INCIDENCE OF TWOLINED CHESTNUT BORER AND *HYPOXYLON ATROPUNCTATUM* ON DEAD OAKS ALONG AN ACIDIC DEPOSITION GRADIENT FROM ARKANSAS TO OHIO

Robert A. Haack and Richard W. Blank[1]

Abstract: The incidence of twolined chestnut borer (TLCB), *Agrilus bilineatus* (Weber), and the canker fungus *Hypoxylon atropunctatum* (Schw. ex Fr.) Cke. was recorded on dead oak (*Quercus*) trees ≥7 cm diameter at breast height (DBH) along an acidic deposition gradient from Arkansas to Ohio in 1989 and 1990. Approximately, one to three hectares of oak-hickory forests were inspected at each of seven study sites: one site in Arkansas, two in Illinois, two in Indiana, and two in Ohio. All sites were broadly analogous with respect to geology, soil, slope, aspect, and forest cover type. Proportionally, more trees in the red oak group had died than trees in the white oak group at the Illinois, Indiana, and Ohio sites. Mean DBH of dead red oaks was greater than that of dead white oaks at all sites. Evidence of TLCB and *H. atropunctatum* attack was observed at all sites on several red oak species (scarlet, blackjack, northern red, and black oak) and white oak species (white, chestnut, and post oak). TLCB attack was generally more common than *H. atropunctatum* on both red oaks and white oaks. Moreover, incidence of both pests tended to be (a) higher on red oaks than on white oaks, and (b) higher in Illinois, Indiana, and Ohio than in Arkansas.

INTRODUCTION

The Ohio Corridor Study is focused on the possible effects of acidic deposition on oak-hickory forests in the lower midwestern United States (LeBlanc et al. 1988, Loucks et al. 1991). This geographic gradient study was one of several forestry-related studies funded in the 1980's as part of the Forest Response Program of the National Acid Precipitation Assessment Program; see Schroeder and Kiester (1989) for program details. The Ohio Corridor Study was originally designed to test the hypothesis that, for analogous stand conditions and soil types, differences in growth responses of oak and hickory along the gradient could be explained by differences in pollutant dose. Seven study sites were selected within or near four national

[1]Research Entomologist and Biological Technician, respectively, USDA Forest Service, North Central Forest Experiment Station, Insect Project, 1407 S. Harrison Road, East Lansing, MI 48823.

Table 1.--Site location data, median stand age of dominant and co-dominant trees, percent of basal area consisting of *Quercus* and *Carya* species (trees ≥10 cm DBH), mean annual precipitation at or near the site (1955-1986), and estimated annual total (wet + dry) sulfate deposition for two time spans (details in Loucks et al. 1991).

	Sites						
Parameter	ARK	DIX	TON	CSF	HNF	EOA	WNF
State	Arkansas	Illinois	Illinois	Indiana	Indiana	Ohio	Ohio
County	Franklin	Pope	Jackson	Scott	Jackson	Adams	Perry
Latitude	35°45′	37°25′	37°38′	38°30′	39°03′	38°40′	39°35′
Longitude	93°47′	88°40′	89°11′	85°50′	86°12′	83°27′	82°03′
Elevation (m)	685	87	121	97	86	101	123
Age (yr)	61	74	105	93	88	99	121
% *Quercus*	98	88	77	86	98	96	87
% *Carya*	1	9	20	6	>1	1	10
% *Q* + *C*	99	97	97	92	99	97	98
Precip (cm)	120.4	118.1	120.3	108.5	112.6	106.2	104.8
Estimated total annual sulfate deposition ($g/m^2/yr$)							
1900-1985	5.51	8.64	7.66	8.68	8.80	9.99	9.89
1955-1986	3.85	6.73	5.97	6.14	6.23	7.16	7.08

forests along a gradient from northwest Arkansas through southern Illinois and Indiana to south central Ohio. Within the United States, the Ohio River Valley has consistently been a region of high sulfur oxide emissions during the 1900's (Gschwandtner et al. 1986). Estimates of total sulfate deposition (wet + dry) during the 1900's show nearly a two-fold increase from Arkansas to Ohio (Table 1; Loucks et al. 1991), with sulfate concentrations decreasing in more recent years. In addition, the Ohio River Valley is recognized as an area of high ozone concentrations within the United States (Lefohn and Pinkerton 1988); however, no major ozone gradient was detected in the present study (Loucks et al. 1991). All study sites were selected to be south of the maximum glacial advance and north of areas where soils have high sulfate absorption capacities. Soils were primarily of the sandy loam types, with low cation capacity (Guillemette 1989, Loucks et al. 1991).

Although the Ohio Corridor Study sites were selected to be highly analogous, subsequent detailed soil and stand-structure studies indicated that the Arkansas site, and some of the Illinois and Ohio plots would have to be withdrawn from analyses when considering only the most narrowly analogous sites (Loucks et al. 1991). Nevertheless, in the present study, we present results from all seven sites.

Aspects of oak decline and mortality were investigated by several researchers in the Ohio Corridor Study (Loucks et al. 1991). Two pests that were commonly associated with dead oaks along the gradient were the twolined chestnut borer (TLCB), *Agrilus bilineatus* (Weber) (Coleoptera: Buprestidae), and the canker fungus *Hypoxylon atropunctatum* (Schw. ex Fr) Cke. These two pests are commonly associated with stressed oaks, especially drought-stressed oaks (Bassett and Fenn 1984, Haack and Benjamin 1982, Lewis 1981, Mistretta et al. 1981, Tainter et al. 1983). The TLCB is recognized as the principal insect mortality agent of stressed oaks in the eastern United States (Haack and Acciavatti 1991). The virulence of *H. atropunctatum* is less well documented; it is recognized as a saprophyte, but it may be a weak parasite on severely stressed trees. No other above-ground pests were commonly found on recently dead and dying oaks across the gradient.

