New Diseases and Epidemics

Regional Effects of Sulfur Dioxide and Ozone on Eastern White Pine (*Pinus strobus*) in Eastern Wisconsin

C. L. REZABEK, J. A. MORTON, E. C. MOSHER, Bureau of Air Management, and A. J. PREY and J. E. CUMMINGS CARLSON, Bureau of Forestry, Wisconsin Department of Natural Resources, Box 7921, Madison 53707

ABSTRACT

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Between 1 July and 25 September of 1985, 10,706 white pine (*Pinus strobus*) at 109 study sites in 30 counties of eastern Wisconsin were surveyed for tipburn and mottling. Tipburn and mottling are visible symptoms of air pollution (sulfur dioxide [SO_2] and ozone [O_3]) injury. White pine study sites in the southeast and east central regions had higher percentages of tipburn and mottling than those in the northeast region of the state. The occurrence of tipburn and mottling is associated with the relatively high SO_2 and O_3 levels in the southeast region of Wisconsin. Tipburn and mottling were found to be related to one another. Tipburn and mottling were also found to be significantly ($P = 0.001$) related to the absence of adjacent vegetation.

Some forest diebacks and declines that have been reported in Europe and in the northeastern United States have been potentially associated with gaseous air pollutants and acid rain, which raises concern for our forest resources in Wisconsin. One tree species in particular, eastern white pine (*Pinus strobus* L.), may be more susceptible to injury by air pollution than any other tree species in North America (7). Air pollution damage to white pine in Wisconsin has been documented in the past (13), but investigations were carried out in specific locations as the problems arose. No comprehensive survey has been conducted on the extent of air pollution damage to white pine in Wisconsin. This study focuses on the extent of damage to white pine from the pollutants sulfur dioxide (SO_2) and ozone (O_3) in eastern Wisconsin.

It is most desirable to select the most sensitive types of trees as bioindicators of air pollution (6). The eastern white pine is sensitive to low levels of pollutants, e.g., 0.05 ppm of O_3 and 0.025 ppm of SO_2 (8).

The objective of this study was to determine the extent and frequency of tipburn and mottling on white pines in eastern Wisconsin caused by the gaseous air pollutants sulfur dioxide and ozone.

MATERIALS AND METHODS

A 30-county area, approximately the eastern half of the state, was surveyed (Fig. 1). An attempt was made to sample five plantations per county selected from the Wisconsin Department of Natural Resources Area Foresters' planting records and national, state, and county forest inventories and travel observations. Locations were chosen to obtain good spatial coverage of each county.

Plantations surveyed were to have been from 5 to 15 years of age and consist of more than 100 trees. In some counties, particularly in northeastern Wisconsin, five plantations could not be found for sampling. Those sites that were sampled in northeastern Wisconsin were either mature plantations, plantations released from aspen overstory, or natural seedings. Because of the low availability of white pines in the north, some survey sites contained less than 100 trees. Only plantations, irregular plantings, and open-grown naturally seeded trees were sampled in this survey. White pines as understory were not sampled because of the filtering effect of the canopy (10).

Within each plantation, 100 trees were sampled. In regular row plantings, a block of 10 × 10 trees was selected. Those plantations occurring along well-traveled roads or agricultural fields were sampled approximately 75 feet from the plantation edges to eliminate possible damage from road salts or pesticide drift. Plantations with irregular patterns such as hillside plantings and naturally seeded trees were sampled randomly. Edges in these plantations were also avoided when they occurred along roads or fields. In mature plantations, 100 trees were selected along edges and exposed pockets where lower branches had needles within reach. Location of each tree within the sample site was recorded as open-grown, edge, side-exposed, or interior.

The exposure type was classified as follows. "Open-grown" was defined as trees bordered on all sides by at least 10 feet of open space. "Edge" trees occurred along stand edges and had at least one side bordered by open space. "Side-exposed" trees were defined as interior trees but bordered on at least one side by 10 feet of space. "Interior" trees were defined as those completely surrounded by adjacent trees.

