PATTERNS OF NORTHERN RED OAK GROWTH AND MORTALITY IN WESTERN PENNSYLVANIA

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Abstract. This study evaluates the extent and cause(s) of an observed decline of northern red oak (*Quercus rubra* L.) on a 50-km portion of a major anticlinal ridge in west central Pennsylvania, and illustrates an approach for evaluating tree declines. Long term annual observations of forest health revealed the onset of crown dieback in 1983, chiefly among red oak, followed by further dieback and mortality. A plot survey in 1994 within 10 stands where increment cores from healthy red oak were obtained in 1986 revealed higher mortality among red oak than other species, higher mortality on ridgetop sites, greater mortality in the northern than southern half of the sample area, and greater mortality among larger diameter red oak. Radial growth and last growth year determined on cores from dead red oak in the 1994 sampling showed highest mortality occurred in 1990-1992. Dead stems displayed spatially-consistent patterns of decreasing growth after 1985. Comparisons with healthy red oak trees revealed a long-term relative growth decline, and relatively lower actual growth after 1969. Radial growth shocks and decreases during 1980-1993 were associated with weather extremes and defoliating insect outbreaks. A persistent, synchronous growth decline began after 1989 in concert with severe gypsy moth defoliation. Greater mortality in certain stands, along with previously discovered disparities in radial growth and tree-ring response to climate, may be related to historic air pollution from Johnstown, a nearby urban/industrial area.

INTRODUCTION

Episodes of tree decline and mortality are well-known phenomena that have historically occurred within various forest ecosystems (e.g., Millers and others 1989). Less well-understood are the precise causes of these episodes, yet the question of causal factors becomes especially important as issues of forest health and sustainable forestry assume greater significance to forestry professionals and the public.

Often, tree declines are only noted after they are well underway, and perhaps only after considerable mortality has occurred. A clearer understanding of the nature and potential causes of decline/mortality episodes would be possible if researchers had specific data and observations before and during the decline/mortality process. Lacking this, reconstruction of some events and conditions may be possible by combining tree-ring analyses with available information on climate, pest/pathogen and other potential stress events within the region, if not the affected stands (McClenahen 1995). Tree-ring variation can chronicle the decline process in terms of tree growth, a surrogate for tree health, that can be explored within the context of presently healthy, outwardly-declining, and dead trees within a population (Tainter and others 1990).

This study was aimed at elaborating the timing and nature of environmental stress events and conditions associated with an observed decline/mortality episode on Laurel Ridge in west central Pennsylvania. Considerable dieback and mortality among the oaks, especially northern red oak (*Quercus rubra* L.), has been observed since the early 1980's on Laurel Ridge. Although this trend in declining forest health was associated with a variety of environmental stress events, especially climate extremes and insect defoliations, the potential role of emissions from regional power generation and local industry in Johnstown cannot be overlooked. A general goal of our study was to determine whether local air pollutant emissions may be a factor in the oak dieback and mortality. Our approach was to assess

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the amount and extent of recent tree mortality, and to develop tree-ring chronologies on Laurel Ridge from standing dead northern red oaks in stands where live red oak chronologies had been previously obtained (ca. 1987). Our objectives were to estimate the amount and timing of recent red oak mortality within these stands, and to assess the possible causes of mortality by evaluating and comparing temporal and spatial growth responses of trees that have died, live (healthy) trees, and documented stress events in the region.

METHODS

Study Area

The study was conducted on Laurel Ridge, an anticlinal ridge of 700-800 m elevation within the Allegheny Plateau Physiographic Province in western Pennsylvania (Figure 1). The climate is continental with a mean growing season temperature of 19.8° C and annual precipitation averaging 104 cm. Soils are well to moderately well drained, very stony loams and silt loams, predominantly Typic Dystrochrepts, occasionally including some Typic Hapludults and Aquic Fragiudults. Forests on Laurel Ridge are second growth mixed hardwoods dominated by northern red oak and other oak species (*Quercus* spp.) on the ridgetop and southerly slopes. Coves and northerly slopes additionally contain black cherry (*Prunus serotina* Ehrh.), red maple (*Acer rubrum* L.), and yellow-poplar (*Liriodendron tulipifera* L.). Fire apparently was an important influence on vegetation of Laurel Ridge at least from colonial times (Harpster 1938) until effective suppression efforts in recent decades. Other factors that strongly influenced present forest composition and condition include the loss of American chestnut (*Castanea dentata* (Marsh.) Borkh.). By chestnut blight, extensive logging for timber and charcoal wood, periodic weather extremes, insect defoliations, and over-browsing by deer.

