Effect of Simulated Saline Cooling Tower Drift on Tree Foliage

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ABSTRACT

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Wet cooling towers used by industries and utilities to dissipate waste heat often release a saline aerosol drift into the surrounding atmosphere. To simulate saline drift, water from a cooling tower basin was sprayed repeatedly during the growing season on small trees of Virginia pine (*Pinus virginiana*), tulip tree (*Liriodendron tulipifera*), California privet (*Ligustrum ovalifolium*), Norway spruce (*Picea abies*), white ash (*Fraxinus americana*), and flowering dogwood (*Cornus florida*). Only dogwood leaves showed significant injury. The intensity of tip and marginal necrosis and Na^+ and Cl^- concentrations increased with the number of sprays per season. The Cl^- concentration ranged from 3,145 to 9,000 μg/g dry weight (dw) for mild to severe foliar necrosis, respectively. Corresponding Na^+ concentrations ranged from 167 to 1,418 μg/gdw. Injury was not related to K^+ or Ca^{++} concentrations. Dogwood may be a useful bioindicator of saline drift.

Additional key words: air pollution.

Large amounts of industrial waste heat may be dissipated by transferring it directly to the atmosphere by means of a wet cooling tower. If brackish water or sea water are used for cooling purposes, a wet cooling tower will release a saline aerosol known as drift which disperses downwind and eventually is intercepted by various surfaces including the foliage of vegetation. Even though several reports (2,20,30–33,37) on this environmental hazard have been published, the long term consequences of saline drift deposition on vegetation in a non-saline habitat still are not well understood.

One set of cooling tower models (24) predicted that the heaviest deposition of drift will occur downwind closest to the tower and that the amount of salt deposited per unit area will decrease inversely as the distance from the tower. Presumably, vegetation closest to the emission source may be the most affected by drift. Bernstein (3) suggested that the effects of changes in soil salinity usually would be minor compared to that of foliar salt deposition.

The purposes of this study were to determine the symptoms caused by simulated saline drift on tree foliage under field conditions, and to determine the ion concentrations associated with foliar injury. A preliminary report has been published (16).

MATERIALS AND METHODS

Field test plots. In March 1975, six field plots were established at the University of Maryland Tobacco Experimental Farm near Upper Marlboro, MD. Each plot measured 4.9 × 11.0 m and contained four rows of 10 trees. The rows were spaced approximately 1.2 m apart with 1.8 m between plots. Each row contained either 2-yr-old Virginia pines (*Pinus virginiana* Mill.) or 1-yr-old flowering dogwoods (*Cornus florida* L.), tulip trees (*Liriodendron tulipifera* L.), or California privets (*Ligustrum ovalifolium* Hassek.).

In March 1976, six additional plots were prepared. These contained Norway spruce (*Picea abies* L. Karst.), white ash (*Fraxinus americana* L.), flowering dogwood, and tulip trees. These species were planted randomly within the four rows of each plot. An exception was one plot, designated 1X, which contained 11 ash, 11 spruce, 10 tulip, and 8 dogwood trees.

All plots were weeded mechanically three times each season. Carbaryl insecticide was applied twice in 1975 to control Japanese beetles. Before the trees in older plots were sprayed in May 1976 they were pruned to a uniform height of 50 cm.

Simulated drift. Cooling tower basin water (CTBW) was collected from the basin of a large natural draft, hyperbolic tower located at Chalk Point, MD, along the brackish Patuxent River. Design and operating characteristics of this tower have been summarized elsewhere (9). Two collections of CTBW were made in 1975 and only one in 1976. Chemical analyses of CTBW (Table 1) were performed by the University of Maryland Soils Laboratory (1).