The objective of the present study was to categorize the dead oaks at each of the seven Ohio Corridor Study sites with regard to tree species or sub-genus, DBH (diameter at breast height), trunk condition and orientation, and incidence of TLCB and *H. atropunctatum* attack.

METHODS

Study Sites

Detailed information on study site selection and baseline information for all permanent plots is found in Guillemette (1989), LeBlanc et al. (1988) and Loucks et al. (1991). Briefly, seven study sites were selected that had similar vegetation, soils, and geology. These oak-hickory sites were selected to have broadly analogous environments, except for the acidic dose. Sites and their abbreviations are Ozark National Forest in Arkansas (ARK), Dixon Springs (DIX) and Touch of Nature (TON) in Illinois, Clark State Forest (CSF) and Hoosier National Forest (HNF) in Indiana, and Wayne National Forest (WNF) and Edge of Appalachia (EOA) in Ohio; administratively, HNF and WNF have been combined and are now known as the Wayne-Hoosier National Forest. Additional location and site data are presented in Table 1. At each site, approved sampling areas (sample elements) were located on upper slopes with southerly aspects in mature oak-hickory stands that showed no evidence of recent fire damage or logging. Eight 0.04-ha permanent plots were established at each site at randomly chosen points within the sample elements. Across the gradient, tree species composition was complex; about 30 different species were encountered on the 56 permanent plots (LeBlanc et al. 1988). The oak and hickory components of each site are presented in Table 2.

During summer 1989, we inspected all dead oaks for TLCB and *H. atropunctatum* on each permanent plot. That procedure, however, provided fewer than 10 suitable dead oaks per site at four of seven sites. To increase the sample size of dead oaks, we revisited all sites in spring 1990 and marked off large sections of practically all approved sample elements at each site for further inspection; approximately 1-3 ha per site.

Tree Measurements

We first determined whether individual dead trees were oaks by using characters such as bark, branching pattern, buds, wilted foliage, distinctive genus-specific beetle galleries, and wood grain. Then, if possible, oaks were assigned to a species or sub-genus group, i.e., the red oak group (ROG) *Erythrobalanus* or the white oak group (WOG) *Lepidobalanus*. Such assignments were usually not done with oaks that had lost all bark and/or were in advanced

Table 2.--Mean basal area (m^2/ha) of hickory (*Carya*) and oak (*Quercus*) species by site for trees ≥10 cm DBH, based on eight 0.04-ha plots per site (LeBlanc et al. 1988).

	Basal area						
Tree species	ARK	DIX	TON	CSF	HNF	WNF	EOA
Hickory species							
Bitternut, *C. cordiformis*	-	-	-	0.49	-	-	-
Pignut, *C. glabra*	-	0.67	1.97	1.15	0.11	-	3.57
Red, *C. ovalis*	0.22	0.46	1.49	-	-	-	0.31
Shagbark, *C. ovata*	-	0.76	0.11	-	-	0.25	0.17
Mockernut, *C. tomentosa*	-	-	-	-	-	0.08	-
Oak species							
White, *Q. alba* L *	7.23	5.24	2.85	2.20	0.83	10.11	0.95
Scarlet, *Q. coccinea* L	-	-	-	0.55	4.77	0.83	-
Southern red, *Q. falcata* E	-	0.50	-	-	-	-	-
Blackjack, *Q. marilandica* E	-	0.06	0.06	-	-	-	-
Chestnut, *Q. prinus* L	-	-	-	19.21	18.71	8.96	19.16
Northern red, *Q. rubra* E	9.97	1.07	1.05	-	-	0.79	1.81
Post, *Q. stellata* L	-	6.18	6.21	-	-	0.32	0.51
Black, *Q. velutina* E	0.26	4.70	2.71	0.68	0.98	5.33	4.08
Red oak group	10.23	6.33	3.82	1.23	5.75	6.95	5.89
White oak group	7.23	11.42	9.06	21.41	19.54	19.39	20.86
All oaks	17.46	17.75	12.88	22.64	25.29	26.34	26.75
All hickories	0.22	1.89	3.57	1.64	0.11	0.33	4.05
All other species	0.18	0.54	0.42	2.05	0.33	0.62	1.11
All species combined	17.86	20.18	16.87	26.33	25.73	27.55	31.67

* L = white oak group *Lepidobalanus* of genus *Quercus*, E = the red oak group *Erythrobalanus*.

stages of decay. Bark was the principal character used for species or sug-genus designation among dead oaks.

Several parameters were recorded for all dead oaks ≥7 cm DBH, using methods modified from McCune et al. (1988). DBH was recorded to the nearest 1 cm with no correction made for bark loss. At times, DBH had to be estimated, especially for stumps and decadent trees. Precision, as indicated by remeasurement of DBH, was within 0-3% of the original values.

Broad categories of tree condition were recorded to allow inference about the timing of death. Dead oaks that could be identified to species or sub-genus were assigned to one of five categories as given in McCune et al. (1988): 1 = small twigs intact, 2 = main trunk solid, small branches gone, 3 = main trunk soft but shape mostly intact, 4 = main trunk deeply rotted, collapsed, and 5 = main trunk gone, only fragments of tree base remaining. Dead oaks that could not be identified to species or sub-genus because of lack of bark or being in an advanced stage of decay were assigned to category 6.