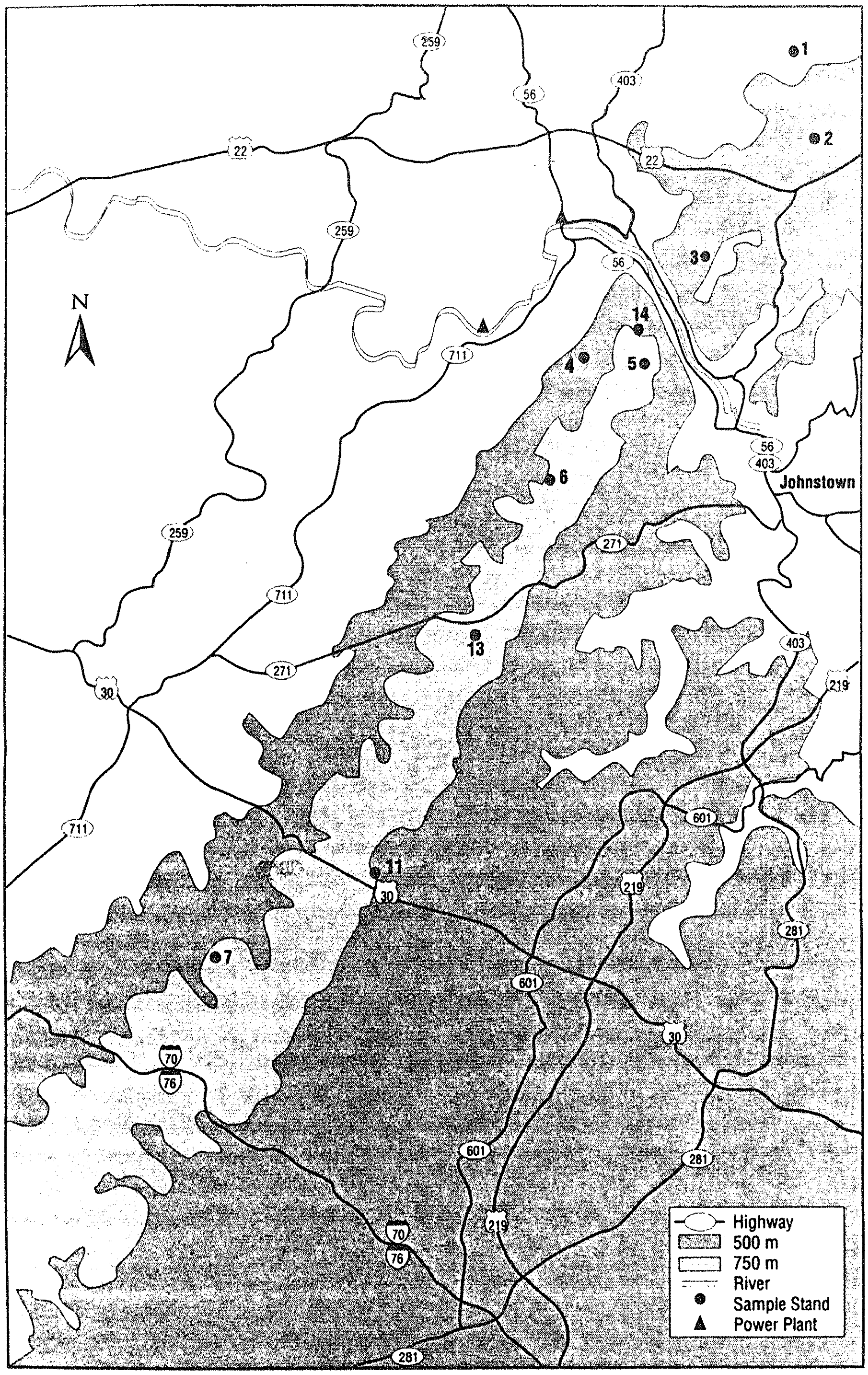
Historically, SO_2 has been a major air pollutant within the vicinity of Conemaugh Gap (Figure 1) since the late 19th century when iron and coke production began in the greater Johnstown area (Brown 1989). Power generating stations on the west side of Conemaugh Gap began operation in 1950 (Seward station, 201 MW generating capacity) and in 1970-71 (Conemaugh station, 1700 MW generating capacity) (Hutnik and others 1989).

Field Procedures

Healthy red oaks were originally cored within 10 stands (1-10 ha) on Laurel Ridge, mostly on upper west slopes and ridgetops, between 1987-1992 (Figure 1). A subsequent tree mortality survey and core sampling of standing dead red oak stems within the same stands in 1994 is the focus of this paper. To estimate the amount of recent tree mortality, 5-7 variable (10 BAF prism) plots were located at 50-m intervals along transects through each stand in 1994. All standing tally trees in the dominant, codominant and intermediate crown classes, living and dead, were measured. Species, crown class, dbh (diameter at 1.37 m height), and live or dead status were recorded. Signs of dieback were noted for live trees, although these data are not consistent because most stands were sampled in October.

Pairs of 5-mm diameter tree cores were extracted from up to 10 standing dead red oak stems (138 cores from 69 trees) that had occupied dominant or codominant crown positions. Nearly all dead candidate trees were sound enough to permit coring. Dead stems identified by the 10 BAF prism at the plot points were sampled if possible, or elsewhere within the stand as necessary; however, it was not possible to locate 10 dead stems anywhere within some stands. The same data collected for the mortality survey were also recorded for cored trees.

Healthy dominant and codominant red oaks (20-22 trees per stand) had been similarly cored and the ring widths were crossdated and measured ca. 1987 as part of an earlier study of growth relationships with climate and air pollution (manuscript prepared). Those tree-ring data are used here to compare the growth of then-healthy red oaks with the growth history of trees that subsequently died. Trees cored in 1987 were not labeled, so it was not possible to determine for certain which, if any, were part of the dead cohort sampled in 1994. Since increment borer wounds were not found on any of the sampled dead stems in 1994 (some were noted on living trees), it appears that few, if any, of the originally cored (healthy) trees had died by 1994.



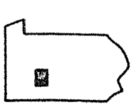


Figure 1. The study area showing numbered sample stands. Scale is 1cm = 3 km.

Annual, systematic observations of forest health, weather-related stress events, SO_2 symptomology on bioindicator species, and the status of pests and pathogens have been conducted by the second and third authors (and their predecessors) several times throughout each growing season since 1968 at selected locations on Laurel Ridge and elsewhere in the region. The records of these observations relevant to Laurel Ridge are summarized here from the unpublished annual reports to provide insights about possible causal agents relating to tree growth and mortality patterns. For the surveys of SO_2 leaf symptoms, planted (e.g., *Pinus sylvestris* L., *P. strobus* L., *Pseudotsuga menziesii* (Mirb.) Franco) and native (e.g., *Betula lenta* L., *Rubus* sp.) species known to be sensitive to SO_2 were examined several times each growing season at the same sites.