Cooling tower drift was simulated by spraying CTBW over the trees with a hand-pushed sprayer which consisted of a reservoir tank pressurized by a CO_2 cylinder. The CTBW was forced through four TLX-SS1 Conejet nozzles (Spraying Systems Co., Wheaton, IL 60187) at 2.72 atm. The median droplet diameter size under these conditions was about 100 μm which is within the range of droplets expected to emanate from the Chalk Point cooling tower (24). A pair of nozzles was mounted on a horizontal bar on each side of the sprayer. The two bars were spaced 1.22 m apart and positioned over the tree row. The two nozzles on each bar were 0.30 m apart and each bar was oriented parallel to the direction of travel. In this way, two tree rows were sprayed simultaneously as the sprayer passed between the rows.

Treatments. The amount of simulated cooling tower drift was regulated by timed spray passes over trees. Prior to spraying, plastic fences were erected to reduce drift contamination between adjacent plots. Since the salinity of CTBW changed according to the composition of the Patuxent River and cooling tower operating conditions, two separate samples of CTBW designated CTBW-1 and CTBW-2 were collected at different times for use in 1975. The first sample, CTBW-1, was used to spray trees for the first five spray treatments from 7 July to 17 July 1975, and contained 8,685 ppm total soluble salts (TSS). The second sample, CTBW-2, was used 25

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times from 18 July until spraying was terminated on 22 Aug. 1975 and contained 13,888 ppm TSS. The CTBW used in 1976 contained 10,200 ppm TSS in addition to other ions (Table 1).

Initially spray nozzles were set 45 cm above ground level. However, to compensate for tree growth the nozzles were raised to 109 cm prior to the 22nd spraying 11 Aug. in 1975. They remained at this height for the rest of 1975 and all of 1976.

Spray was deposited on two rows per pass by pushing the sprayer the length of the plot in 13 sec. This treatment was designated 1X and covered all trees in the plot once.

In 1975 six treatments were applied: a no-spray (NS) control; a tap water (Tap) control (two passes with tap water); and one (1X), two (2X), three (3X), and four (4X) passes with CTBW. Sprays were applied in the morning starting 7 July and 30 times thereafter through 22 Aug.

In 1976 the NS, Tap, 1X, and 2X plots prepared in 1975 (designated *old* plots) were given the same treatments as in 1975. The 3X and 4X plots of 1975 were not sprayed during the 1976 season but were kept for observations of plant recovery from injury. The NS, Tap, 1X, and 2X treatments were repeated on four of the six plots prepared in 1976 (designated *new* plots). The remaining two new plots received a 1/2X treatment by reducing spray time, or a 1/10X treatment by diluting one part CTBW with nine parts tap water. The 43 sprays began on 7 July 1976 and continued through 3 Sept. 1976.

Calculation of salt deposition. In 1975 an experiment was performed to estimate the rate of simulated drift deposition (17). With CTBW-2, one pass was approximately equal to 1.89 g TSS/plot. Assuming even distribution over the plot, this was equivalent to 0.353 kg TSS/ha. However, at a nozzle height of 109 cm, the spray pattern in calm air was 40 cm wide at ground level. Assuming this pattern with a moving sprayer then only 17.6 m^2 of the plot received spray, at a rate equivalent to 1.074 kg TSS/ha for one pass. These estimates indicated a deposition range from 0.353 to 1.074 kg TSS/ha for one pass (1X).

To obtain another estimate of salt deposition the following tests were conducted on a relatively calm day. Seven-centimeter diameter disks of filter paper backed with Parafilm were placed in 11-cm diameter petri dishes. Five dishes were placed at each height at ground level, 50 cm, and 100 cm in a plot along the tree rows and sprayed with two passes of CTBW-2. Each filter paper disk and the rinse water from the upper Parafilm surface were placed in a flask and analyzed for Cl^-. Average depositions calculated for CTBW-2 per pass for 0, 50, and 100 cm were 0.100, 0.176, and 0.587 kg TSS/ha, respectively. These results, and similar calculations for other CTBW samples, indicated that the range for one pass was about 0.1 to 1.0 kg TSS/ha depending upon the calculation method, height of receptor surface, and wind conditions. At the 50 cm height, the depositions of CTBW-2 and CTBW collected in 1976 were about 0.176 and 0.129 kg TSS/ha for one pass, respectively.

