COMPOSITIONAL, STRUCTURAL AND CHEMICAL CHANGES TO FOREST VEGETATION FROM FRESH WATER WET COOLING TOWER DRIFT

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ABSTRACT

A five year study to assess the impact of wet mechanical draft cooling towers on forest communities was conducted at the Palisades Nuclear Plant. Sampling plots located at various distances from the cooling towers were sampled for plant species compositional and structural analysis. Leaf tissue and soil samples were collected for chemical analysis. Areas within 90 m of the cooling towers have suffered severe compositional and structural changes as a result of ice and chemically induced damage. Calculation of diversity indices show that there has been a reduction in species diversity within 60 m of the cooling towers. Calcium, sodium and sulfur loadings for plant tissue show significant ($P = 0.05$) increases within 60 m, and in some cases up to 85 m, of the cooling towers. Leaching of soil bases appear not to have increased by an increased deposition of anions.

BACKGROUND

An alternative to once-through cooling at electric generating stations is the use of cooling towers. Cooling towers lessen the impact to the aquatic system by essentially closing the cooling water loop. Consequently, less water is required, thermal discharges to the receiving water are reduced, and impingement and entrainment of aquatic organisms is reduced. However, the operation of wet cooling towers has the potential to cause an adverse impact to the terrestrial system through the effects of drift. Drift may adversely affect the terrestrial ecosystem by: (1) adding an increased chemical load to vegetation in the vicinity of the cooling towers, (2) increasing leaching of soil cations (bases) by excess anions and (3) adding a physical stress to vegetation through ice accumulation during the winter months.

To assess the potential environmental impacts of operating cooling towers at the Palisades Nuclear Plant (Consumers Power Company), a study was designed to quantify compositional, structural and chemical changes in the vegetation and soil that may result from cooling tower drift deposition.

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The Palisades Nuclear Plant is located on Lake Michigan in southwestern Michigan, USA. Two mechanical draft wet cooling towers, each with 18 cells (Figure 1), were constructed during 1972-73 as a retrofit to the Plant, which was initially designed and operated with once-through cooling using Lake Michigan water. Each cooling tower is 198 m long, 15.2 m wide and 19.8 m high, and is designed to cool 757,000 liter min^{-1} of condenser cooling water. While the towers are operating 16% sodium hypochlorite (NaOCl) is added to the cooling water at an average rate of 472 liter day^{-1} to control biofouling in the condensers and cooling towers. Sulfuric acid (H_2SO_4) is added to the cooling water at an average rate of 2,620 liter day^{-1} to maintain suitable pH to inhibit scaling in the condensers and cooling towers.

Lake Michigan water averages 33.6 ppm calcium, 10.6 ppm sodium, 9.0 ppm chloride and 22.2 ppm sulfate.[1] The cooling tower basin water averaged 100 ppm calcium, 28 ppm chloride and 435 ppm sulfate over a 28 month period.

Sand dunes that rise up to 60 m above Lake Michigan surround the cooling towers. These dunes are classified as the coastal blowout type that are generally aligned at right angles to the shoreline often with very steep slopes. The cooling towers were constructed in interdunal depressions; consequently, much of the surrounding terrain is at a higher elevation than the top of the cooling towers (Figure 1).

The dominant forest community at the study site is comprised of red oak (*Quercus rubra* L.), sugar maple (*Acer saccharum* Marsh.) and beech (*Fagus grandifolia* Ehrh.) typical of much of the successionally advanced sand dune communities along the eastern shores of Lake Michigan. However, the forests surrounding the cooling towers are dominated by red oak, white pine (*Pinus strobus* L.), sassafras (*Sassafras albidum* [Nutt.] Nees.) and white ash (*Fraxinus americana* L.), typical of earlier successional communities on stabilized sand dunes.

PROCEDURES

The study was initiated during 1973 while the cooling towers were under construction in order to obtain at least one year of preoperational data. However, due to extended outages at the Palisades Plant, preoperational data were collected during 1973 and 1974. The cooling towers became operational in April of 1975 and continued into December 1975 at which time the Plant was shut down for repairs. During May 1976 the Plant resumed operation and continued through December 1977.

Fifteen circular sampling plots were established at selected distances from the cooling towers to examine compositional, structural, and chemical changes to the vegetation and soil as a result of cooling tower operation (Table I). One plot was eliminated from the vegetation sampling soon after the study began due to destruction from construction activities. Each plot is 0.008 ha in size, in which the occurrence of all plant species was recorded. Within this plot, four-m^2 quadrats were located in the four cardinal directions 3 m from the plot center. All species present in each of the quadrats were counted and recorded. Percentage cover was recorded for