Laboratory Procedures

Densities (stems/ha) of live and dead stems were computed and summarized from the prism plot data for each species. The air-dried tree cores were glued onto labeled wooden holders, surfaced with a series of successively finer sandpapers, and crossdated visually to assure correct assignment of ring years. Ring widths were measured to 0.01 mm precision, and the visual crossdating was verified using a computer program (COFECHA, Holmes 1983).

The last growth year was estimated for each dead tree on the basis of the two cores. This year was taken as the best estimate of the year preceding death. Ring width measurements made on each crossdated core from both live trees cored ca. 1987 and dead trees cored in 1994 were analyzed to evaluate the growth patterns prior to death and in relation to growth behavior of apparently healthy red oaks. First, mean stand basal area increment patterns from dead stems were computed and plotted to observe general growth patterns and trends in relation to known stress events and the timing of mortality. Second, mean annual basal area increment differences between the live and dead red oaks were compared graphically to identify widespread relative discrepancies in growth behavior. The resulting time series of growth difference was subjected to intervention detection analysis (Box and Jenkins 1976, Downing and McLaughlin 1990, McClenahen 1995) to identify significant ($P = 0.20$) relative step or pulse types of growth shocks (i.e, negative growth interventions) experienced by trees that later died.

RESULTS

Mortality Survey

Total live stem density varied among stands, from stand 7 with 181 stems/ha to stand 6 with approximately 97 stems/ha (Table 1). However, the lower densities are partly a result of recent mortality (e.g., stands 6 and 2). Northern red oak constituted a high proportion of the canopy stems in most of the sampled stands, but the numbers of dead northern red oak stems ranged from none (stands 4, 13 and 14) to >32 stems/ha (Table 1). On average, red oaks comprised >68% of the dead stems.

Where oak species other than northern red oak were present, they also experienced high percentages of mortality (Table 2). Non-oak species comprised one-half or less of the composition of the sampled stands, and percent mortality was generally less than that of the oaks. Stands 7 and 13 had comparatively large components of black cherry and, in stand 13, less northern red oak. These stands are on relatively broad, concave ridgetops that are slightly more mesic than the others. The highest percentages of dead northern red oaks tended to occur in ridgetop stands near to, or downwind (northeast) of, the Conemaugh Gap area where the power generating stations and Johnstown are located (Figure 2). However, no northern red oak mortality was recorded in stands 4 and 14 which lie on mid- to lower slope positions nearest to the generating stations, or in stand 13 located slightly upwind and on a relatively mesic ridgetop site with comparatively few northern red oaks. Dominant and codominant stems of other species showed a geographical pattern of mortality similar to that of northern red oak, with no mortality again recorded in stands 4, 13, or 14. As noted above, many of the same stands with high northern red oak mortality also had relatively high percentages of dead trees of other species. This further suggests that trees in these northeastern stands may have been exposed to greater stress (with the exception of the more mesic stands).

Table 1. Mean stocking of live and dead dominant and codominant trees and northern red oaks in the sampled stands.

Stand No.	Canopy Trees Live	Canopy Trees Dead	Northern Red Oak Live	Northern Red Oak Dead
		-no. of stems/ha-		
1	128.3	45.8	34.0	12.9
2	104.0	43.3	47.8	32.1
3	125.4	29.8	97.9	20.7
4	120.8	0.0	51.7	0.0
5	127.4	26.1	116.8	23.0
6	97.3	29.3	89.0	29.3
7	181.0	6.5	72.6	3.1
11	155.1	18.4	93.4	14.7
13	144.3	0.0	37.7	0.0
14	137.9	0.0	56.7	0.0
Mean	**132.2**	**19.9**	**69.8**	**13.6**

As trees increase in size, they become more susceptible to stress in part due to an increasing ratio of respiring tissue to photosynthetic tissue (Mueller-Dombois, 1992). A t-test of mean dbh between dead and live canopy northern red oaks over all stands (n = 233 and 60, respectively) revealed that the dead trees were significantly (P = 0.003) larger by an average of 6.0 cm (mean dbh = 51.5 and 45.4 cm). This difference was most evident in stand 6, where all of a cohort of larger, older northern red oaks had died. These larger trees were apparently residuals from the previous stand. Ring counts ranged between 102 and 184 years, but heart rot generally precluded age determinations. This supports the general belief that older and larger trees disproportionately succumb to stresses that induce widespread mortality (Mueller-Dombois 1992).

Tree-Ring Data

A total of 132 cores from 69 standing dead red oaks in nine stands were successfully crossdated and the ring widths measured. At least one core from each sample tree was crossdated (95.6% of all cores). No dead northern red oaks were found for sampling in a tenth stand (stand 13), and only one specimen was obtainable in stand 4. The outermost ring was nearly always present on at least one of the two cores extracted from each tree (extensively decayed stems were not sampled, but such stems were rare). Absent rings are another potential problem in establishing the year of death (Mast and Veblen 1994). We did not independently test for the occurrence of missing rings among northern red oaks approaching death. However, unlike some coniferous species (Mast and Veblen 1994, McClenahen and McCarthy 1990), it is unlikely that northern red oaks are capable of surviving more than a year or two in so moribund a state. Although the total chronology period for most stands extended back into the nineteenth century, the selected common analysis period beginning in 1920 often included only about half of the cores, or less. In fact, the distribution of approximate dead tree ages (earliest ring) shows that most of the dead trees were around 70-80 years old (median age 77 years), but with 19% over 100 years old (Figure 3). These age distributions generally reflect the ages of trees in the sampled stands, along with the tendency for older and larger trees to disproportionately die as noted earlier.

Table 2. Average numbers of dominant and codominant stems and percent dead stems by species in sampled stands. Stands are sequenced from north to south on Laurel Ridge.