One branch from each tree was selected to be sampled. Branches were chosen on sides in sunlight because better visibility was needed to observe needle damage. It should be noted that a greater amount of damage may occur on branches in high sunlight because stomata remain open in sunlight and allow a greater amount of pollutants to enter the needle (11), thus the needles analyzed may represent the most heavily damaged area on the tree. Trees were sampled at breast height, approximately 4 feet above the ground.

Visible damage on second-year needles only was assessed. The current year's needles were not examined. Two types of visible damage to needles were identified

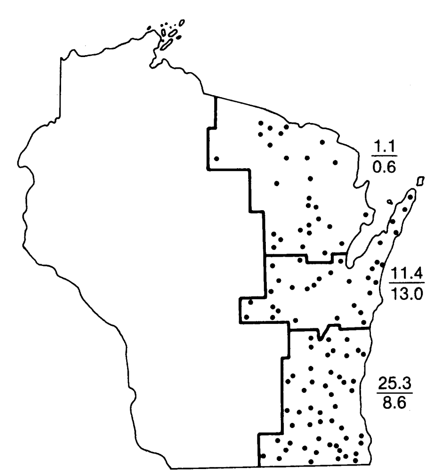

Fig. 1. The location of 109 study sites in eastern Wisconsin and the percentage of white pines exhibiting symptoms of air pollution injury in each region: southeast, east-central, and northeast. The top number represents the percentage of sampled white pines with tipburn injury. The bottom number represents the percentage of sampled white pines with mottling injury.

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and recorded: tipburn and mottling.

Tipburn is defined as the area at the tip of the needle displaying a red-brown discoloration. Those needles with discolorations such as yellow tips and yellow bands were not classified as tipburn. Severity of tipburn was not assessed, only its presence or absence was noted.

Mottled needles were defined as those needles with randomly scattered gray and white flecks. Those needles that displayed distinct yellow spots, yellow bands, or yellow spots with brown centers were not classified as mottled. The extent of mottling was recorded as being either 0, 5, 25, or 50% of a needle exhibiting symptoms, according to a key for stem rust of cereals adapted for use in this study (9). When the percentage of coverage was between two categories, the lower category was recorded.

The percentage of white pines exhibiting tipburn or mottling characteristics were calculated at the county and regional level. Values for each county were based on the total number of trees sampled within the county. Counties were then grouped into three regions: southeast, east-central, and northeast. Visible damage to white pines was calculated for each region.

RESULTS

In this survey, 10,706 trees in 109 plantations were sampled. White pines with tipburn needle damage were most frequent in southeastern Wisconsin (Figs. 1 and 2). Of the white pines surveyed in the southeast, 25.3% exhibited tipburn. This percentage is compared with the east-central region where 11.4% of the sampled trees exhibited tipburn and with the northeastern region where 1.1% of the white pines exhibited tipburn (Fig. 1). These percentages suggest a gradient of decreasing tipburn damage from southeast to northeast in Wisconsin.

Values for significant mottling damage to white pines were also calculated on the county and regional level. Significant mottling was defined as damage to more than 25% of the needle surface. As shown in Figure 1, 8.6% of the white pines in southeastern Wisconsin exhibited significant mottling damage. Sampled trees in the east-central region had the greatest percentage of significant mottling (13.0%). In contrast, sampled trees in the northeast region had the lowest percentage of significant mottling (0.6%). The occurrence of mottling does not differ between regions as does tipburn, but in general, mottling damage does decrease from the southeast to the northeast regions of the state.

Of the trees with significant mottling, 15% also had tipburn (Table 1). Of the trees with little or no mottling, 6% exhibited tipburn. Thus, trees with significant mottling had a higher percentage of tipburn.