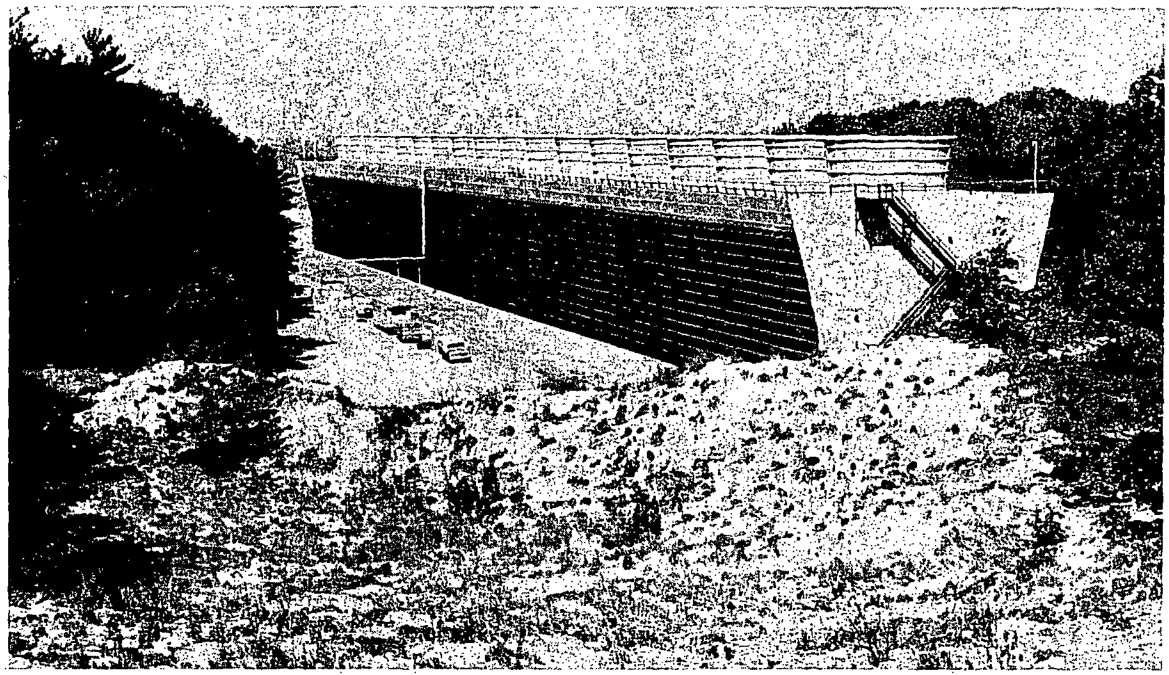

Figure 1. One of two mechanical draft cooling towers at the Palisades Plant site.

TABLE I
Palisades Drift Study: Sampling Plot Locations

Plot No	Distance From Nearest Cooling Tower (M)
1	30.5
2	61.0
3	121.9
4	182.9
5	61.0
6	182.9
7*	30.5
8	56.4
9	45.7
10	83.8
11	36.6
12	61.0
13	143.3
14 (Control)	670.6
15 (Control)	823.0

*Eliminated from vegetation sampling due to disturbance from construction activities.

mosses in each quadrat.

Leaf samples of Q. rubra and S. albidum were collected on each plot at three levels (upper, middle and lower) in the canopy for chemical analysis of Ca, K, Cu, Fe, Mg, Mn, Na, Zn, P and S. These two species were selected because they were present on all sample plots. Additionally, the above-ground parts of a herbaceous species were collected from each plot for the same chemical analysis. Inconsistency in the forest floor species composition between plots resulted in five different herbaceous species being sampled across the 14 plots. Smilacina stellata (L.) Desf. was sampled most frequently on 6 plots of the 14 plots.

Plant tissue samples were oven-dried at 70°C for 24 hours, ground in a blender and stored in Whirlpak bags prior to chemical analysis. Plant tissue was not washed prior to chemical analysis. Hence, results are reported as total ion load.[2]

Concentrations of Ca, K, Cu, Fe, Mg, Mn, Na and Zn in plant tissue were determined by ashing a 1.0 g sample at 500°C for 8 hours. The ash was dissolved in 5.0 ml of 20% HCl, filtered and brought to 50 ml with distilled water. Elemental levels were then determined by atomic absorption spectrophotometry. To eliminate chemical interferences, 0.5% lanthanum was added to the sample for Ca and Mg analyses.

On each plot a soil sample was collected by taking twelve to fifteen 1.9 cm diameter soil cores to a depth of 15 cm. The soil cores were thoroughly mixed and a representative sample taken for chemical analysis of Ca, K, Cu, Fe, Mg, Mn, Na, Zn, Cl and S. Immediately following collection the soil samples were air-dried and sieved through a 2 mm mesh screen.

Extractable soil Ca, K, Cu, Fe, Mg, Mn, Na and Zn were determined by shaking 5.0 g of soil and 20 ml of 0.05 N HCl + 0.025 N H_2SO_4 for 15 minutes, allowed to stand overnight, and shaking again for 5 minutes. The mixture was filtered, brought to 50 ml with the acid extraction solution, and analyzed by atomic absorption spectrophotometry. Sulfur content of plant tissue and soil was determined by the Leco high-frequency combustion titration method.

Compositional sampling was conducted once during the last week of April or first week of May, to include Spring ephemerals, and once during the last two weeks of June. Sampling of plant tissue and soil for chemical analyses took place during the last two weeks of June. A total of five years (1973-1977) is included in the sample period, two preoperational and three operational years.