Injury evaluation. Dogwood was evaluated for foliar injury (leaf necrosis) because symptoms were clearly defined on this species. The total number of noninjured and injured leaves per tree were counted to obtain a percent injury figure. To aid in estimating the intensity of leaf injury, the affected leaves were tallied in four categories of leaf necrosis: 0-25%, 26-50%, 51-75%, and 76-100%. These evaluations were made after the 10th, 21st, and 30th spray treatments on 24 July, 8 Aug., and 22 Aug., 1975 and after the 33rd and 39th spray treatments on 20 Aug. and 30 Aug., 1976.

Leaf collection and analyses. At the end of each season, leaves were collected for ion analyses. Plastic gloves always were worn when handling leaves to prevent contamination. In 1975, 20 leaves were collected randomly from each dogwood tree in each plot. Half of each sample was submerged under about 6 L distilled water, gently shaken, then transferred to two other containers successively for similar washings. The remainder of the sample was not washed. In 1976, 40 leaves were collected from each dogwood and ash tree. All of these samples were washed three times with distilled water as described. Samples were dried at 90 C for 48 hr, ground in a Wiley mill fitted with a 0.97-mm (20-mesh) screen and stored in glass vials until analyzed.

Chloride (Cl^-) was determined by a chloride electrode and modification of the potentiometric titration technique of LaCroix, et al (26). A 0.25 g leaf sample was shaken with 0.1 N HNO_3 (50 ml) for 15 min and then titrated while stirring with 0.01 N $AgNO_3$:0.1 N HNO_3. The end-point was the millivolt reading of a sample of the nitric acid used for extraction. Chloride standards were titrated at the beginning of each test series and a standard curve was calculated by regression analysis. Two replications of each sample were analyzed. Results are reported in μg Cl^- per g leaf dry weight (gdw).

Analysis of cations in leaves. Because of the limited amount of leaf tissue, cation analyses were carried out on bulked samples. Samples from each of the 10 trees of each species from each plot were placed randomly into two subgroups representing five trees. One-half g samples of dried leaf tissue from each tree in a subgroup were mixed together for a total of 2.5 g. These combined samples were analyzed by atomic absorption. Samples were ashed at 495 C for 12 hr, dissolved in 5 ml 20% (v/v) HCl and heated to boiling. This mixture was filtered through Whatman No. 40 ashless filter paper and the filtrate was diluted to 100 ml with distilled water. An additional 1/10 dilution of all samples was made. Samples for Na^+ and K^+ analysis were diluted with distilled water and samples for Ca^{++} analysis were diluted with a 1% (w/v) $SrCl_2$ solution to suppress interference. Two replicates of each sample for each cation were analyzed.

Soil analysis. Soil from each plot was sampled in 1976 before and after the spray season. Six random samples per plot were taken to a depth of 25 cm. These were bulked, mixed thoroughly, and analyzed for total soluble salts (1).

RESULTS

Dogwood. In 1975, marginal and tip necrosis first appeared on the leaves of trees that had received the two heaviest spray treatments (3X and 4X) after the seventh spraying. In 1976 leaf necrosis first appeared on trees that had received the most severe treatment (2X) after the eleventh spraying. Leaf wrinkling and curling were observed on all trees with foliar necrosis. Typically, marginal necrosis, with a distinct demarcation between necrotic and living tissue, developed on injured leaves. A sharp, dark-red pigmented line often separated the living green tissue from the necrotic zone.

The heaviest spray treatments also caused symptoms to appear earlier, with a greater final percentage of leaf injury, than the lighter ones (Fig. 1, 2). In 1975 no injury appeared on the control leaves; the 1X treatment had 14% injury compared to 93% for the 4X treatment. In 1976 no injury appeared on the controls, the 1/10X

TABLE 1. Partial analyses of cooling tower basin water (CTBW) and tap water used for simulated saline aerosol drift spraying in 1975 and 1976