In all three regions, tipburn was found more frequently on trees grown in the open (Fig. 3). In southeastern Wisconsin, 43.5% of the open-grown trees exhibited tipburn injury, whereas only 7.2% of the

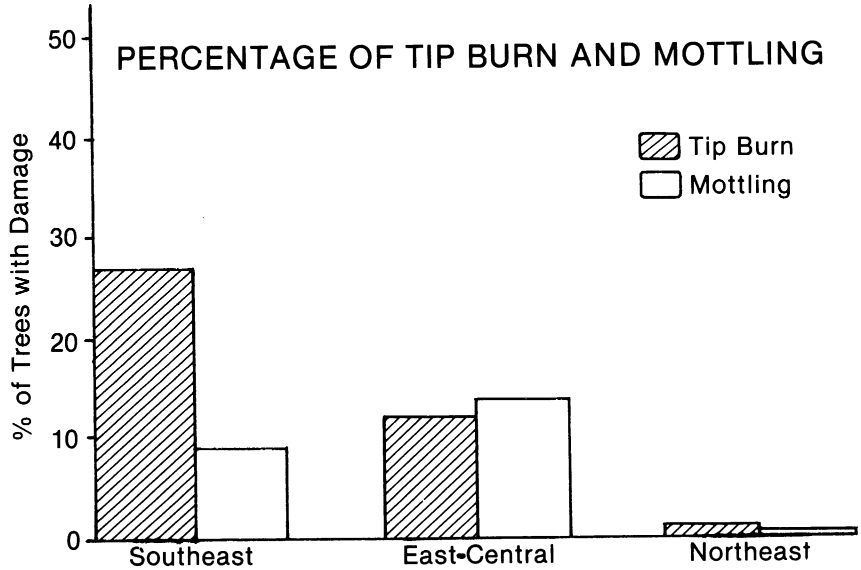

Fig. 2. The percentage of sample trees with tipburn and the percentage of sample trees with mottling injury in each region: southeast, east-central, and northeast.

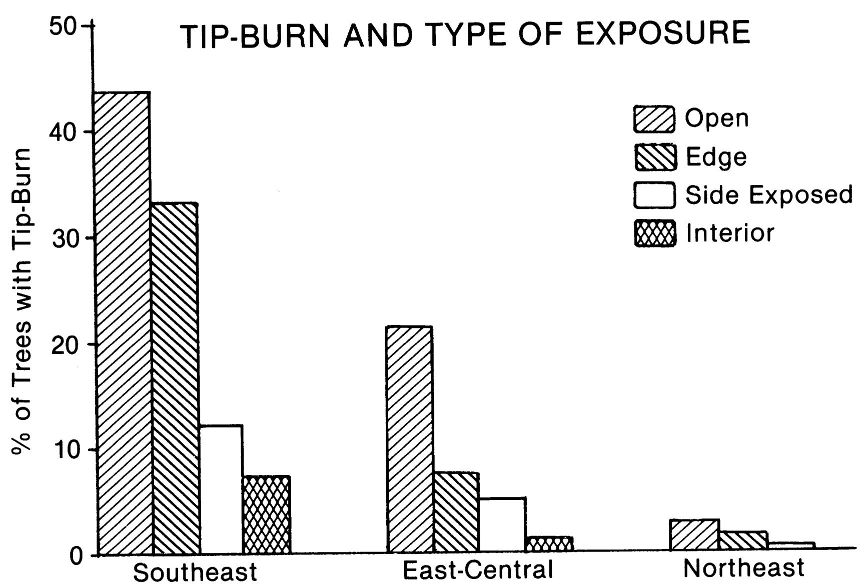

Fig. 3. The percentage of sample trees with tipburn injury classified according to the type of exposure or location of the tree within the stand for each region: southeast, east-central, and northeast.