RESULTS

Visible Structural Changes

About 3 to 4 months after the initial start-up of the cooling towers, P. strobus trees began showing visible signs of chemically induced injury in areas up to 90 m from the cooling towers. Continued operation of the cooling towers during the following season aggravated the injury to P.

strobus trees so that by the end of the summer most were nearly defoliated (Figure 2). Deciduous tree species began showing visible signs of chemical injury during the second summer of operation (Figure 3) so that by the end of the summer, defoliation of deciduous tree species up to 90 m from the towers was well advanced (Figure 4). High deposition rates of sulfate in this area is presumed to be responsible for leaf necrosis and subsequent defoliation of the arborescent species.[3]

Severe icing conditions during the winter of 1976-77 added to vegetation injury by breaking branches and tree crowns (Figure 5). By the third summer (June 1977) of operation the forest canopy had been nearly eliminated in the more severely impacted areas by the combination of cooling tower drift chemicals and ice (Figure 6). Herbaceous ground cover and woody sprouts comprised most of the remaining vegetational cover.

Compositional Changes

Compositional changes in species number and densities at the study site that may have resulted from the effects of cooling tower drift are quantified by the use of the Shannon diversity index[4] (Figure 7). The Shannon index is expressed as follows:

$$H = -\sum_{i=1}^{n} (P_i \log P_i)$$

where H = diversity index (amount of entropy)

P_i = relative importance of each species as a fraction of the total community, or the abundance of each species as a fraction of the abundance of all species combined.

Those sample plots which are less than 60 m from the cooling towers show a definite trend toward reduction in plant species diversity between 1975 and 1977. In general the reduction in species diversity in these areas resulted from nearly complete elimination of the forest canopy (Figure 6) and a subsequent reduction and/or elimination of the shade tolerant species and an increase in density of shade intolerant species in the understory. For example, the average density for Solidago caesia more than doubled from 1975 to 1977 while Taxus canadensis was nearly eliminated in those areas less than 60 m from the cooling towers. This downward trend in plant species diversity is expected to continue to a point where only a few resistant species are able to tolerate high deposition rates of sulfate. Ammophila breviligulata (beach grass), from observation, appears to be somewhat resistant to the high deposition rates, whereas all other indigenous species appear to be affected to some degree. The sulfate deposition rate in areas less than 60 m from the cooling towers averages between 8 and 12 g m^{-2} $month^{-1}$.[3]

It may also be postulated that a reduction in plant species diversity will take place in the forested areas 60 to 85 m from the cooling towers as a result of continued cooling tower operation. Canopy defoliation and resultant reduction in plant species diversity appears to be progressing