	Stand Number									
	1	2	3	14	5	4	6	13	11	7
Northern RedOak										
Stems/ha	46.9	79.9	118.6	56.7	139.8	51.7	118.3	37.7	108.1	75.7
% dead	27.5	40.2	17.4	0.0	16.4	0.0	24.8	0.0	13.6	4.1
White Oak										
Stems/ha	43.3	17.7	-	-	-	0.9	1.8	-	-	-
% dead	67.2	39.0	-	-	-	0.0	0.0	-	-	-
Chestnut Oak										
Stems/ha	-	8.6	6.4	47.8	-	27.5	-	-	15.2	-
% dead	-	50.0	100.0	0.0	-	0.0	-	-	15.1	-
Black Cherry										
Stems/ha	34.6	-	17.6	6.3	6.7	-	5.5	94.4	9.7	90.6
% dead	0.0	-	15.3	0.0	46.3	-	0.0	0.0	14.4	3.8
Red Maple										
Stems/ha	28.2	33.1	6.8	19.2	7.0	28.7	-	12.2	38.9	19.2
% dead	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0	0.0	0.0
Other Hdwds										
Stems/ha	21.1	8.0	5.8	7.9	-	11.9	1.0	-	1.6	2.0
% dead	18.0	0.0	0.0	0.0	-	0.0	0.0	-	0.0	0.0
Totals										
Stems/ha	174.1	147.3	155.2	137.9	153.5	120.7	126.6	144.3	173.5	187.5
% dead	26.3	29.4	19.2	0.0	17.0	0.0	23.1	0.0	10.6	3.5

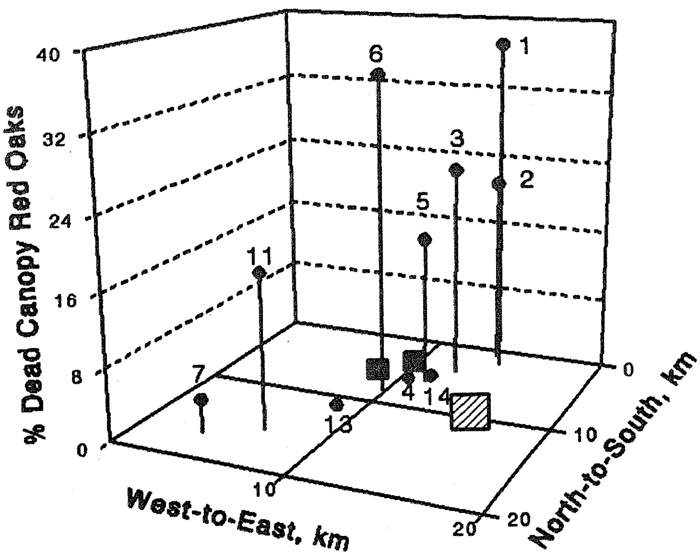


Figure 2. Percentages of dead dominant and codominant red oaks in sampled stands. Solid squares indicate power generating stations, the crosshatched square indicates the location of Johnstown.

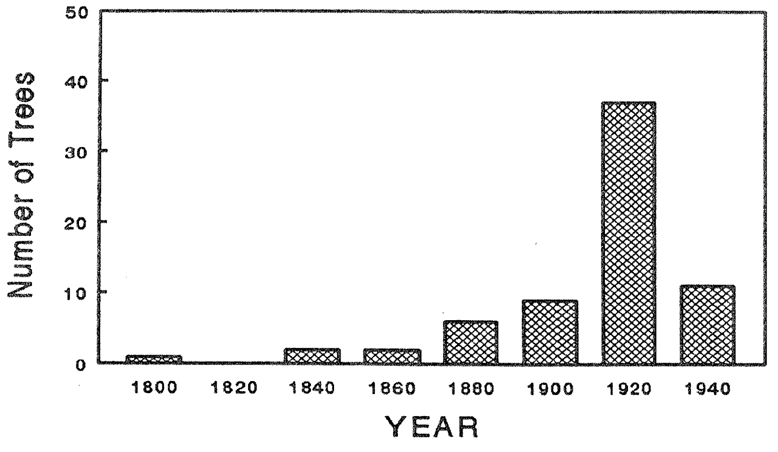


Figure 3. Distribution of approximate pith years for cored dead northern red oaks.

Figure 4 reveals that the distribution of last growth years among all sampled trees peaked in 1990 and 1991. It is difficult to know in exactly which years these trees would have appeared to be dead relative to the final growth ring since foliage may have died within the last growth year, or the tree may have failed to flush the following year. Thus, observable peak northern red oak mortality on Laurel Ridge should have been evident between 1990 and 1992. Our annual observations of forest health and potential stressors indicate that significant oak mortality and branch dieback first appeared in 1983, a drought year that was preceded by a cankerworm defoliation in 1982 (Table 3). Oak dieback and mortality continued through 1989 and 1990 when gypsy moth defoliations occurred. Our 1991 report stated "significant oak mortality on the ridgetops," which was reported in 1992 as "still ongoing." In 1993, crown dieback of oaks was listed as the most severe disease problem among broad-leaved species, and dieback (but not new mortality) was noted to continue into 1995. Thus, our general observations of oak mortality on Laurel Ridge confirm the tree-ring estimate of peak northern red oak mortality in 1991 and 1992.