Table 1. Percentage of white pine (*Pinus strobus*) with tipburn for two categories of mottling

Tipburn	Mottling 0–5%	Mottling 25–50%
Absent		
Number	8,344[a]	1,518
Percent	94	85
Present		
Number	567	277
Percent	6[b]	15[b]
Total	8,911	1,795

[a] Frequency of trees with tipburn.
[b] Z score of proportional difference = 39.22. Significance level at $P = 0.001$.

Table 2. Percentage of white pine (*Pinus strobus*) with tipburn for two categories of exposure

Tipburn	Exposure class: Open-grown	Exposure class: Interior
Absent		
Number	3,950[a]	4,961
Percent	73	94
Present		
Number	1,496	299
Percent	27[b]	6[b]
Total	5,446	5,260

[a] Frequency of trees with tipburn.
[b] Z score of proportional difference = 91.49. Significance level at $P = 0.001$.

interior trees were affected. Tipburn percentages for edge trees and other partially exposed trees fell between the percentages found for open-grown and interior trees. The same pattern was found in the east-central and northeast regions.

Of the open-grown trees, 27% exhibited tipburn injury, whereas only 6% of the interior trees were affected (Table 2). This difference was found to be significant at the $P = 0.001$ level. Thus, open-grown trees are more likely to exhibit tipburn injury than are trees less exposed.

Mottling data was categorized by exposure class for each region (Fig. 4). The pattern shown here by regions is much less clear than it is for tipburn. Of open-grown trees, 9% exhibited significant mottling, whereas only 6% of interior trees showed such injury (Table 3). This difference was significant at the $P = 0.001$ level. Open-grown trees with tipburn were more likely to show mottling injury than less exposed trees.

Sulfur dioxide is usually concentrated at localized sites near emission sources. Monitoring sites are usually set up to monitor these specific SO_2 emission sources. Ozone, on the other hand, is formed in the atmosphere from a number of pollutants on a regional basis. Data on SO_2 and O_3 concentrations are presented here (Fig. 5) to show how the incidence of tipburn and mottling damage are generally associated with high SO_2 and O_3 concentrations in the state.

Table 3. Percentage of white pine (*Pinus strobus*) with significant mottling (greater than 25% injury) for two categories of exposure

	Exposure class	
Tipburn	**Open-grown**	**Interior**
0–5%		
Number	4,937[a]	4,925
Percent	91	94
>25%		
Number	509	335
Percent	9[b]	6[b]
Total	5,446	5,260

[a] Frequency of trees with tipburn.
[b] *Z* score of proportional difference = 13.39. Significance level at $P = 0.001$.

Maximum 1-hr O_3 concentrations were measured across the state in 1984 (Fig. 5). These monitoring sites were used to represent rural O_3 concentrations where plantations are located. Relatively few monitoring sites are located in northeastern Wisconsin. Consistently low levels of monitored O_3 led to the removal of monitoring sites in that region. Monitoring sites in the southeastern region of the state report the highest levels of O_3. Concentrations as high as 0.19 ppm were reported in Racine in 1984.

Annual modeled 1980 SO_2 concentrations in Wisconsin were used in this survey (Fig. 5). Because SO_2 monitoring sites record localized concentrations and do not represent concentrations in rural areas where most of the white pine plantations are located, computer-modeled SO_2 concentrations for rural areas were developed. Note that SO_2 concentrations in the vicinity of major emission sources such as Green Bay, the Wisconsin River Valley, and Milwaukee may be higher than those rural-modeled concentrations (Fig. 5). In the past, white pine and other tree species downwind of these SO_2 major sources have been damaged (13). Sulfur dioxide concentrations are highest in the southeastern region of the state, with values of 14.0 μg/m at Manitowoc and 12.6 μg/m at Lake Geneva.