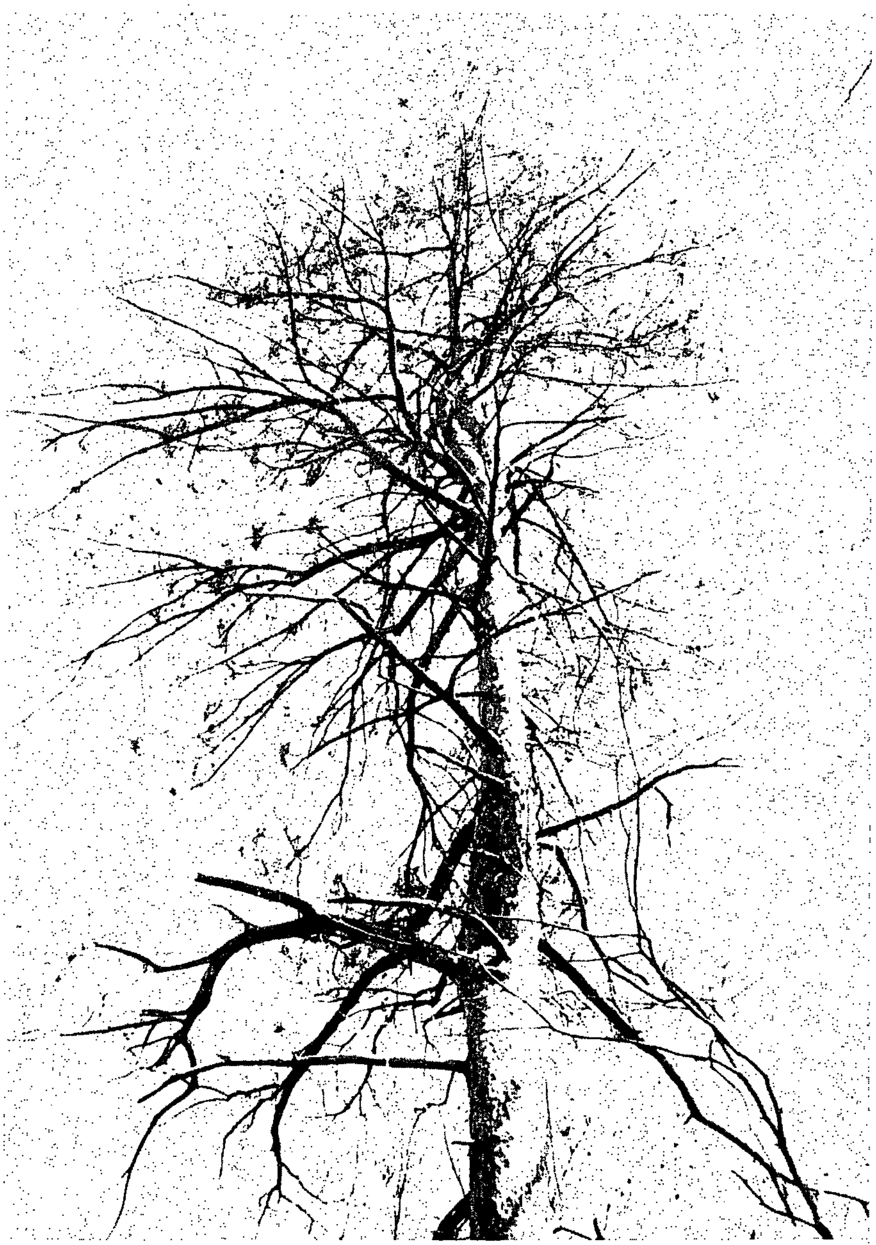

Figure 2. Chemically induced necrosis and defoliation of <u>Pinus strobus</u> during the first summer of cooling tower generation.

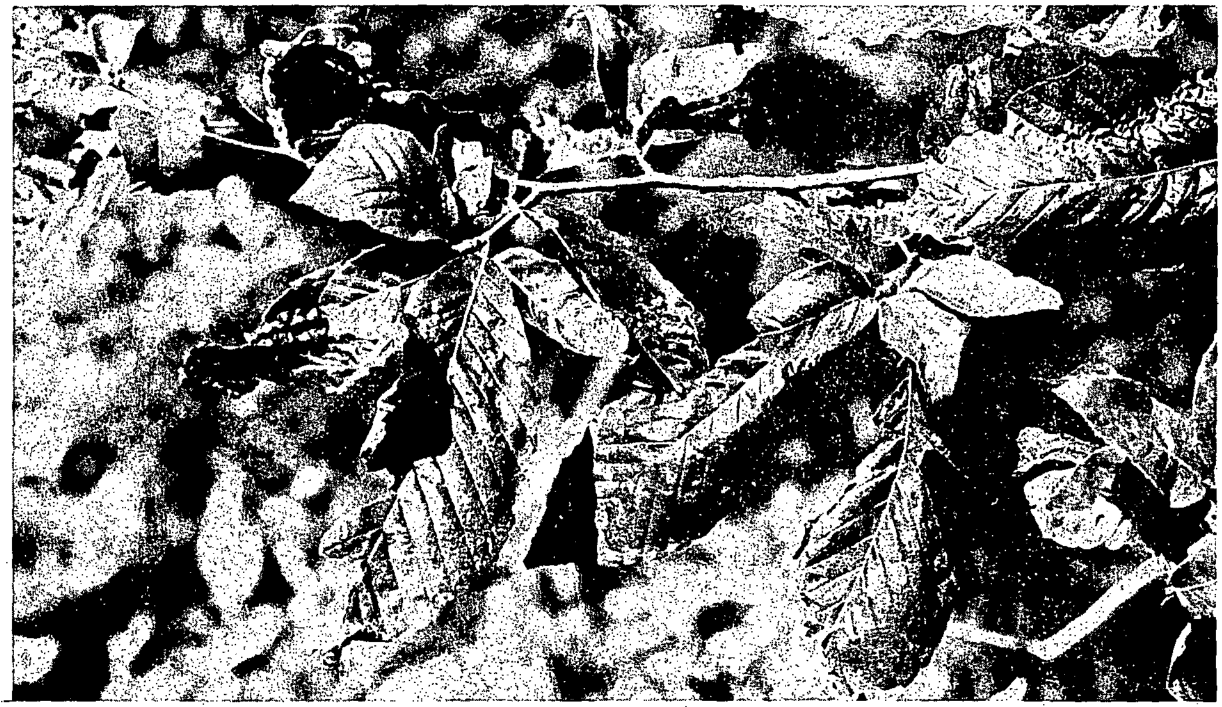

Figure 3. Chemically induced injury to deciduous species (<u>Fagus grandifolia</u>) during the second summer of cooling tower operation.

Figure 4. Defoliation of deciduous species (<u>Quercus rubra</u>) during the second summer of cooling tower operation.