We estimated percent of bark lost from the main trunk using 10% intervals, with remeasurements never exceeding ±1 interval. In addition, we recorded orientation of the main trunk as either standing, leaning but not touching the ground, fallen on the ground, or only remains of the stump existed.

Definitive signs of TLCB and *H. atropunctatum* were used to designate a dead oak as having been definitely attacked. For TLCB, the distinctive meandering larval galleries on the sapwood surface or D-shaped adult exit holes on the bark surface were used as positive evidence of TLCB attack (Haack 1989, Haack and Acciavatti 1991). In trees that had died the previous growing season (1989), TLCB larvae and pupae were often found because the 1990 surveys took place before adults emerged.

We designated trees as having *H. atropunctatum* infection if we observed one or more stromata on the main trunk as illustrated in Fenn and Holland (1984), Thompson (1963), and Van Arsdel (1972). We recognize that this method underestimates the actual level of *H. atropunctatum* because some infections may not yet have developed stromata, and others may never develop stromata.

On standing trees, the lower 2 m of trunk were always inspected for both pests; upper portions of the main trunk were examined from the ground for *H. atropunctatum* stromata. On leaning trees and those on the ground, nearly the entire trunk was inspected. Typically, incidence of TLCB and *H. atropunctatum* on oaks assigned to trunk conditions 4-6 could not be assessed with high accuracy due to lack of bark and to advanced stages of decay. Although standing trees had the smallest percentage of their trunk area inspected at close range, we consider the TLCB data reliable because this beetle attacks to ground level in the year of tree death (Haack and Benjamin 1982).

RESULTS

Characteristics of Dead Oak Trees

We inspected a total of 1384 dead oaks (≥7 cm DBH) on the seven sites (Table 3). Of the eight oak species found on the study plots, dead individuals of seven species were found: white (*Q. alba* L.), scarlet (*Q. coccinea* Muenchh.), blackjack (*Q. marilandica* Muenchh.), chestnut (*Q. prinus* L.), northern red (*Q. rubra* L.), post (*Q. stellata* Wangenh.), and black oak (*Q. velutina* Lam.) (Table 2). No dead southern red oak (*Q. falcata* Michx.) were found; however, this species was recorded at only one site (DIX; Table 2).

DBH of dead oaks ranged from 7 to 75 cm; mean DBH for red oaks exceeding that of white oaks at all sites (Fig. 1). The 10- to 19-cm DBH class was the most heavily represented at each site. Mean DBH for all dead oaks combined was smallest in ARK and greatest in EOA; mean DBH was positively correlated with median stand age (r^2=0.61, P<0.038, N=7 sites).

In general, dead oaks in trunk-condition categories 3 and 6 were the most frequently assigned (Table 3). Trunk condition patterns were broadly similar between red oaks and white oaks (data not shown). Based on examination by others of dead oaks ≥20 cm DBH on these same sites, oaks in trunk-condition categories 1 and 2 had died in the past 10 years, and those in categories 3 to 5 had died more than 10 years ago (Loucks et al. 1991).

Table 3.--Number or percent of dead oak trees ≥7 cm DBH in various categories by site.

	Site							
Category *	All	ARK	DIX	TON	CSF	HNF	WNF	EOA
Number of dead oaks in all trunk orientation categories (N=1384 trees total)								
All, conditions 1-6	1384	235	309	176	123	285	130	128
All, conditions 1-3	698	139	207	110	51	100	33	58
ROG, conditions 1-3	268	63	61	45	17	33	19	30
WOG, conditions 1-3	430	76	146	65	34	67	14	28
Number of standing or leaning dead oaks (N=647 trees total)								
All, conditions 1-6	647	156	183	63	52	115	33	45
All, conditions 1-3	493	113	157	56	40	75	15	37
ROG, conditions 1-3	189	50	55	23	14	21	9	17
WOG, conditions 1-3	304	63	102	33	26	54	6	20
Percent of all dead oaks (N=1384) by trunk condition (%)								
Condition 1	4	9	4	5	4	4	2	3
Condition 2	10	14	9	4	6	10	3	19
Condition 3	37	36	54	53	32	23	21	23
Condition 4	15	32	10	6	25	12	17	9
Condition 5	4	7	1	2	4	5	9	2
Condition 6	30	2	22	30	30	50	49	44
Percent of all dead oaks (N=1384) by percent bark lost (%)								
0 - 5 %	23	33	37	28	14	14	3	17
10 - 20 %	15	23	21	19	11	8	6	10
30 - 70 %	15	20	10	13	15	16	14	13
80 - 90 %	13	19	8	8	23	10	19	12
95 -100 %	34	5	24	32	37	52	58	47
Percent of all dead oaks (N=1384) by trunk orientation (%)								
Standing	43	62	56	33	43	37	20	30
Leaning	3	4	3	3	0	4	5	5
Fallen on the ground	51	34	41	64	56	57	61	53
Stump only	3	0	0	0	1	2	14	12

* ALL = all red oaks, white oaks, and oaks of unknown species combined; ROG = red oak group; WOG = white oak group.

Percent of bark lost from the main trunk of dead oaks is given in Table 3. Overall, most dead oaks in Arkansas and Illinois had lost relatively little bark (0-20%), while most dead oaks in Indiana and Ohio had lost most of their bark (80-100%). Patterns of percent bark lost were generally similar between red oaks and white oaks (data not shown). There was a positive correlation between percent bark lost and trunk condition category (r^2=0.66, P<0.001, N=1384 trees).

