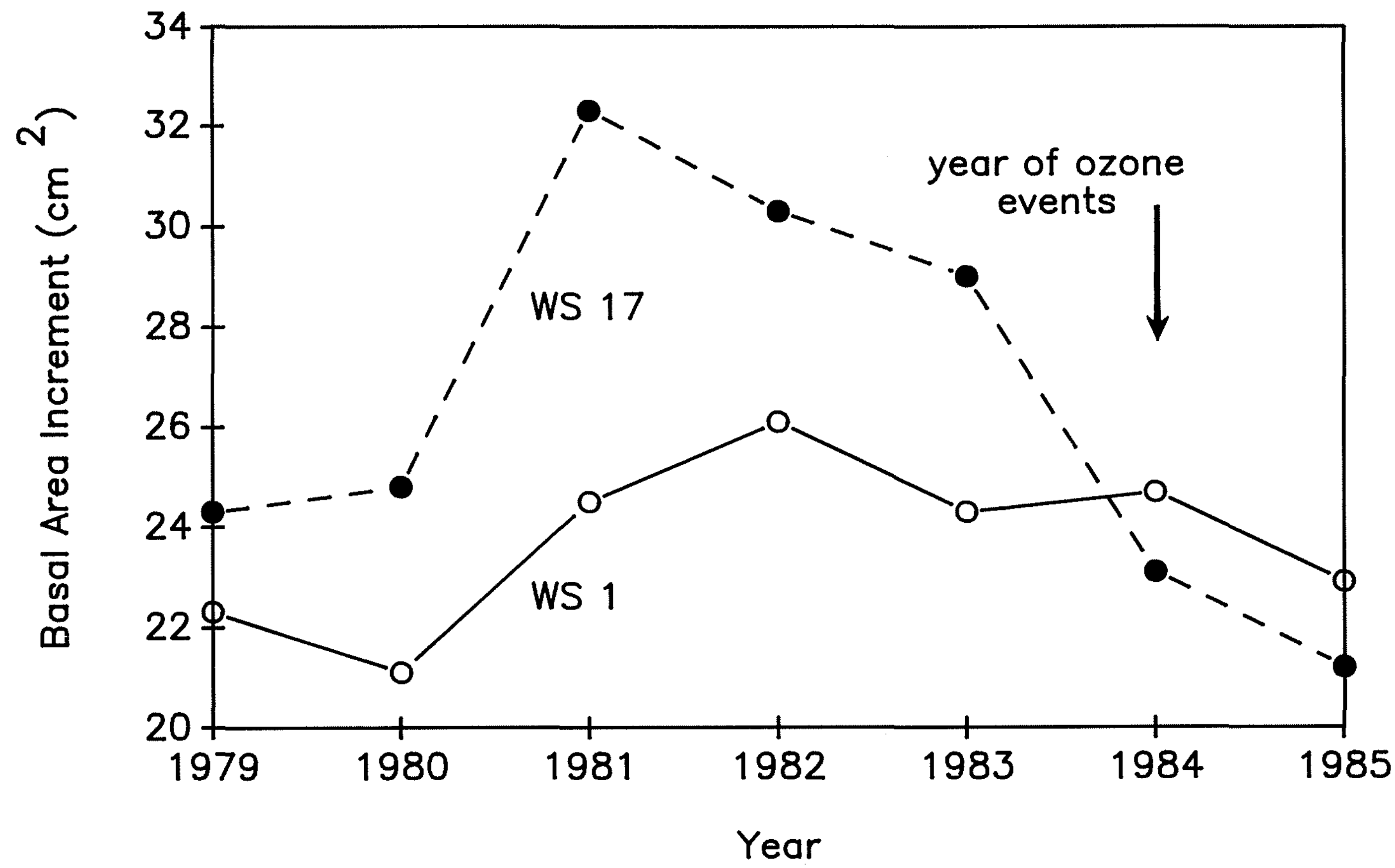

Figure 3. Annual BAI for dominant and codominant 28 yr old white pine on Coweeta WS 17 (O_3 symptomatic in 1984) and WS 1 (O_3 asymptomatic from

Table II

Comparison of BAI (cm^2) of white pine on Coweeta WS 17 in 1984 to year average BAI from 1979 to 1983. Values are significantly diff (ANOVA) at the $p < 0.05$ level ($n = 12$)

	BAI (cm^2)	F-value	P > F
1979-1983 $\bar{X}$	28.14	7.13	0.0218
1984	23.05		

different treatments for 5 hr day^{-1} on four consecutive days in week. Between exposures, ramets were watered and maintained in cha filtered air.