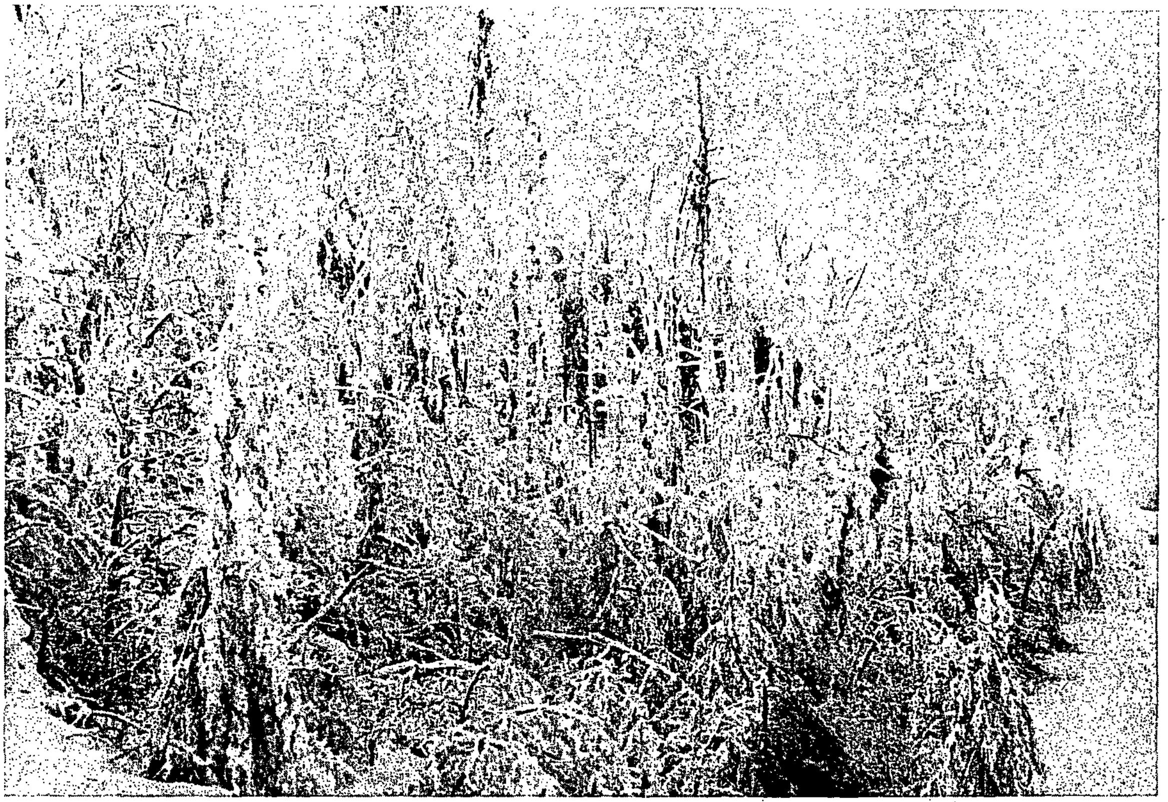

Figure 5. Ice damage to vegetation during the winter of 1976-77.

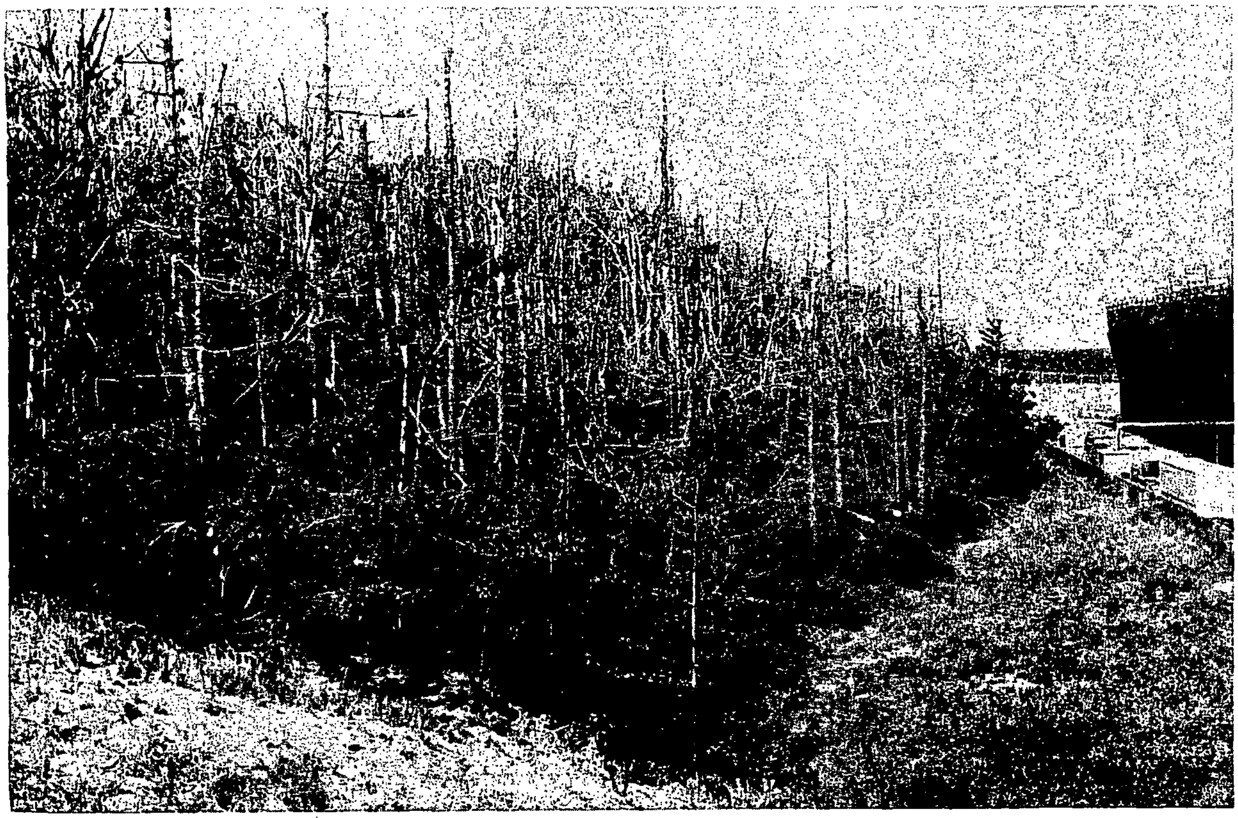

Figure 6. Nearly complete canopy elimination in the more severely impacted areas (June 1977). Compare this area after 22 months of cooling tower operation with the same area prior to operation on the left side of Figure 1.