Percent of dead oaks in each trunk-orientation category is presented in Table 3. The ARK and DIX sites had the highest percentage of dead oaks in the standing position, whereas most were on the ground at the other five sites. Trees in the leaning category accounted for 0-5% of the dead oaks at any one site. Decayed stumps (with no obvious associated trunk) were found only at the Indiana and Ohio sites, suggesting some prior logging.

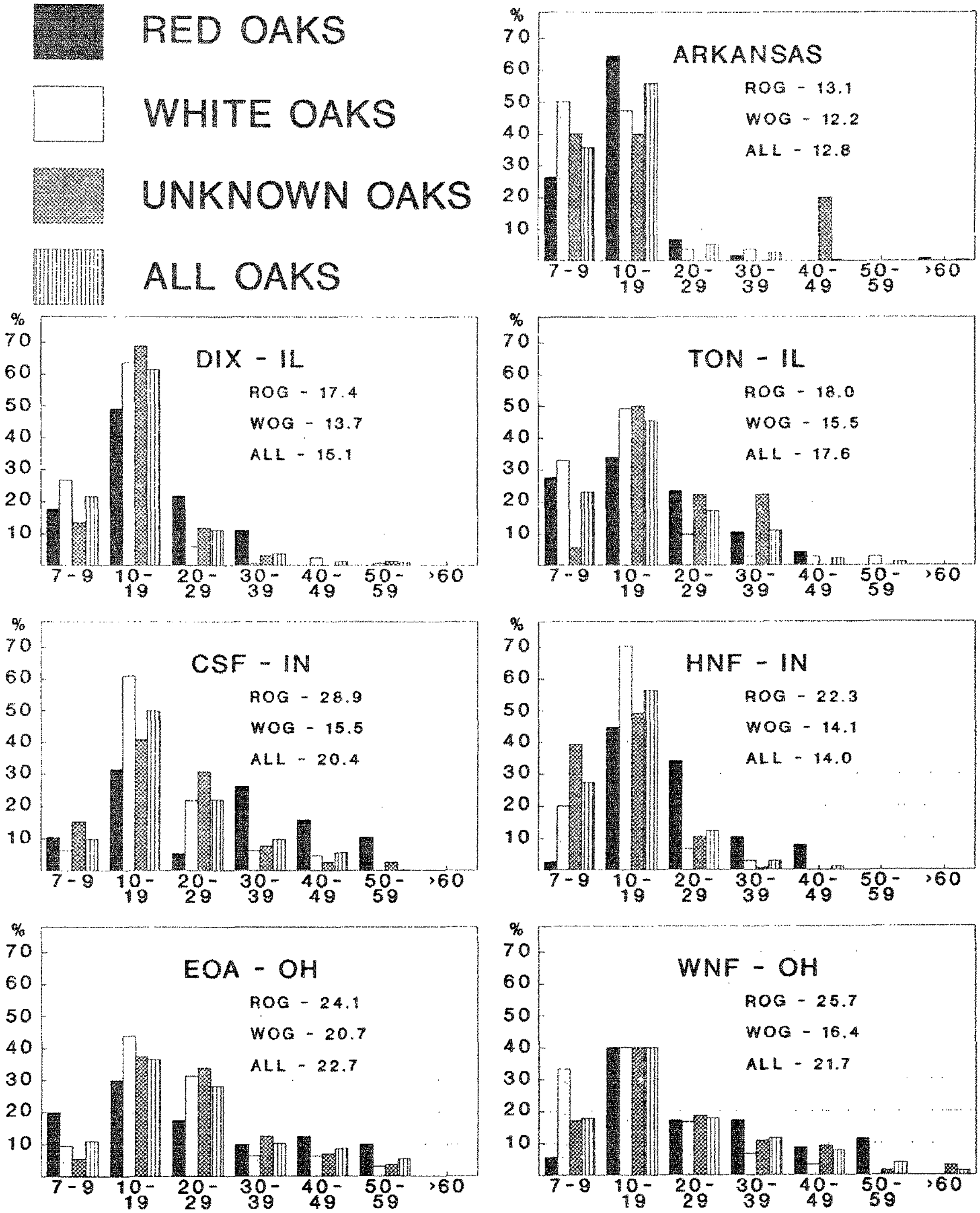

Figure 1. Percent of dead oaks for each site in various groupings by DBH (cm); N values given in Table 3. Unknown oaks are those in trunk-condition category 6 for which species determination was not made. Numbers within each box represent the mean DBH for all dead red oaks (ROG), all dead white oaks (WOG), and all dead oaks combined including those in trunk condition category 6 (ALL).

The above parameters were reanalyzed after restricting the data set to only oaks ≥10 cm DBH and again for oaks ≥20 cm DBH. In general, similar distributions were observed in trunk condition categories, percent bark lost, and trunk orientation (data not shown).

Proportions, on a basal-area basis, were calculated for living oaks in the red oak and white oak groups, using data presented in Table 2. Similarly, using DBH measurements of the dead oaks from the present study (trunk condition categories 1-3 only), basal area of red oaks and white oaks were determined for eact site and the proportions calculated. Comparisons of these two sets of proportions (Fig. 2), indicated slightly increased white oak mortality in ARK, slightly increased red oak mortality at DIX in Illinois, and greatly increased red oak mortality at the remaining five sites, especially CSF in Indiana.