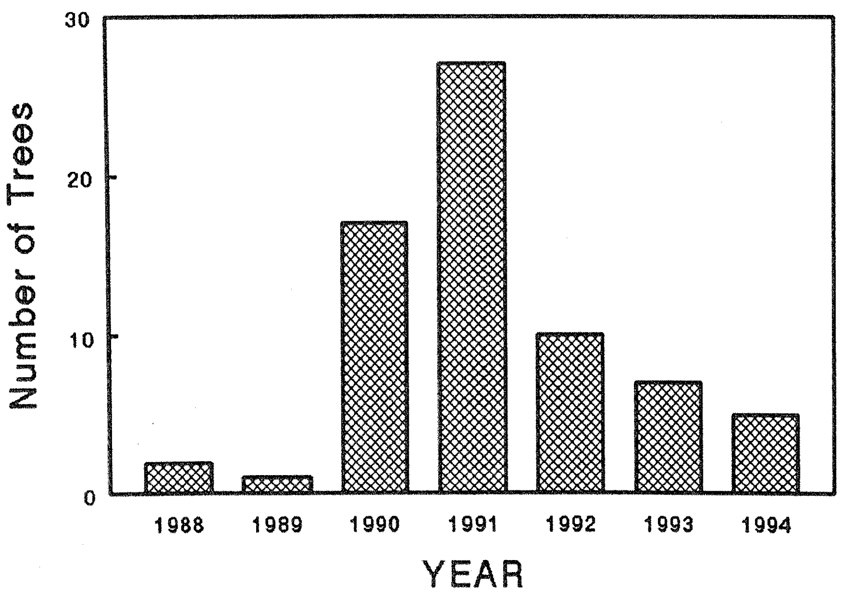


Figure 4. Distribution of last growth years for cored dead northern red oaks on Laurel Ridge.

Table 3. Summary of major forest health and pest/pathogen problems observed within the Laurel Ridge study area from 1968 through 1994 (years with no unusual problems omitted).

YEAR	EVENTS
1968	Periodic (17-year) cicada outbreak.
1969	Localized forest tent caterpillar defoliation.
1970	Localized forest tent caterpillar defoliation centered in the vicinity of stand 3 (100% defoliation); defoliation also probable in stands 4, 5, 6, and 14. Conemaugh Unit 1 on line in May; SO_2 injury recorded on bioindicator species (*Betula lenta* L. and others) near stand 3.
1971	Severe forest and eastern tent caterpillar defoliation centered near stand 3, defoliation probable in stands 4, 5, 6, and 14. Conemaugh Unit 2 on line in May; SO_2 injury on bioindicator species near stand 3.
1972	Moderate to severe leaf tatter on maple and oak due to Hurricane Agnes, especially at stand 6 and other exposed ridgetop sites. Severe regional frost the first week of June.
1973	Relatively lower SO_2 symptom severity on bioindicator species near stand 3.
1974	Relatively severe SO_2 symptoms on bioindicator species near stand 3.
1975	No unusual conditions reported; the "...entire study area [was] relatively free of defoliating insects." Relatively moderate SO_2 symptom severity on bioindicator species near stand 3.
1976	Insect injury minimal. Severe frost in mid-May after exceptionally warm April and early May; no mention of frost injury specific to oak. Frost injury worst at higher elevation. No SO_2 symptoms on bioindicator species near stand 3; extensive SO_2 injury on native species downwind from generating stations (an SO_2 episode occurred in June).
1977	Weather extremes: alternating cold and warm periods in February, warm and dry in April, cool and wet in early May, (>32° C in mid-May followed by a late May frost).
1980	Moisture stress in late summer.
1982	Severe cankerworm defoliation, including oaks on Laurel Ridge. Unusual weather: cold, snowy winter, late spring, warm and dry mid-April through mid-May, cool and rainy into June, hot summer with below average precipitation.
1983	Considerable top dieback and tree mortality on Laurel Ridge, primarily on ridgetop. Severe anthracnose on oak leaves. A drought year.
1984	Shot-hole feeding injury severe on leaves of oak and black cherry on Laurel Ridge. Trace SO_2 injury on sensitive species near stands 3, 4, 14, and 6.
1985	Periodic (17-year) cicada the most severe foliar injury; shot-hole feeding injury also prevalent on northern red oaks and black cherries.

(Table 3 continued)

(Table 3 continued)

YEAR	EVENTS
1986	An early spring and light June frost caused no apparent damage. Shot-hole injury common on oaks and black cherry. Dead branches from 1985 cicada injury evident. Oak dieback and mortality on Laurel Ridge continued.
1987	Mid- and late-summer heat waves, followed by cooling that prematurely ended the growing season in early autumn. Shot-hole injury common on oaks and black cherries.
1988	Oak dieback and mortality continues on Laurel Ridge. Severe drought the last 3 weeks of June and first 2 weeks of July. Drought most severe in the north and decreasing in the southern part of the study area. High temperatures from June through August, interspersed by low temperature events, one in June with temperatures of -1 C.
1989	Severe defoliation by gypsy moth, ca. 100% in some areas of Laurel Ridge. Oaks largely refoliated by autumn.
1990	Severe gypsy moth defoliation, especially on Laurel Ridge; high incidence of top-dieback noted on oaks. Dormant-season temperatures fluctuated greatly.
1991	Severe oak dieback and mortality on Laurel Ridge. More mortality, dieback, and sparse foliage among oak (and other species) than in 1989-1990. Light gypsy moth defoliation. Extremely hot from May through autumn, with 50% below-normal precipitation.
1992	Continued high oak mortality and dieback, especially on Laurel Ridge. Light to no gypsy moth defoliation. Cool growing season, good growing conditions.
1993	Continued severe, widespread oak dieback and mortality. Insect defoliation light. Comparatively minimal SO_2 injury. Hot, somewhat dry growing season

The tree ring data from dead stems are probably only indicative of trees that died in the previous 6-7 years; stems from earlier mortality may be too decayed for core sampling. However, very few stems in the sampled stands were not cored due to decay, suggesting that the mortality patterns in Figure 4 are probably representative of the years since about 1988. Regardless, our cores from dead trees would not likely have included the initial oak mortality that we observed ca. 1983.