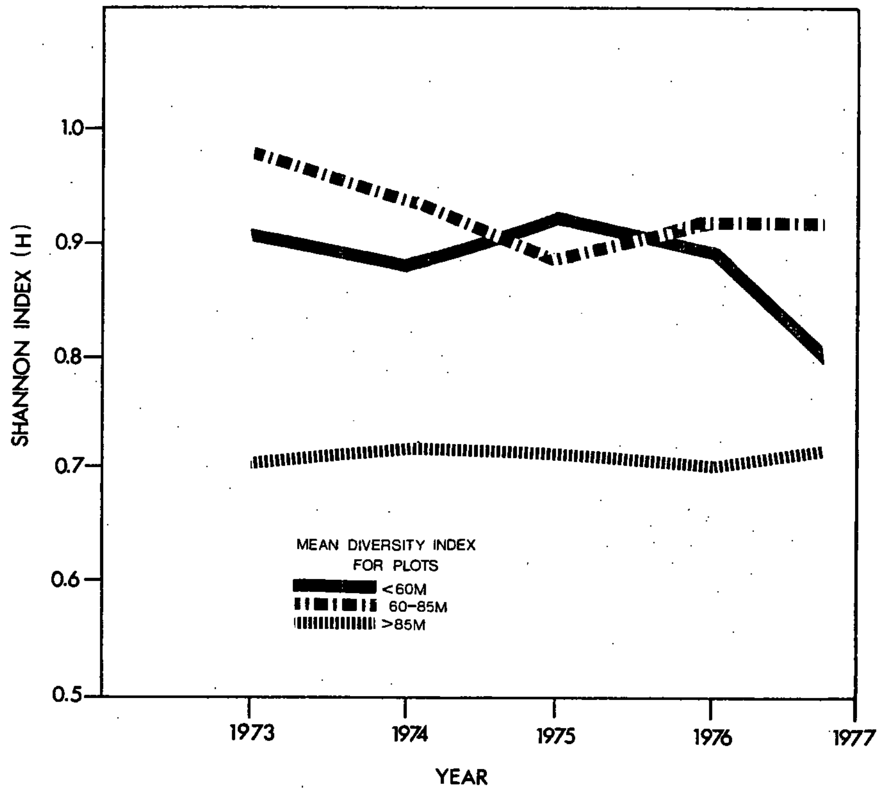

Figure 7. Annual variations in plant species diversity. Diversity indices calculated from plot quadrat data.

further from the cooling towers. As the canopy is removed the understory is exposed to the chemical effect.

Although significant alterations in percentage moss cover were not seen in the data, the mosses on those plots where the canopy was reduced or eliminated appeared somewhat necrotic and generally dehydrated.

Chemical Changes

Of all the elements examined in leaf tissue, calcium, sodium and sulfur showed major changes in concentration through the period of study (Figures 8, 9 and 10 and Table II). Each of the points on the curves are mean values for 4, 4, and 6 plots in the less than 60 m, 60 to 85 m, and greater than 85 m categories, respectively.

Although there is a trend to increasing concentration of calcium for the three species examined during the study period, there is a general decrease in mean calcium loadings for these three species from 1974 (preoperational) to 1975 (Figure 8). This decrease can be attributed to the added rinsing effect during the month of the 1975 sampling period. During the month of the 1974 sampling period about 2.5 cm of precipitation fell, while during the month of the 1975 sampling period over 10 cm of precipitation fell. The especially inconsistent trends for the *S. stellata* curves (Figure 8) are the result of few samples. In many cases the point plotted on the graph for *S. stellata* is the result of only one or two analytical values. Using the t-test [5] all three species show a significant ($P = 0.05$) increase in calcium loadings from 1974 through 1977 for the less than 60 m curves.

Average sodium loadings for the three species and the three distance groupings show definite trends of increasing amounts in leaf tissue during the study period (Figure 9). Average sodium loadings during 1977 for leaf tissue on those plots within 60 m of the cooling towers were found to be over 600 μg g^{-1} for all three species (Table II). These average loadings are considerably higher than sodium loadings reported for Virginia pine growing along the saline Patuxent River.[2] Mean sodium values plotted for the curves representing distances less than 60 m and 60 to 85 m are significant at $P = 0.05$ for all three species. Highest sodium value found in an individual sample was 1500 μg g^{-1} (dry weight).

Sulfur loadings on the three plant species examined also showed significant ($P = 0.05$) increases from 1974 levels to 1977 levels within 60 m of the cooling towers (Figure 10). Sulfur increase for *Q. rubra* is also significant ($P = 0.05$) for the plots from 60 to 85 m. In the areas close to the cooling towers sulfur loadings on leaf tissue have nearly doubled for *Q. rubra* to more than tripled for *S. stellata* from 1974 to 1977 (Table II).