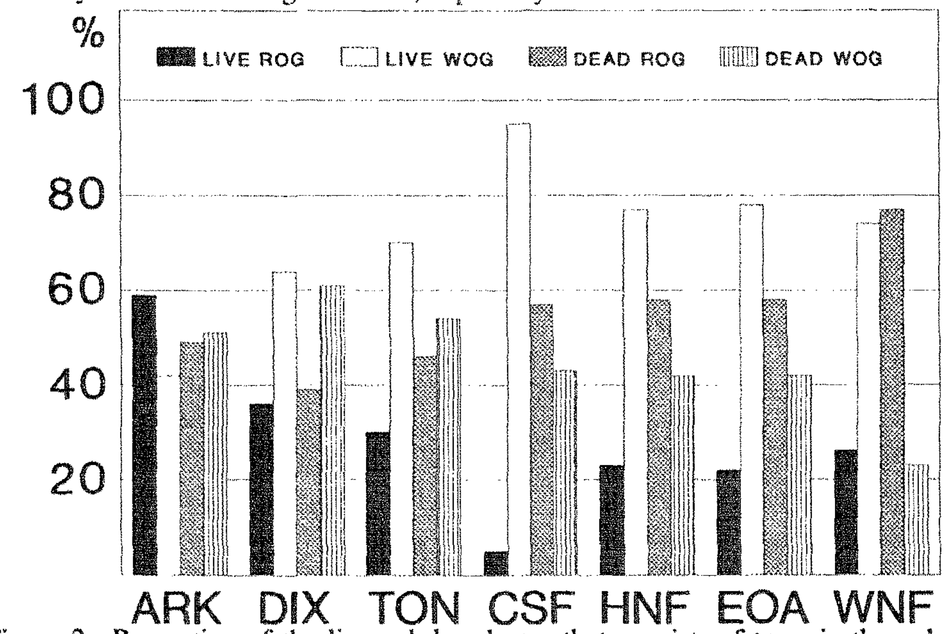

Figure 2. Proportion of the live oak basal area that consists of trees in the red oak group (ROG) compared with those in the white oak group (WOG) (as given in Table 2), and similarly for the proportion of dead oak basal area (from the present study).

Borer and *H. atropunctatum* Infestation Patterns

Both TLCB and *H. atropunctatum* were commonly associated with the dead oaks at all sites. Signs of both pest organisms were noted on individual white, scarlet, blackjack, chestnut, northern red, post, and black oaks at each site where those trees were found as listed in Table 2. For oaks ≥7 cm DBH in trunk- condition categories 1-3, for which signs of attack were most reliable, incidence of TLCB and *H. atropunctatum* attack was lowest in ARK and generally higher in Illinois, Indiana, and Ohio (Fig. 3). In general, more dead red oaks had been attacked by TLCB and *H. atropunctatum* compared with white oaks (Fig. 3). Evidence of attack by both TLCB and *H. atropunctatum* was found on several individual trees, especially red oaks (Fig. 3). The number of dead oaks lacking evidence of attack by either pest declined from west to east (Fig 3).

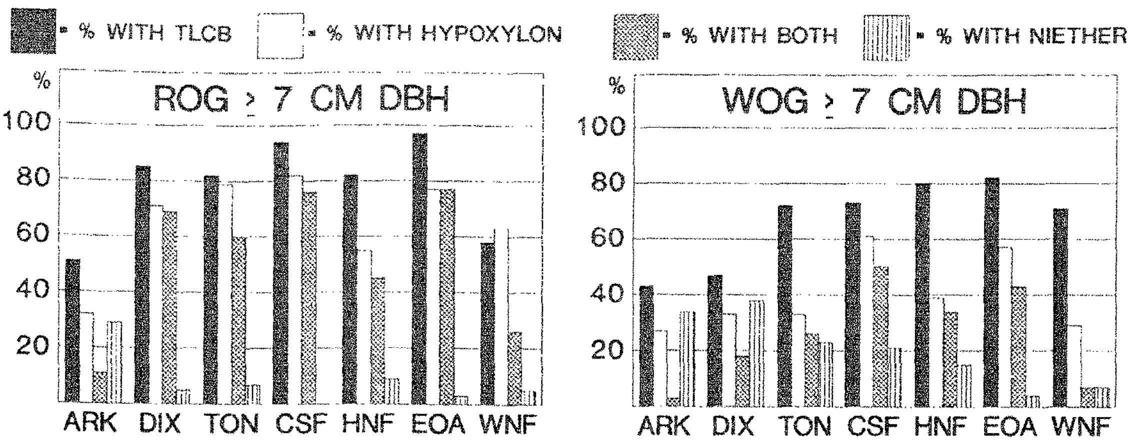

Figure 3. For each site, percent of dead oaks with evidence of TLCB and *H. atropunctatum* attack; based on oaks in trunk-condition categories 1-3 and all trunk orientations (N values given in Table 3).

DISCUSSION

Results of this study indicate that (a) oak mortality occurred at all study sites, (b) that red oaks suffered proportionally greater losses than white oaks at six of the seven sites, and (c) that TLCB and *H. atropunctatum* were commonly associated with dead oaks. Many others have reported episodes of oak decline in the 1980's, especially after drought (Law and Gott 1987, Mistretta et al. 1981, Stringer et al. 1989, Tainter et al. 1983). In the Ohio Corridor Study, historical weather data (1900-1987) indicated similar growing season climate at all sites (including incidence and duration of droughts), although much year-to-year variation did occur (Loucks et al. 1991).