Sample	Ionic and total soluble salt concentration (ppm)						
	Cl^-	Na^+	K^+	Ca^{++}	Mg^{++}	NO_3^-	Total soluble salts
CTBW–No.1–1975	4,497	2,140	86	147	125	0.1	8,685
CTBW–No.2–1975	8,734	4,320	165	244	232	1.0	13,888
CTBW–1976	6,300	3,150	166	242	162	6.9	10,200
Tap Water–1975[a]	2.8	20	1.2	30	0.8	0.8	200
Tap Water–1976[a]	2.5	1.4	1.7	30	0.5	0.6	127

[a]Tap water was collected at the University of Maryland, Tobacco Experimental Farm, near Upper Marlboro, MD.

treatment, or the 1/2X treatment. Injury in the other plots (Fig. 3) ranged from 6% (1X, old plots) to 22% (2X, old plots). All foliar injury in 1976 was in the 0-25% leaf necrosis category.

Analysis of foliar ion concentrations of dogwood for both years indicated significant Cl^- accumulation to be directly correlated with number of spray treatments (Table 2). For each ion, means were analyzed by the Student-Newman-Keuls (SNK) multiple range test (34) to find significant differences between the mean values for each treatment at $P \leq 0.05$. The SNK tests also were used to analyze leaf injury data on dogwood and ash.

A regression analysis of leaf injury and Cl^- data was used to predict a threshold value for injury (17, Fig. 4).

An apparent injury threshold of 2,852 μg/gdw was indicated by the following regression equation:

$$\overline{Y} = 0.01562X - 44.552$$

in which $\overline{Y}$ is the predicted percentage of leaves injured and X is μg/gdw leaf Cl^-. The coefficient of determination was 0.93. The regression calculations excluded zero symptoms; the greatest mean

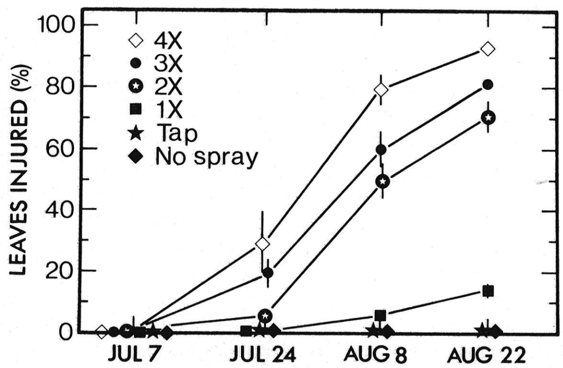

Fig. 1. Leaves injured on dogwood (*Cornus florida* L.) in 1975 after one (1X), two (2X), three (3X), and four (4X) passes over the trees with simulated saline drift. The means of 10 trees and standard errors are provided. Cooling tower basin water sample 1 (8,685 ppm) was used to simulate drift until July 17 and sample 2 (13,888 ppm) was used thereafter.

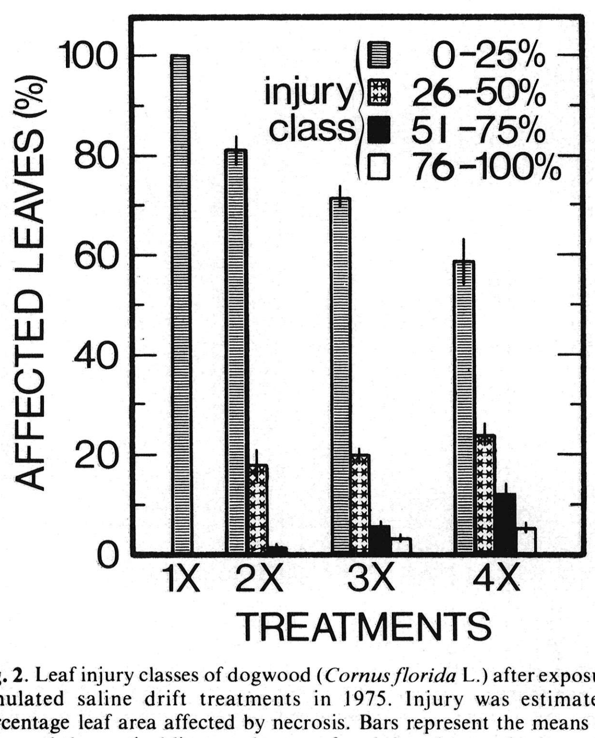

Fig. 2. Leaf injury classes of dogwood (*Cornus florida* L.) after exposure to simulated saline drift treatments in 1975. Injury was estimated as percentage leaf area affected by necrosis. Bars represent the means of 10 trees and the vertical lines at the top of each bar the standard errors.