DISCUSSION

Tipburn and mottling damage were found more frequently in the southeastern and east-central regions than in the northeastern region of the state. Figure 1 shows the distribution of air pollution damage to white pines in eastern Wisconsin. The number of trees affected by air pollution damage decreases from the south to the north. In general, tipburn and mottling were found to be associated (i.e., those trees that exhibited tipburn damage also tended to show evidence of mottling damage). Because of the higher concentrations of gaseous air pollutants in southeastern Wisconsin and the higher frequencies of visible damage to white pine needles in southeastern Wisconsin, tipburn and mottling may be associated with the higher SO_2 and O_3 levels in the southeast.

Ozone levels in Wisconsin are high enough to account for the damage to white pine found in the survey. Berry and Ripperton (2) found that white pines exposed to 0.06 ppm of O_3 for 4 hr produced tipburn injury in the lab. Costonis and Sinclair (5) also demonstrated tipburn damage to white pines in the lab after exposure to 0.03 ppm of O_3 for 48 hr, up to 0.07 ppm of O_3 for 4 hr. Vegetation throughout the midwest and northeast is exposed to O_3 concentrations of 0.05–0.07 ppm on a recurring basis (1).

Damage has also been caused by low concentrations of SO_2, but damage to white pine needles most likely occurs when the two gases are combined (3,12). Costonis (4) reported on the effects of O_3 and SO_2 on white pines. He found that trees in the laboratory showed signs of damage when exposed independently to 0.05 ppm of SO_2 for 2 hr and 0.05 ppm of O_3 for 4 hr. Damage was also evident after the exposure of white pines to a mixture of 0.05 ppm of O_3 and 0.025 ppm of SO_2 for 6 hr (8). The greatest amount of damage was reported when trees were first exposed to O_3 or SO_2 separately and then exposed to the mixture of O_3 and SO_2. Sulfur dioxide has been recorded as

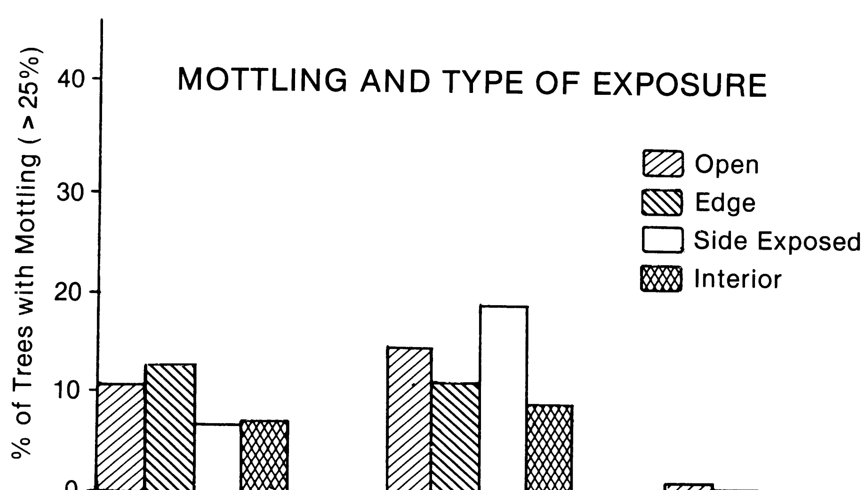

Fig. 4. The percentage of sample trees with mottling injury classified according to the type of exposure or location of the tree within the stand for each region: southeast, east-central, and northeast.

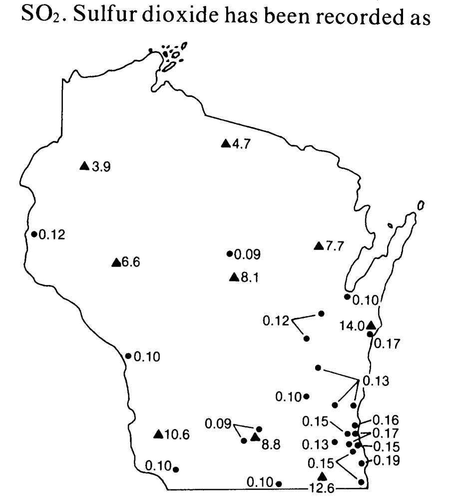

Fig. 5. The closed triangle represents the 1980 computer-modeled SO_2 concentrations (μg/m) in Wisconsin. The closed circle represents the 1984 maximum hourly O_3 concentrations (ppm) recorded in Wisconsin. Note the higher concentrations in the southeastern (metropolitan) corner of the state.

high as 0.209 and 0.207 ppm at emission sources in Peshtigo and Green Bay in 1984, whereas O_3 was reported as high as 0.19 ppm in Racine in 1984 (14).