Other Recent Reports of Oak Decline

Several local and regional reports of oak decline have appeared in recent years, and the occurrence of TLCB and *H. atropunctatum* has been mentioned in most; see Kessler (1989) and Millers et al. (1989) for more detailed reviews. For example, in Arkansas, Mistretta et al. (1981) reported widespread oak mortality following the 1980 drought. Both red oaks and white oaks were affected. Of 215 dead oaks examined, *H. atropunctatum* was evident on 49% of the red oaks and 32% of the white oaks: TLCB was not specifically recorded. Of 215 living oaks examined, only 3 had obvious *H. atropunctatum* stromata.

In Missouri, severe oak mortality was recorded by Law and Gott (1987) after the droughts of 1980 and 1983. Red oaks suffered the greatest mortality, especially scarlet and black oaks. TLCB and *H. atropunctatum* were commonly observed on the dead oaks but not quantified.

In addition, Pallardy et al. (1988) have reported increased red oak mortality in central Missouri during the period 1968-1982.

In Kentucky, Stringer et al. (1989) reported widespread oak mortality associated with droughts. Again, red oaks suffered the greatest mortality, mostly scarlet and black oak. Mortality was greatest on xeric sites, on mid- and upper slopes. TLCB was found on 100% of the dead and dying oaks inspected; *H. atropunctatum* was not recorded.

Tainter et al. (1983) reported increased oak mortality in South Carolina after the 1978 and 1980 droughts. Red oaks were the most commonly affected. *Hypoxylon atropunctatum* was evident on practically all dead oaks and on several declining but still living oaks as well.

In a southwide study by Starkey and Oak (1989), oak mortality was associated with sites characterized by shallow rocky soils, upper slopes, and a predominance of red oak species, especially black and scarlet oak. Red oaks suffered more mortality than white oaks; TLCB and *H. atropunctatum* were commonly observed on dead oaks but not quantified.

Incidence of TLCB and *H. atropunctatum*

TLCB and *H. atropunctatum* were commonly associated with dead oaks in our study. TLCB has been documented as a principal mortality agent of stressed oaks, especially those affected by drought and defoliation (Cote and Allen 1980, Dunbar and Stephens 1976, Dunn et al. 1986, Haack and Benjamin 1982). In contrast, the role of *H. atropunctatum* is less clear. Although *H. atropunctatum* fruiting bodies (stromata) are commonly found on recently dead oaks (Karasevicz et al. 1984, Lewis 1981, Thompson 1963, Van Arsdel 1972), they are rare on healthy-appearing or declining oaks. Except for Thompson (1963), most pathologists consider *H. atropunctatum* only a weak parasite, and primarily a secondary invader (Bassett and Fenn 1984).

Detailed work on the ecology of *H. atropunctatum* was conducted in Arkansas by Bassett and Fenn (1984). They isolated *H. atropunctatum* from branches of 57% and trunks of 11% of 300 healthy-appearing oaks, indicating that this fungus is well- positioned to colonize quickly. Moreover, isolation frequencies were similar between healthy-appearing red oaks and white oaks. After girdling of 196 healthy oaks, *H. atropunctatum* developed within 5 months on 77% of the red oaks and 70% of the white oaks.

In our study, several dead oaks had no obvious signs of TLCB or *H. atropunctatum* attack, especially many white oaks (Fig. 3). Some dead oaks were wind-blown, and a few others had been struck by lightning; such oaks would not be attractive to TLCB adults unless the trees were damaged close to or during the adult flight season. We did not examine root systems of the dead oaks, so we do not know the extent of colonization by *Armillaria* spp., another important complex of weak parasites that attack stressed trees. *Armillaria* often attacks root systems concurrently with TLCB (Wargo 1977). Moreover, we do not know what portion of the observed mortality was the result of suppression or competition. For example, the high numbers of small-diameter dead oaks in Arkansas (Fig. 1), may reflect the lower median age of that site (Table 1), and that active "self-thinning" was occurring.

Greater Susceptibility of Red Oaks

Higher mortality rates of red oaks versus white oaks can be partially explained in terms of differences in xylem translocation. That is, conduction in the red oak group occurs primarily in the outermost annual ring, while conduction in white oaks occurs in the outer two to three annual rings (Kozlowski and Winget 1963, Kramer and Kozlowski 1979). As a result, red oaks are more susceptible to the girdling action of feeding borer larvae, because only the outer growth ring needs to be severed to effectively girdle and kill a branch or the entire tree. Repeated annual attacks may be necessary to kill part or all of a white oak.

Loucks et al. (1991) presented another theory to explain the greater mortality of red oaks, which is based on the apparent greater sensitivity of red oaks vs. white oaks to ozone (Reich et al. 1986, Loucks et al. 1991). Given the high ozone levels in the Ohio River Valley (Lefohn and Pinkerton 1988), this theory suggests that during periods of drought stress, it is the ozone- sensitive red oaks that succomb first to pest attack.

Pollutant Effects on Plant-Pest Interactions

Air pollution stress is known to induce a diverse array of biochemical, morphological, and physiological changes in trees (Kozlowski and Constantinidou 1986). The possibility that these changes could alter plant-pest interactions has been a topic of several reviews (Alstad et al. 1982, Baltensweiler 1985, Fuhrer 1985, Hain 1987, Heagle 1973, Hughes and Laurence 1984, Huttunen 1984, Lechowicz 1987, Mattson and Witter 1990). Moreover, several studies have shown increased insect populations with increased dose of various aerial pollutants (Bolsinger and Fluckiger 1987, Cobb et al. 1968, Dohmen 1988, Hughes and Voland 1988, Neuvonen and Lindgren 1987, Spencer et al. 1988, Stinner et al. 1988, Trumble et al. 1987).