TABLE 2. Ion concentration in dogwood leaves after various treatments of simulated cooling tower (saline aerosol) drift

	Average ion concentration ± standard error[x,y] of leaves sampled from:											
	Trees planted in 1975								Trees planted in 1976			
	1975 Samples (μg/gdw)				1976 Samples (μg/gdw)				1976 Samples (μg/gdw)			
Treatment[z]	Cl^-	Na^+	K^+	Ca^{++}	Cl^-	Na^+	K^+	Ca^{++}	Cl^-	Na^+	K^+	Ca^{++}
No spray	1,203±148 a	180± 18 a	11,171±619 a	15,286±198 a	839± 75 a	153±14 a	11,009± 91 a	20,156±762 a	1,189± 66 a	140± 6 a	11,369±570 a	19,178±286 a
Tap water	1,277±120 a	224± 38 a	9,042±469 b	16,087±158 ab	749± 73 a	125± 7 a	9,789±562 ab	20,156±715 a	851± 70 b	166± 9 a	12,680±296 b	20,572±431 a
1/10X	...	...	...	...	...	...	...	...	1,482±134 a	133±10 a	10,936±626 a	18,443±570 a
1/2X	...	...	...	...	...	...	...	...	2,088±150 c	178±13 a	10,380±519 a	18,165±724 a
1X	3,830±302 b	246± 32 a	7,365±234 c	18,624±1,049 c	3,145± 53 b	167±22 a	8,890±510 bc	23,562±585 b	3,554±328 d	176±23 a	11,094±129 a	18,347±284 a
2X	6,474±472 c	652± 17 b	7,656±568 c	19,054±643 c	5,383±494 c	290± 9 b	7,805±277 c	25,803±766 c	3,988±347 d	279±11 b	10,700±253 a	19,178±820 a
3X	9,000±427 d	1,418±120 c	7,370±227 c	18,963±237 c	...	...	...	...	...	...	...	...
4X	8,744±414 d	1,913±130 d	6,863±387 c	17,637±482 bc	...	...	...	...	...	...	...	...

[x]Means in the same column followed by the same letter are not significantly different, $P \leq 0.05$.

[y]Chloride values are averages of 10 trees. For cation analyses, leaf samples from 10 trees were randomly segregated into two groups and those of a group were combined. For each group two analyses were made for each cation, and the resulting four values were averaged.

[z]X is defined as the amount of cooling tower basin water sprayed on the trees per plot relative to the amount delivered in one spray designated as 1X.

Cl^- value in nonsymptomatic foliage was about 2,000 μg/gdw.

Significant increases from control levels of Na^+ were found only in leaves that had received treatments of 2X or greater. Generally, the leaves from the control plots had higher K^+ levels than those from salt-treated plots. Leaf Ca^{++} appeared unaffected by spraying treatments (Table 2).

Other species. No injury was found on leaves of the other species. An exception was the tulip poplar stipules which displayed marginal necrosis on some of the 2X, 3X, and 4X treatments. White ash leaves accumulated Cl^- as a function of spray treatment but the highest level, 2,749 μg/gdw for the 2X treatment, was lower than any 1X treatment in dogwood. Sodium levels in leaves of white ash were slightly higher than in dogwood but there was no incremental accumulation. Concentrations of Ca^{++} and K^+ in white ash leaves were not affected by spraying.

Soil analysis. There were no accumulations of total soluble salts in the soil due to spraying of CTBW. Total soluble salts were consistently lower at the end of the spray season than at the beginning.