The location of each tree sampled was recorded to determine whether or not visible damage was associated with location and exposure within the plantation. It was mentioned earlier that overstory vegetation can act as an air filter for pollutants. Vegetation density and the presence of adjacent vegetation can also prevent air pollutants from reaching certain trees within the plantation. Therefore, location of the sample trees in the plantation is important in assessing the extent of air pollution damage.

Most damage, especially tipburn, occurred on trees that grew in open plantations or at the edges of plantations (Figs. 3 and 4). Tipburn and mottling were found more frequently on trees that had little or no adjacent vegetation.

The higher incidence of mottling in side-exposed trees in the east-central region cannot be explained. Patterns of mottling do not seem as defined or obvious as do those of tipburn. Because mottling may be caused by lower levels of pollutants (10), the mottling damage to white pines may not be as uniform as the damage caused by high levels of pollutants, characterized by tipburn damage to needles.

It was suggested that surveying plantations may overrepresent trees that are genetically more susceptible to air pollution damage than a natural population of trees, and may account for the high proportion of damage found in southeastern Wisconsin. From interviews with area foresters and many plantation owners, we found that most of the plantation trees sampled were purchased as seedlings from the Wisconsin Department of Natural Resources. Most of these trees were grown at the DNR F. G. Wilson Nursery in Boscobel, which obtains seeds from naturally occurring white pine sources in northern and central Wisconsin. Many of the weaker trees in the nursery stock die before being sold to private landowners. White pine cuttings or clones are not sold at this nursery and were not included in this survey, except for trees examined at the Oconto River Seed Orchard in northeastern Wisconsin. The Oconto River trees represent a population of white pines that were genetically developed to resist white pine blister rust and were grown from grafts of the parent trees. There were a few cases were Christmas tree growers or landowners with special needs brought in white pines from outside the state. These cases accounted for a small percentage of the total number of sampled trees. In general, the genotype of the plantation trees surveyed in this study is similar to that of natural populations of white pine.

From observations made while sampling each plantation, it appeared that damage was greatest in younger, open plantations rather than older, more mature stands. This may be attributed to the possibility that the more sensitive trees in the mature plantations have been culled out through selective cuts, thinning, or mortality caused by competition. The weaker, less resistant trees may still be present in the younger stands. Most of these young stands are located in the southeast and east-central areas of the state while older, more mature stands made up most of the survey sites in northeastern Wisconsin. The lower incidence of damage in the northeast may be influenced by removal of sensitive trees in older plantations and not due to lower air pollution concentrations. Because of these observations, further research should be conducted in northeastern Wisconsin to investigate nonvisible damage that may be occurring in mature forest ecosystems due to gaseous air pollutants.

The white pines sampled in five northeastern counties included some natural white pine stands. These are open fields where natural white pine regeneration has occurred. Compared with cultivated plantations, selection pressures may be greater in natural white pine stands and sensitive trees would have poorer survival. This may account for the lack of trees sensitive to air pollution in the northeast and may reflect the low incidence of damage found in northeastern Wisconsin.

This survey demonstrates that white pines in southeastern and east-central Wisconsin exhibit symptoms of air pollution damage. This visible damage can be related to higher concentrations of SO_2 and O_3 in that region. Location of trees within the plantation affected the occurrence of air pollution damage to white pines. Those trees with maximum exposure had a greater incidence of air pollution damage.

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