Although TLCB is a common mortality agent of oaks stressed by drought and defoliation, there are no published reports of it attacking oaks stressed by pollutants or acidic deposition. Similarly, there are no reports linking *H. atropunctatum* attack to pollution stress. Our study, with only seven sites, was not robust enough to link pest attack to acidic deposition, or to any other pollutant. However, it is plausible that pollutants could stress oaks sufficiently to increase tree susceptibility to TLCB attack, especially during periods of drought.

ACKNOWLEDGMENTS

The authors thank Thomas Armentanao, Kenneth Kessler, David LeBlanc, and Bruce McCune for their critical reviews of an earlier draft of this manuscript; and Cathy Love for assistance in the field. This research was partially supported by funds provided by the Northeastern Forest Experiment Station, Eastern Hardwoods Research Cooperative, within the US Environmental Protection Agency-USDA Forest Service Forest Response Program. The Forest Response Program is part of the National Acid Precipitation Assessment Program.

LITERATURE CITED

Alstad, D. N., G. F. Edmunds Jr., and L. H. Weinstein. 1982. Effects of air pollution on insect populations. Annu. Rev. Entomol. 27:369-384.

Baltensweiler, W. 1985. "Waldsterben": forest pests and air pollution. Z. Ang. Entomol. 99:77-85.

Bassett, E. N., and P. Fenn. 1984. Latent colonization and pathogenicity of *Hypoxylon atropunctatum* on oaks. Plant Dis. 68:317-319.

Bolsinger, M., and W. Fluckiger. 1987. Enhanced aphid infestation at motorways: the role of ambient air pollution. Entomol. Exp. Appl. 45:237-243.

Cobb, F. W., Jr., D. L. Wood, R. W. Stark, and J. R. Parmeter, Jr. 1968. IV. Theory on the relationships between oxidant injury and bark beetle infestation. Hilgardia 39:141-152.

Cote, W. A., III, and D. C. Allen. 1980. Biology of two-lined chestnut borer, *Agrilus bilineatus*, in Pennsylvania and New York. Ann. Entomol. Soc. Am. 73:409-413.

Dohmen, G. P. 1988. Indirect effects of air pollutants: changes in plant-parasite interactions. Environ. Pollut. 53:197-207.

Dunbar, D. M., and G. R. Stephens. 1976. The bionomics of the two-lined chestnut borer. In J. F. Anderson and H. K. Kaya (eds.) Perspectives in Forest Entomology, p. 73-83. New York: Academic Press.

Dunn, J. P., T. W. Kimmerer, and G. L. Nordin. 1986. The role of host tree condition in attack of white oaks by the twolined chestnut borer, *Agrilus bilineatus* (Weber) (Coleoptera: Buprestidae). Oecologia 70:596-600.

Fenn, P., and R. T. Holland. 1984. Changes in wood properties of upland oaks invaded by *Hypoxylon atropunctatum*. Ark. Agric. Exp. Sta. Rep. 286. 9p.

Fuhrer, E. 1985. Air pollution and the incidence of forest insect problems. Z. Ang. Entomol. 99:371-377.

Gschwandtner, G., K. Gschwandtner, K. Eldridge, C. Mann, and D. Mobley. 1986. Historic emissions of sulfur and nitrogen oxides in the United States from 1900 to 1980. J. Air Pollut. Control Assoc. (JAPCA) 36:139-149.

Guillemette, R. N. 1989. Reconnaissance survey of geological substrates at the study sites, Ohio Corridor Project. Holcomb Research Institute, Butler University, Indianapolis, Indiana. HRI Rep. 133. 43p.

Haack, R. A. 1989. The twolined chestnut borer. USDA For. Serv., North Central For. Exp. Sta., Northern Hardwoods Note 7.08. 2p.

Haack, R. A., and R. E. Acciavatti. 1991. Twolined chestnut borer. USDA For. Serv., Forest Insect & Disease Leaflet No. 168 (in press)

Haack, R. A., and D. M. Benjamin. 1982. The biology and ecology of the twolined chestnut borer, *Agrilus bilineatus* (Coleoptera: Buprestidae), on oaks, *Quercus* spp., in Wisconsin. Can. Entomol. 114:385-396.

Hain, F. P. 1987. Interactions of insects, trees and air pollutants. Tree Physiol. 3:83-102.

Heagle, A. S. 1973. Interactions between air pollutants and plant parasites. Annu. Rev. Phytopath. 2:365-388.

Hughes, P. R., and J. A. Laurence. 1984. Relationship of biochemical effects of air pollutants on plants to environmental problems: Insect and microbial interactions. In M. J. Koziol and F. R. Whatley (eds.) Gaseous Air Pollutants and Plant Metabolism, p. 361-377. London: Butterworths.

Hughes, P. R., and M. L. Voland. 1988. Increase in feeding stimulants as the primary mechanism by which SO2 enhances performance of Mexican bean beetle on soybean. Entomol. Exp. Appl. 48:257-262.

Huttunen, S. 1984. Interactions of disease and other stress factors with atmospheric pollution. In M. Treshow (ed.) Air Pollution and Plant Life, p. 321-356. New York: Wiley.

Karasevicz, D., W. Merrill, and B. Towers. 1984. Biodeterioration of oak trees dead following gypsy moth defoliation. Phytopathology. 74:871. (Abstract)

Kessler, K. J., Jr. 1989. Some perspectives on oak decline in the 80's. In Proc. 7th Central Hardwood Forest Conference, Carbondale, IL, March 5-8, 1989. USDA For. Serv. Gen. Tech. Rept. NC-132, p. 25-29.