Findings most relevant to this paper are the impacts of O_3 exposu net photosynthetic rate (Pnet). Photosynthetic rates were measured LCA2 Portable Photosynthesis System) on current-year foliage and year foliage (> 1 yr) immediately after exposures at the end of we and 2. Three ramets of each clone were used for each exposure and rates were averaged across all clones ($n = 9$). After the first we exposure, Pnet was significantly lower for the 100 ppb and 200 ppb exposures compared to the zero O_3 exposures (Table III).

Table III

Mean net photosynthesis (SE) in μmol m^{-2} s^{-1} for white pine c exposed to controlled O_3 concentrations. Statistical tests (ANOVA 0.05) were made between treatments within week and age class. followed by the same letter do not differ (LS-Means; $p < 0.05$).

	1 wk		2 wk	
Treatment*	Current	Past	Current	Past
0	4.16(0.33)^a	3.35(0.23)^a	3.67(0.60)^a	3.06(0.25)
100 ppb	1.53(0.35)^b	1.83(0.24)^b	1.92(0.64)^{ab}	1.76(0.27)
200 ppb	1.39(0.31)^b	1.91(0.23)^b	1.73(0.56)^b	2.21(0.27)

* O_3 treatments: 5 hr dy^{-1}, 4 dy wk^{-1}

There were no significant differences in Pnet rates between 10 200 ppb exposures and rates were similar between current-year and year foliage. Compared to Pnet rates at zero O_3 levels, rates reduced an average of 55% for the two O_3 exposures. Similar reduc in Pnet were observed after the second week of exposures (Table III) Although the minimum O_3 level (100 ppb) is slightly higher than episodi ambient levels estimated for 1984, these chamber experiments indicat that reduced rates of Pnet are potentially a significant cause of tl growth reductions associated with the O_3 episodes.

4.2 Nutrient responses

The effects of O_3 stress on ecosystem nutrient dynamics were examined l analyzing nutrient concentrations of vegetation and stream water. In tl latter case, 16 yr of continuous stream chemistry data provided a go baseline for detecting changes in biogeochemical cycles. For vegetatio the opportunity to detect impacts was more limited.

Increment cores used in growth analysis were analyzed for nutrients l routine procedures established at Coweeta (Reynolds and Deal, 1987) Concentrations of the major cations and P in stemwood increment of 19 were essentially identical to the average stemwood nutrient concentra tions of the preceding 5 yr (Table IV). Foliar nutrients were n sampled in 1984, but potential impacts of O_3 stress were examined fr nutrient analysis of needlefall collected in 1985, which primari represented current-year foliage exposed to the O_3 episodes in 198 Nutrient concentrations were compared to foliar values for needlefall 1987 because 1986 was a record drought, and hence atypical of nutrie recycling processes. There were no consistent differences in nutrie concentrations of needlefall between years (Table IV), but the lack sampling prior to senescence in 1984 limits our evaluation of O_3 impac on foliar nutrients. Thus, the main observable effect of O_3 stress aboveground plant nutrient was reduced net plant accumulation of maj cations and P since stemwood concentrations remained unchanged but wo increment was significantly reduced.

Table IV

Summary of nutrient concentrations in stemwood and needlefall for whi pine on Coweeta WS 17 prior to, during, and/or after O_3 damage in 1984.

Vegetation component	Year(s)	Nutrient concentrations (% d.w.) K	Ca	Mg	P	N
Stemwood	1979 to 1983	0.027	0.043	0.010	0.005	0.06
	1984	0.027	0.043	0.008	0.005	NA
Foliage (needlefall)	1987	0.179	0.526	0.106	0.025	0.41
	1985	0.119	0.619	0.102	0.029	0.45

* Insufficient sample tissue available for chemical analyses.

Stream water chemistry has been sampled weekly on WS 17 and oth Coweeta watersheds since 1971 (Swank and Waide, 1988). Prior analys has shown that changes in concentrations of nitrate-N (NO_3^--N) are sensitive indicator of forest ecosystem disturbances at Coweeta su clearcutting, insect infestations, and species conversions (Swank, 1 Monthly NO_3^--N concentrations for the stream draining WS 17 during are similar in both pattern and level to the long-term average mo concentrations (Figure 4). However, throughout 1985 NO_3^--N levels substantially above average values. Seasonal concentration patterns similar with lowest levels in the winter months and highest leve late summer. Throughout the 1985 growing season, monthly N concentrations frequently exceeded long-term concentrations by more 70%. Over 1985, the average monthly concentration increased fı baseline value of 0.15 to 0.27 mg L^{-1}. These changes are h significant since the standard error of estimates for monthly long concentrations are typically less than 10% of the mean.