It is suspected that sulfur as sulfate is responsible for the acute vegetation damage in these areas which show high sulfur loadings in leaf tissue. As stated earlier these areas receive high deposition rates of sulfate. Other salts, such as CaCl, or NaCl, acting alone or synergistically with sulfate compounds possibly could be responsible for part of the

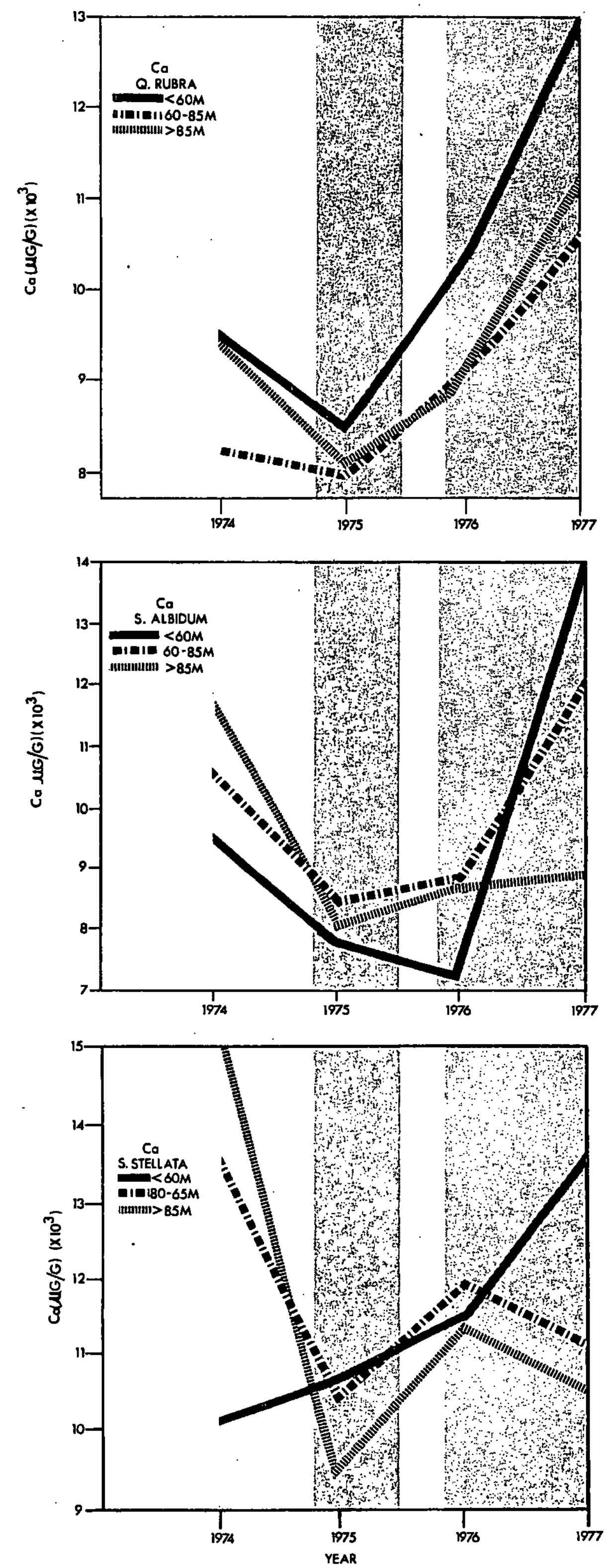

Figure 8. Annual variations in calcium levels in leaf tissue for three plant species. The shaded areas indicate periods of cooling tower operation.