DISCUSSION

The findings reported here corroborate previously obtained data on symptoms and phytotoxicity of salt in saline coastal zones (6), highway de-icing operations (cf. literature reviewed in 18,21–23,35,36,38), and saline irrigation water (4,7,12,14,19,39). Many authors also reported Cl^- accumulation in leaves of some species with increasing age of the leaves (10,15,25). Regardless of whether the salt was absorbed through the roots or leaves, in many species the Cl^- present in leaves showing necrosis was reported between 0.4 to 1.8% on a dry weight basis (3,5,7,8,14,21,22,38). In our results, the average Cl^- in injured dogwood leaves ranged from approximately 0.3 to 0.9% on a dry weight basis for the lower and upper limits of injury, respectively.

Sodium and chloride accumulated in dogwood foliage as a function of the number of spray treatments (Table 2). It is tempting to ascribe phytotoxicity to either Na^+ or Cl^- although there remains a possibility of synergistic interaction of both ions.

Leaf Cl^- and injury during the 1975 and 1976 seasons were almost identical. For example, leaves of trees from the 1X treatment in 1975 averaged 3,830 μg/gdw of Cl^- with 14% injured leaves whereas the trees from the 2X treatment for the new plots of 1976 averaged 3,988 μg/gdw with 13% injured leaves (Fig. 1 and 3). Although the spray treatments and CTBW salinity were different for both years, it is significant that the percentage leaf injury occurred at nearly the same Cl^- levels.

The injury levels and Cl^- concentrations in leaves of dogwoods in 1976 were less than those for the same treatments in 1975. However, this may be explained by the fact that the CTBW collected in 1976 had a lower concentration of soluble salts (10,200 ppm) than that used in 1975 (13,888 ppm).

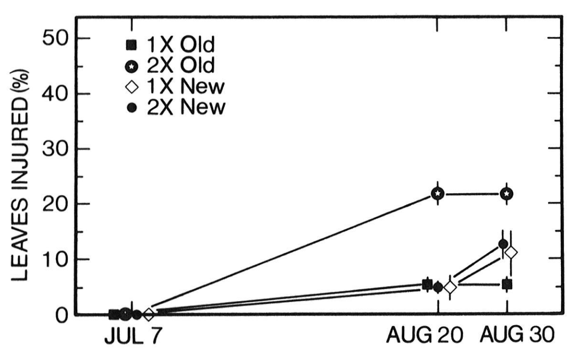

Fig. 3. Percentage leaf injury on dogwood (*Cornus florida* L.) in 1976 after one (1X) and two (2X) passes over the trees with simulated saline drift. Dogwoods planted in 1975 and sprayed in 1976 are designated old, and those planted in 1976 are referred to as new. Data are means of 10 trees and standard errors except for the 1X new treatment plots (diamond), in which there were eight trees per plot. Cooling tower basin water (10,200 ppm) collected once in 1976 was used for the entire season.

There is some evidence that leaf Cl^- may have been cumulative in the older trees. By comparing the values in Fig. 2 and Table 2, in 1976 trees from the 2X treatment of the old plots had an average injury level of 22%, about twice that of the trees from the other plots showing injury in 1976 (Fig. 2), and also had a much greater average Cl^- concentration in their leaves, 5,383 μg/gdw (Table 2). This observation has implications for long-term accumulation of salt in tissues. In 1975 these same trees were sprayed with a higher concentration of CTBW and had a greater injury by the end of the season, 71% (Fig. 1). They also contained greater concentrations of Cl^- in the leaves, 6,474 μg/gdw (Table 2). During the 1976 season these older trees received the same treatment as the new trees in the new 2X plots. The older 2X trees had significantly higher leaf injury, 22 vs 13%, and Cl^- concentration, 5,383 vs 3,988 μg/gdw. Possibly there was a buildup of Cl^- in the wood of the trees during the first season and Cl^- was translocated to the leaves the following season.