The mean basal area growth patterns of dead northern red oaks are shown for each stand in Figure 5. A severe mid-1960's drought that occurred throughout the Northeast represents one of the most pronounced and widespread growth shocks that occurred on Laurel Ridge. This growth shock was also generally prominent in the healthy trees cored ca. 1987. However, growth of dead northern red oaks in several stands was either not severely impacted by this drought, or growth recovery occurred immediately afterward (viz., stands 1, 2, 3, 4, and 14). Conversely, growth of trees in stands 5, 6, 7, and 11 failed to fully recover and a general decreasing growth trend followed. It is interesting to note that stand 5, which may have been most exposed to Johnstown pollutant emissions, subsequently exhibited an increasing growth trend beginning in the late 1970's and early 1980's coincident with dramatic reductions in the Johnstown steel industry (Brown 1989).

Another notable feature of the growth trends for individual stands is the widespread, negative growth shocks apparent in the early 1970's (Figure 5). These were seen mostly in either 1971 (stands 1, 4, and 14) or 1972 (stands 2, 3, 5, 6, 11, and perhaps 7). These growth shocks were also evident among the live northern red oak chronologies. The timing of these growth shocks approximately coincided with several potential stress events: (1) the startup of

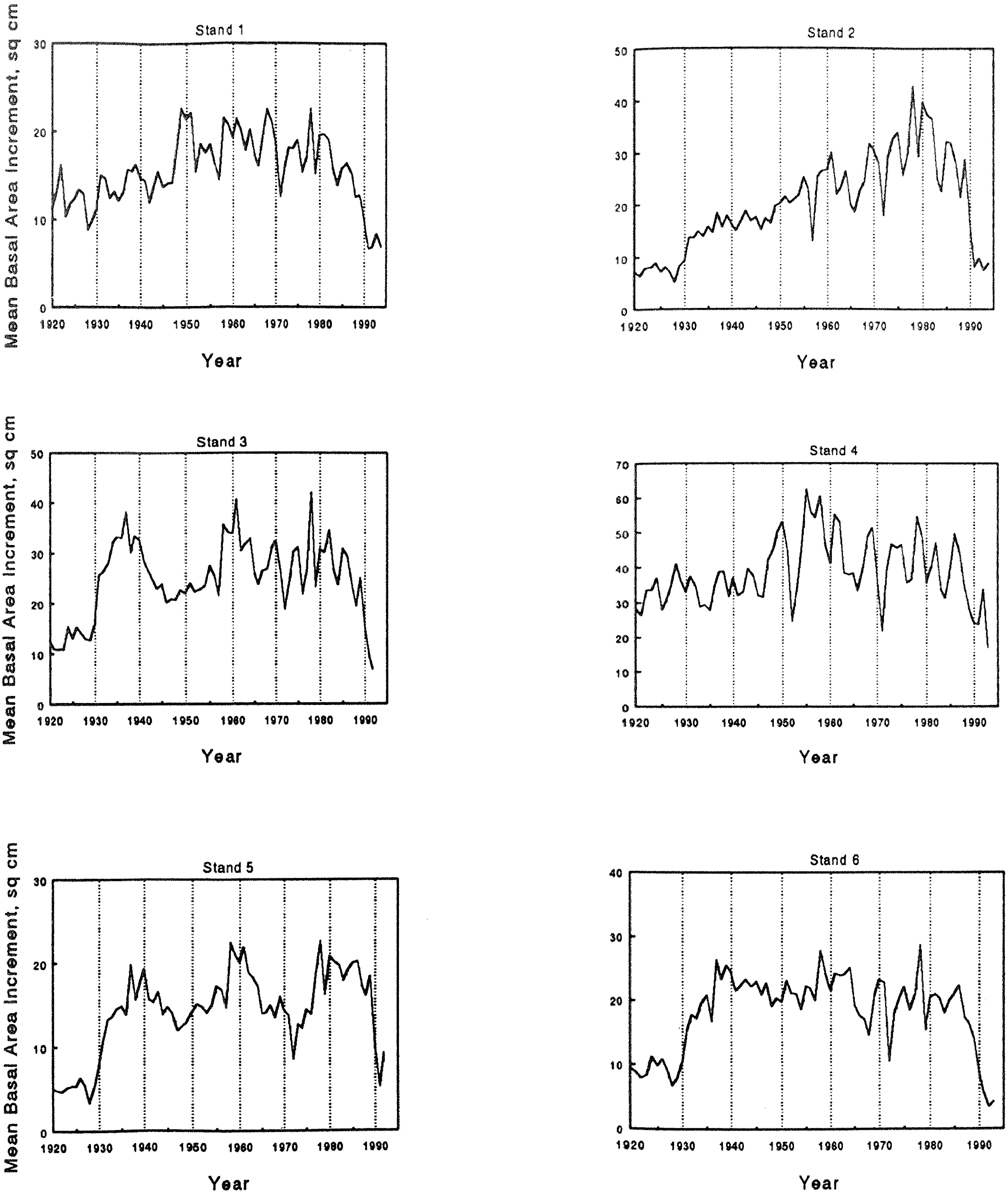


Figure 5 (continued)