The extent to which elevated NO_3^--N concentrations can be relat O_3 damage on WS 17 was examined in several ways. First, it wa: surprising to see a lag between cause and effect; *i.e.* no chan; stream chemistry in 1984 when O_3 damage occurred but a stream chem response in 1985. Previous research at Coweeta has shown similar d following disturbances such as clearcutting. The lag between chang biogeochemical cycles on the landscape, and their measurable effec the weir, integrates the responses of biological and hydrolo processes and physical factors such as soil depth (Swank, 1988). Se the stream draining WS 1 was assumed to be a "control" (no O_3 damage WS 17. Although baseline concentrations of NO_3^--N on WS 1 are te lower than WS 17, both show the same mean monthly concentration m and minima (Figure 4). In 1984 concentrations on WS 1 were sli below the average long-term monthly concentrations while values in were slightly above the average (*i.e.* 0.04 *vs* 0.06 mg L^{-1} in the gr season). In both years, monthly differences were not significant be they encompass the standard error of the monthly long-term means. it appears that a small but significant release of NO_3^--N was assoc with the O_3 damage on WS 17.

Response patterns for other stream nutrients, examined in the manner, were similar to that for NO_3^--N. For example, concentratio K^+, a biologically important and mobile nutrient, were elevated in on WS 17, while there was little or no change on WS 1 (Figur Changes in Ca^{2+} concentrations on WS 17 were smaller and only occurr several months while Mg^{2+}, NH_4^+-N and PO_4^{3-} concentrations did not d from long-term averages.

Taken collectively, these data indicate that the nutrient cycl some ions were altered by O_3 damage to white pine on WS 17. Chang several key processes could be postulated to explain elevated nut levels in stream water such as: (1) accelerated mineralizatio nitrification in response to increased forest floor temperature result of the leaf area reduction, and (2) reduced plant nut accumulation. However, altered nutrient cycles due to O_3 damag probably short-lived and the small elevated concentrations of s nutrients measured in this study are of little consequence to quality.

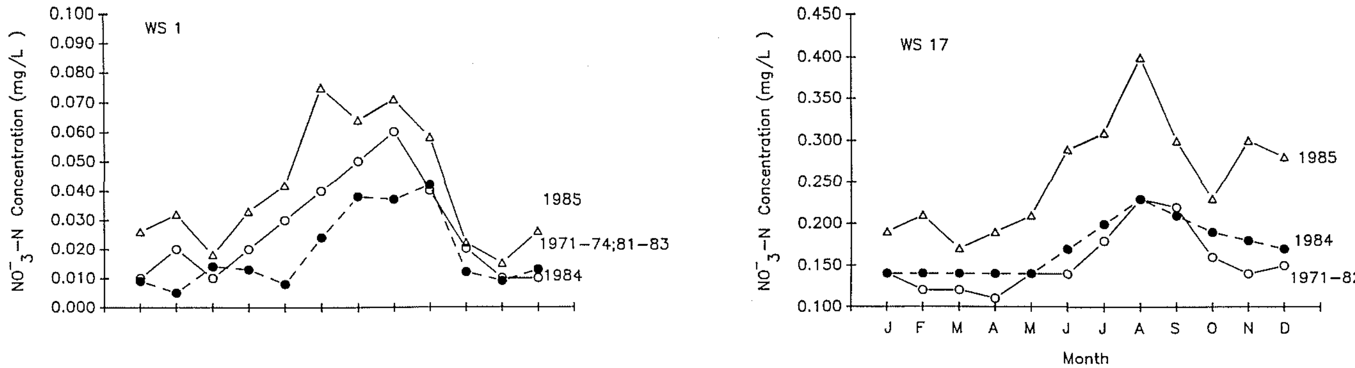

Figure 4. Mean monthly concentrations of NO_3^--N in streams draining white pine-covered watersheds at Coweeta for baseline years compared to monthly concentrations during 1984 and 1985. White pine on WS 17 was O_3 symptomatic in 1984 while pine on WS 1 was asymptomatic.