Dogwood leaves tended to accumulate Na^+ with increased spraying, especially in the highest treatments. However, under less severe spray treatments this accumulation could not be as closely associated with leaf injury as the Cl^- accumulation. All trees from the 1975 and 1976 1X treatment showed injury, but the Na^+ levels in their leaves were not significantly different from either symptomless controls or 1/10X and 1/2X treatments which showed no injury (Table 2). Leaves of trees that received 2X treatments or greater showed significant increases of Na^+. Levels of Na^+ present in leaves of woody plants injured under various saline conditions have been reported to range from 2,000 to 10,000 μg/gdw (3,14,29). The Na^+ content of leaves of dogwood trees showing injury in this study averaged from 176 to 1,913 μg/gdw but those of uninjured trees ranged from 125 to 246 μg/gdw.

The principal toxic ion inducing injury to sugar maple (23), Norway maple (38), honeylocust (12), and English ivy (13) under saline conditions was thought to be Cl^-. Considering the relatively low levels of Na^+ in the dogwood leaves, the absence of a significant difference between Na^+ concentrations in the leaves of controls and low spray treatments, injury to dogwood leaves was most likely due to a toxic accumulation of Cl^-. With more severe spray treatments there may be interaction between Cl^- and Na^+ contributing to leaf injury.

In dogwood leaves, K^+ decreased with increased numbers of spray treatments (Table 2). Several other authors have reported depressed K^+ levels with increased Na^+ in foliage (3,14,19,38).

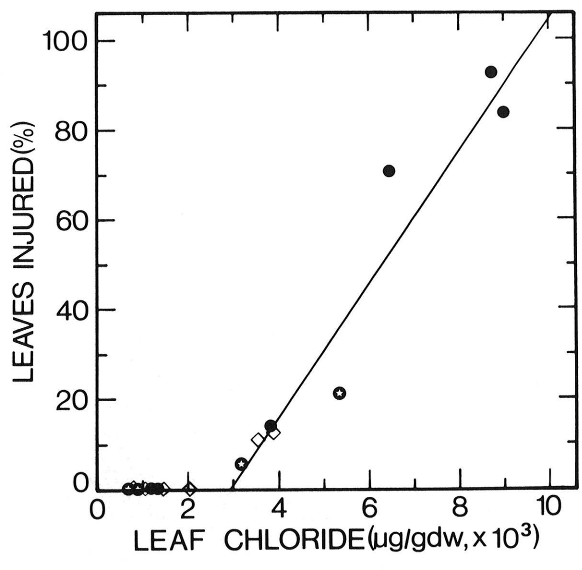

Fig. 4. Relationship between leaves injured and leaf chloride in dogwood (*Cornus florida* L.). Solid dots (•) refer to trees planted in 1975 and sprayed in 1975, and stars (✪) represent the same trees sprayed in 1976; diamonds (◇) refer to trees planted in 1976 and sprayed the same year. The means of 10 trees are shown for each point except for the point at 3,145 μg/g which was based on eight trees.

Natural levels of Ca^{++} in dogwood leaves are relatively high, ranging from 1.72 to 2.90% (27,28). Concentrations measured in this study (1.53 to 2.58%) were consistent with this natural range. No association between Ca^{++} concentrations and leaf injury was found. Leaf injury due to salinity is not often associated with high Ca^{++} levels (14,19,38).

Slight leaf injury appeared on only a few ash trees. Levels of Cl^- in ash leaves were less than those of similarly treated dogwoods. The treatments and μg/gdw Cl^- levels in ash leaves were as follows: no spray, 324; tap water spray, 290; 1/10X, 437; 1/2X, 922; 1X, 1,443; 2X, 2,749. The no-spray and tap water spray were not significantly different but all other treatments were different as indicated by the SNK test. A few leaves from two trees of the 2X treatment exhibited marginal necrosis but no injury was apparent on any other treatment. In a similar study under greenhouse conditions, white ash was reported to be slightly more susceptible than dogwood to injury induced by saline aerosols (30). Field conditions used in our study probably moderated the response of ash trees to saline aerosol. The accumulation of Cl^- and Na^+ by dogwood foliage and subsequent injury beyond certain levels suggest that dogwood species may serve as an excellent salt drift bioindicator in field studies (11).

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