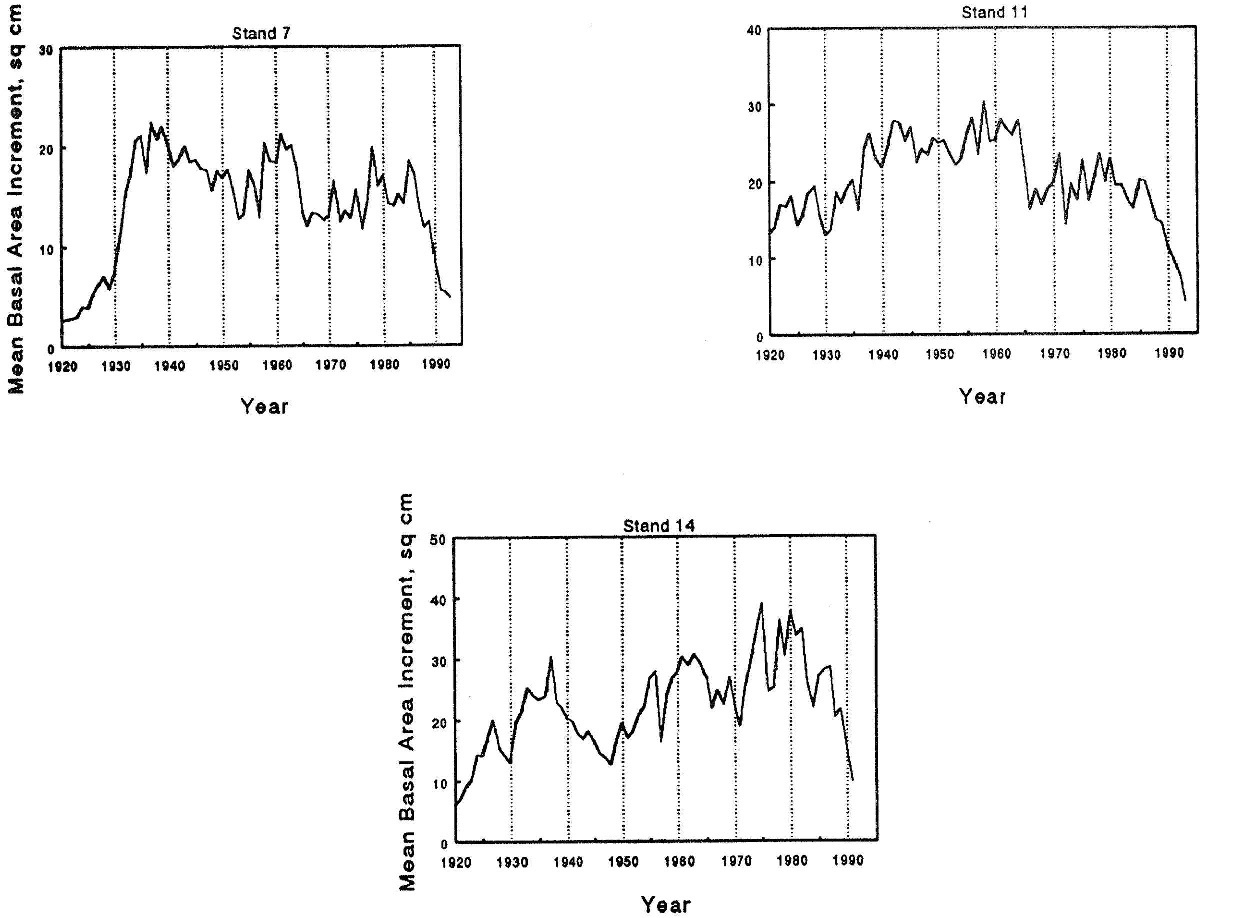


Figure 5. Mean stand basal area growth patterns of cored dead northern red oaks.

the Conemaugh power station in 1970 and 1971, (2) the initial, localized appearance of SO_2 symptoms on leaves of some sensitive species on Laurel Ridge, (3) a series of forest and eastern tent caterpiller outbreaks of varying defoliation severity and spatial distribution on Laurel Ridge in 1969 and especially 1970-1971 and, (4) several weather-related stress events (Table 3).

Most of the dead northern red oak chronologies reveal sharply decreasing growth trends beginning in 1988, a year of severe drought, until death occurred (Figure 5). Interestingly, some stand chronologies showed slight, temporary growth recovery in 1989 despite the severe gypsy moth defoliation in that year.

Evaluation of the time series of mean growth trend differences between relatively healthy (cored ca. 1987) and dead northern red oaks (cored in 1994) was conducted to establish the timing of major and widespread growth shocks (i.e., step and pulse interventions) that registered more severely among the dead northern red oaks on Laurel Ridge (Figure 6). Early growth of the dead northern red oaks, relative to the healthy trees, decreased consistently from 1920 until around the 1950's, possibly a result of stand dynamics, an artifact of early sample depth, or a predisposing condition to decline. Intervention analysis shows that growth of the dead northern red oaks was comparatively more strongly reduced by stresses around 1952, 1980, and 1985.

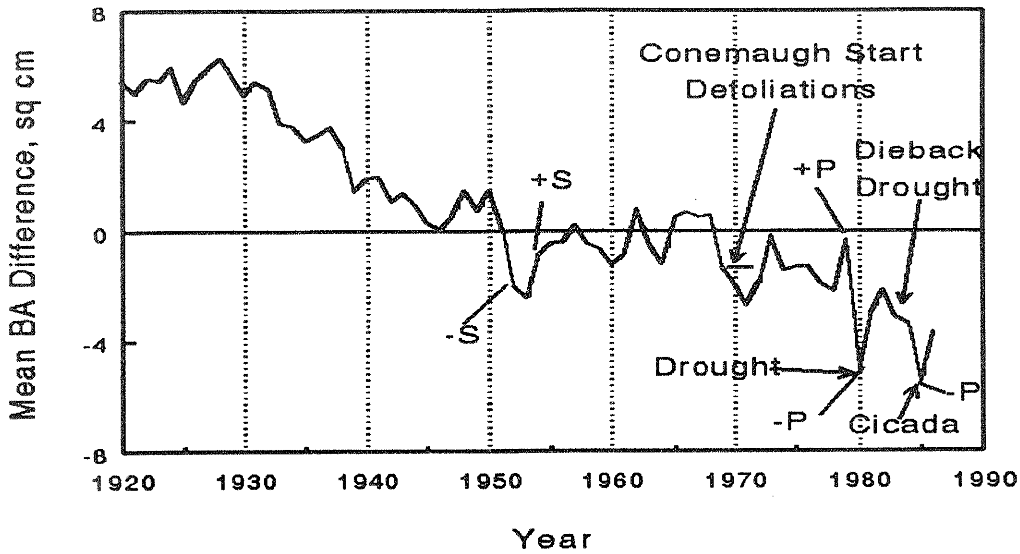


Figure 6. Time series of mean basal area growth differences between dead and live northern red oaks (dead minus live) cored on Laurel Ridge. Significant (P = .20) positive (+) and negative (-) step (S) and pulse (P) growth interventions are indicated.