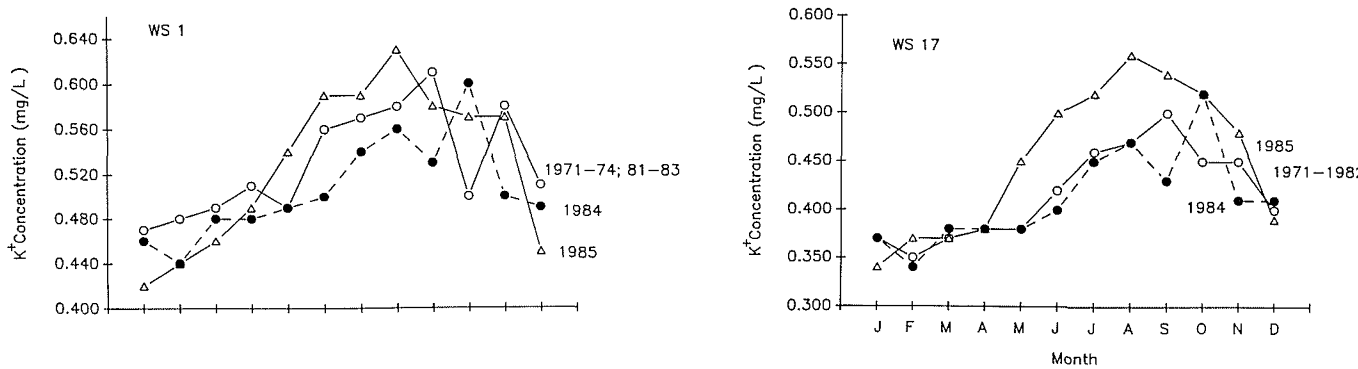

Figure 5. Mean monthly concentrations of K^+ in streams draining white pine-covered watersheds at Coweeta for baseline years compared to monthly concentrations during 1984 and 1985. White pine on WS 17 was O_3 symptomatic in 1984 while pine on WS 1 was asymptomatic.

4.3 Disease and insect responses

Several studies have indicated that oxidant air pollution may predis pines to biotic stresses such as insects and root diseases (James *et* 1980; Lackner and Alexander, 1983; Miller, 1983). Two studies initiated on WS 17 in 1985 to assess increased susceptibility of tree root pathogens and to bark beetle attacks.

A root disease survey was conducted in the white pine plantation WS 1 (O_3 asymptomatic) and WS 17 (O_3 symptomatic) in late fall 1 Soil-root samples were taken from 10 plots systematically distrib throughout each watershed and roots were clinically examined for dis symptoms (Leininger *et al.*, 1990). No root pathogens were found on segments taken from WS 17 and less than 1% of all root segments sam on WS 1 contained the only true root pathogen recovered, *Heterobasi annosum* (Fr.) Bref. Thus, it is unlikely that root disease and O_3 in interacted pathogenically on WS 17.

Predisposition of O_3-damaged white pine to bark beetle attacks studied on WS 17 (Berisford, 1987). A technique for inducing bark be attacks by simulated lightning strikes was applied to eight codomi white pines with evidence of severe O_3 damage and eight trees of sim size with no apparent damage. The response of *Ips* spp. beetle treated trees and adjacent untreated trees within 15 m of treated t was monitored for 9 weeks. Treated trees were immediately attacke *Ips* spp. beetles including *I. gradicollis* (Eichnoff), *I. pini* (Say), relatively small numbers of *I. avulsus* (Eichnoff). Statistical anal showed no significant differences in timing of initial attacks, at density, attack sequence, or species of *Ips* relative to O_3 dam Furthermore, there were no attacks on adjacent trees which were stressed by the simulated lightning treatment. Findings indicate tha stress at the level which occurred on WS 17 was insufficient predispose trees to *Ips* beetle attacks. Subsequent observations of plantation during the severe drought period of 1986 to 1988 epidemic populations of southern pine beetle (*Dendroctonus front* Zimmerman) caused widespread mortality of pitch pine (*Pinus rigi* revealed no attacks of this beetle in the white pine population.

5. Conclusions

Ozone damage to white pine on WS 17 was clearly visible in the gro season of 1984. Reductions in BAI of dominant and codominant trees attributed to the combined effects of reduced photosynthesis and e senescence and loss of foliage due to O_3 stress. However, there wer obvious carryover effects of O_3 on growth in 1985. Growth response all tree sizes in the population are under study but impacts currently unknown. There were no observable effects on nutr concentrations of stemwood or needlefall, but net nutrient accumula was reduced due to reductions in wood increment. Evidence for alt ecosystem biogeochemical cycles induced by O_3 damage was found in sm elevated NO_3^--N and K^+ concentrations in stream water. However, magnitude of nutrient releases were of little consequence to w quality. Ozone stress did not predispose trees to root pathogens or beetle attack.

The O_3 events and related white pine damage in 1984 represented ac conditions. Ozone injury was followed in 1986 through 1988 with the m severe drought observed in the region in this century. During 19 precipitation substantially exceeded average values. We have documen large growth reductions and changes in stream chemistry associated w drought conditions; although this ecosystem was severely stressed consecutive years by O_3 and drought, stemwood increment and str nutrient have returned to prestress levels during 1989. It appears t impacts of episodic O_3 stress in a relatively vigorous forest ecosyst as represented by the white pine forest on WS 17, are short-lived, that processes of growth and biogeochemical cycles are highly resili to stress. The same observation may or may not apply when O_3 exposure chronic and there are few visible damage symptoms.

Acknowledgments

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