Kozlowski, T. T., and H. A. Constantinidou. 1986. Responses of woody plants to environmental pollution. For. Abst. 47:5-51.

Kozlowski, T. T., and C. H. Winget. 1963. Patterns of water movement in forest trees. Bot. Gaz. 124:301-311.

Kramer,P. J., and T. T. Kozlowski. 1979. Physiology of Woody Plants. New York: Academic Press.

Law, J. R., and J. D. Gott. 1987. Oak mortality in the Missouri Ozarks. In: Proc. 6th Central Hardwood Forest Conference, Knoxville, TN, February 24-26, 1987. p. 525-526.

LeBlanc, D. C., P. W. Somers, T. V. Armentano, and C. C. Myers. 1988. Permanent plot establishment and tree baseline data: the Ohio corridor study. Holcomb Research Institute, Butler University, Indianapolis, Indiana. Rep. 143. 108p.

Lechowicz, M. J. 1987. Resource allocation by plants under air pollution stress: implications for plant-pest-pathogen interactions. Bot. Rev. 53:281-300.

Lefohn, A. S., and J. E. Pinkerton. 1988. High resolution characterization of ozone data for sites located in forested areas of the United States. J. Air Pollut. Control Assoc. (JAPCA) 38:1504-1511.

Lewis, R., Jr. 1981. *Hypoxylon* spp., *Ganoderma lucidum*, and *Agrilus bilineatus* in association with drought related oak mortality in the south. Phytopathology 71:890. (Abstract)

Loucks, O. L., T. V. Armentano, J. Foster, J. Fralish, R. Haack, R. Kuperman, D. LeBlanc, B. McCune, B. Pedersen, and P. Somers. 1991. Pattern of air pollutants and response of oak- hickory ecosystems in the Ohio corridor. In The Eastern Hardwoods Research Cooperative: A Summary of Project Results. USDA Forest Service Gen. Tech. Rept. NE- . (in press)

Mattson, W. J., and R. A. Haack. 1987. The role of drought stress in outbreaks of plant-eating insects. BioScience 37:110-118.

Mattson, W. J., and J. A. Witter. 1990. Pollution induced changes in forest-insect relationships. In Proc. 19th IUFRO World Congress, Section 2, Montreal, Canada, August 5-11, 1990. p. 152-163.

McCune, B., C. L. Cloonan, and T. V. Armentano. 1988. Tree mortality and vegetation dynamics in Hemmer Woods, Indiana. Amer. Midl. Natr. 120:416-431.

Millers, I., D. S. Shriner, and D. Rizzo. 1989. History of hardwood decline in the eastern United States. USDA For. Serv. Gen. Tech. Rept. NE-126. 75p.

Mistretta, P. A., C. E. Affeltranger, D. A. Starkey, S. A. Covington, and Z. M. Wortham. 1981. Evaluation of oak mortality on the Ozark National Forest, Arkansas. USDA For. Serv., SE Area, State and Private For., Rpt. 81-2-26. Alexandria, LA. 15p.

Neuvonen, S., and M. Lindgren. 1987. The effect of simulated acid rain on performance of the aphid *Euceraphis betulae* (Koch) on silver birch. Oecologia 74:77-80.

Pallardy, S. G., T. A. Nigh, and H. E. Garrett. 1988. Changes in forest composition in central Missouri: 1968-1982. Amer. Midl. Natr. 120:380-390.

Reich, P. B., A. W. Schoettle, and R. G. Amundson. 1986. Effects of O_3 and acid rain on photosynthesis and growth in sugar maple and northern red oak seedlings. Environ. Pollut. A 40:1-16.

Schroeder, P., and A. R. Kiester. 1989. The Forest Response Program: National research on forest decline and air pollution. J. For. 87(1):27-32.

Spencer, H. J., N. E. Scott, G. R. Port, and A. W. Davison. 1988. Effects of roadside conditions on plants and insect. I. Atmospheric conditions. J. Appl. Ecol. 25:699-707.

Starkey, D. A., and S. W. Oak. 1989. Site factors and stand conditions associated with oak decline in southern upland hardwood forests. In Proc. 7th Central Hardwood Forest Conference, Carbondale, IL, March 5-8, 1989. USDA For. Serv. Gen. Tech. Rept. NC-132. p. 95-102.

Stinner, D. H., B. R. Stinner, and D. A. McCartney. 1988. Effects of simulated acidic precipitation on plant-insect interactions in agricultural systems: corn and black cutworm larvae. J. Environ. Qual. 17:371-376.

Stringer, J. W., T. W. Kimmerer, J. C. Overstreet, and J. P. Dunn. 1989. Oak mortality in eastern Kentucky. South. J. Appl. For. 13:86-91.

Tainter, F. H., T. M. Williams, and J. B. Cody. 1983. Drought as a cause of oak decline and death on the South Carolina coast. Plant Dis. 67:195-197.

Thompson, G. E. 1963. Decay of oaks caused by *Hypoxylon atropunctatum*. Plant Dis. 47:202-205

Trumble, J. T., J. D. Hare, R. C. Musselman, and P. M. McCool. 1987. Ozone-induced changes in host-plant suitability: interactions of *Keiferia lycopersicella* and *Lycopersicon esculentum*. J. Chem. Ecol. 13:203-218.

Van Arsdel, E. P. 1972. Some cankers on oaks in Texas. Plant Dis. 56:300-304.

Wargo, P. M. 1977. *Armillariella mellea* and *Agrilus bilineatus* and mortality of defoliated oak trees. For. Sci. 23:485-492.