The temporary step growth decrease in 1952-1953 (Figure 6) roughly coincides with a 1953-1955 drought (mean growing season precipitation deficit of 100 mm), and a series of defoliator outbreaks in the mid-1950's in many areas of Pennsylvania (Nichols 1968). An apparent relative growth shock in 1970-1971 probably due to the tent caterpillar infestation was not significant, suggesting that the growth impact of this defoliation was not very different between the healthy and dead northern red oaks. Conversely, drought in 1980 and a 17-year cicada outbreak in 1985 seem to have affected the growth of the dead northern red oak group more severely than the healthy trees. From these relative patterns of growth behavior, it appears that the dead northern red oaks had been predisposed (after Mueller-Dombois 1992) to growth decline relative to the general population by about 1980. The predisposing factor(s) may have been all or some combination of drought and defoliators in the 1950's, the statistically non-significant but notable growth shocks in 1970-1972, or other general stresses that more or less adversely affected northern red oak growth on Laurel Ridge (such as drought in the 1960's). However, the steady, long-term relative growth decline of the dead cohort from around 1930 until the late 1940's (Figure 6) may be indicative of even earlier predisposing factor(s) such as extreme drought (1931) and/or microsite conditions.

DISCUSSION AND SUMMARY

Tree-ring analyses, annual field observations of tree health, and a tree mortality survey revealed that a contemporary tree mortality episode on Laurel Ridge was largely confined to oaks, especially northern red oak, the predominant oak species in these ridgetop stands. Between 0 and 40% of northern red oaks were dead in the 10 sampled stands. The variation in percentage of dead trees appeared to be partly related to moisture relationships, with less mortality on relatively mesic and (or) lower slope sites. The episode of high northern red oak mortality began about 1990, peaked in 1991-1992, and decreased through 1994. The amount of 1994 mortality remained greater than pre-episode levels (1988 and 1989), indicating that the episode, though subsiding, had not yet ended.

The chronology of stress events, documented since 1968, allows some inferences regarding factors that may have caused this decline and mortality episode. The 1980 relative growth shock, induced by drought, may have been the inciting factor that initiated declining growth and health among the cohort of trees that ultimately died (Figure 6). Subsequent stresses, such as the defoliation by cankerworm in 1982, drought in 1983 and 1988, periodic cicada injury in 1985 and, finally, gypsy moth defoliations in 1989 and 1990, probably contributed to the spiral of decline leading to death. We first observed external indication of declining health, in the form of widespread branch dieback, in 1983. The dead tree chronologies in all stands showed a period of precipitous basal area growth decrease beginning after 1985 (Figure 5), implying that the major stress factor(s) were prevalent throughout the Laurel Ridge study area. It would be interesting to know whether the growth and health of declining trees would have recovered in the absence of the 1988 drought and the severe gypsy moth defoliations in 1989 and 1990. Regardless, the succession of stress events beginning around 1980 evidently triggered the sharp growth decrease and widespread crown dieback among northern red oaks on Laurel Ridge that resulted in the high mortality detected by our qualitative and quantitative field observations and from the tree-ring chronologies.

In addition to site factors, geographical patterns suggest that greater northern red oak mortality tended to occur northeast of the Conemaugh Gap, generally downwind of local power generating stations and the industrial city of Johnstown. High mortality in this direction was largely confined to upper elevation stands directly above Johnstown and to the northeast, while stands on the ridge slopes nearest to, and downwind of, the generating stations (on the opposite side of the ridge from Johnstown) had little to no oak mortality. The SO_2 concentration patterns in the region are not known. SO_2 injury was found on bioindicator species near stand 3 in the early years of the Conemaugh station startup, but symptoms there have been absent since the mid-1970's. We have consistently observed SO_2 symptoms on *Rubus* sp. on the ridge slope above Johnstown. We previously reported that leaf sulfur concentrations are greater nearest the generating stations (and Johnstown) in the northeast (downwind) direction (Hutnik and others 1989), while foliar O_3 injury on a bioindicator species (hybrid poplar) was unrelated to, or slightly lower near, the generating stations (Davis and others 1993). This suggests that both Johnstown industries and the generating stations have contributed to leaf sulfur concentrations and to localized foliar SO_2 symptoms. Another of our studies indicates that historical industrial emissions from Johnstown may have adversely affected northern red oak growth and response to climate variation in some of these stands (manuscript in review). The issue of whether the startup of the Conemaugh generating station in 1970-1971, or the concurrent severe tent caterpillar defoliations, played a role in the negative growth perturbations is being further investigated. Preliminary results revealed that ring-width chronologies of yellow-poplar (a non-host species) lacked the negative growth interventions seen in northern red oak (a host species), confirming that defoliation by insects was the most likely cause of northern red oak growth reductions in 1970-1972. The prevalence of the northern red oak growth intervention throughout the study area lends additional weight to this notion. Thus far, our results do not indicate that the power generating stations had a significant impact on tree health or northern red oak mortality on Laurel Ridge.

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