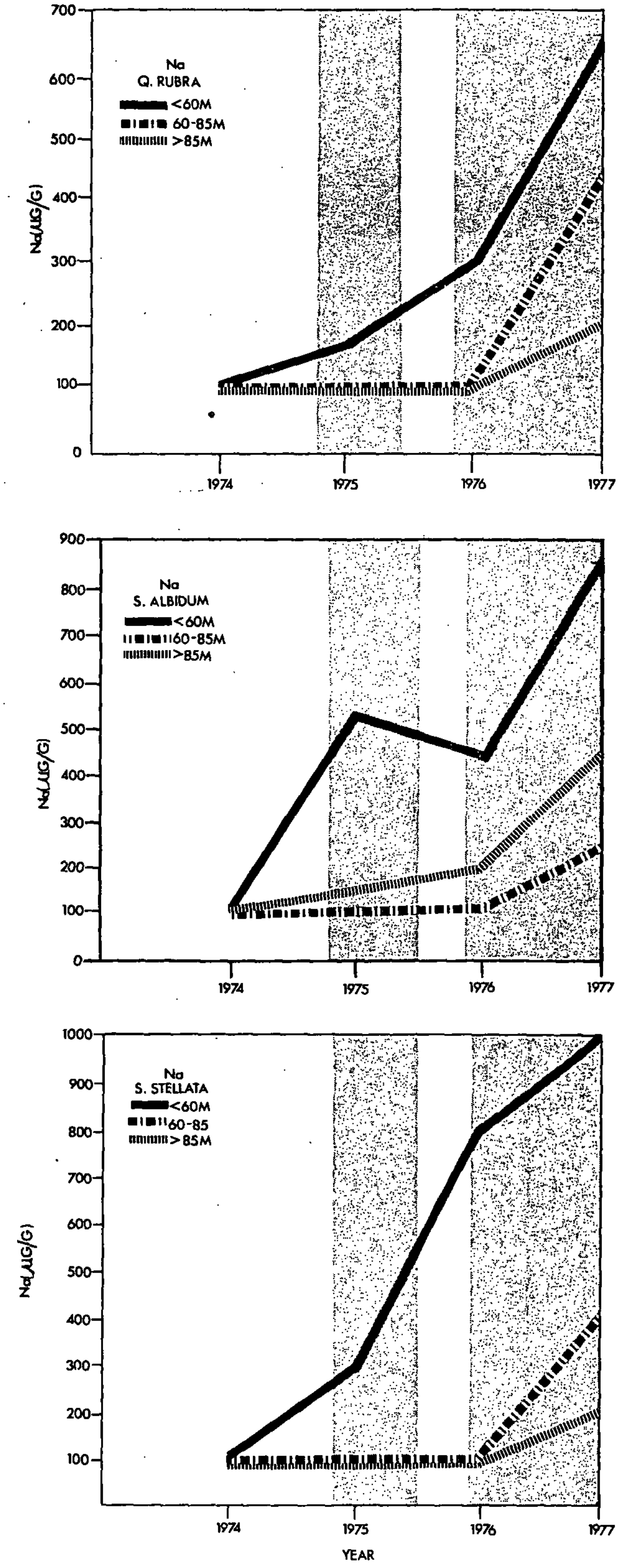

Figure 9. Annual variations in sodium levels in leaf tissue for three plant species. The shaded areas indicate periods of cooling tower operation.

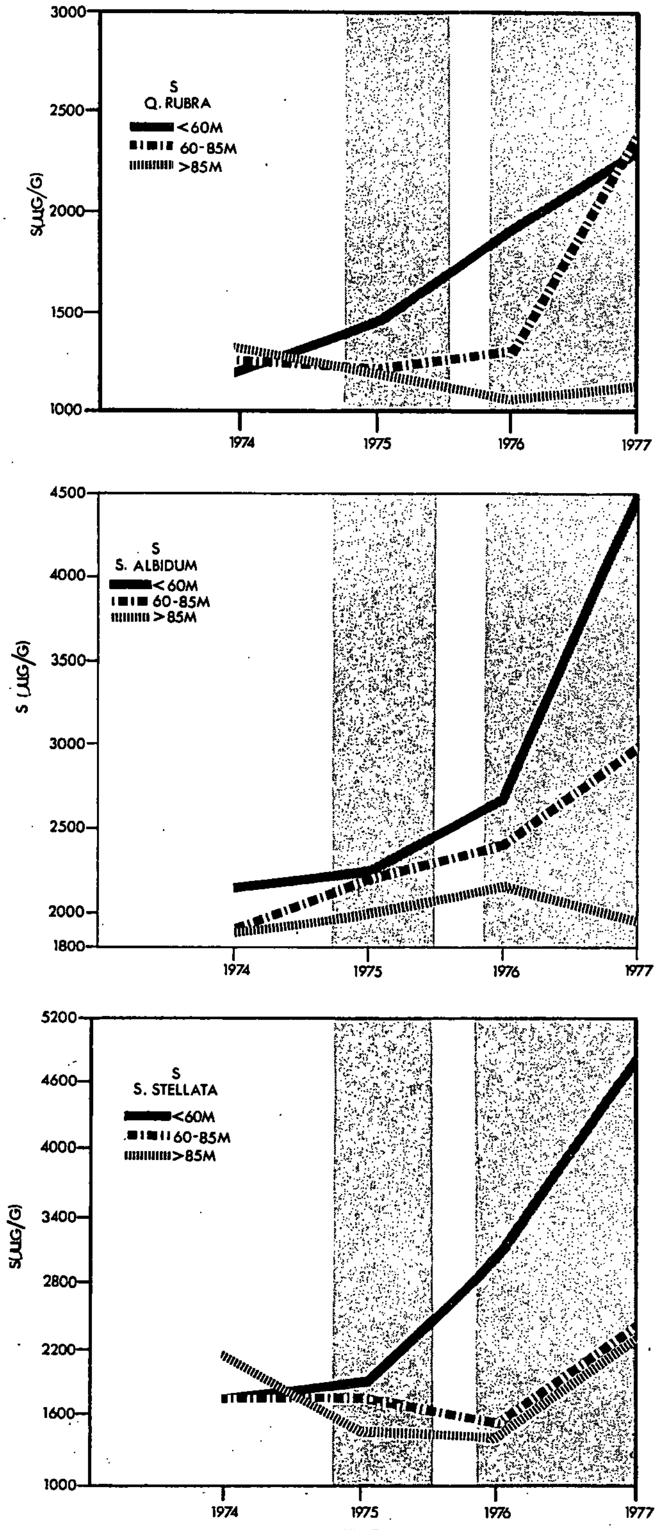

Figure 10. Annual variations in sulfur levels in leaf tissue for three plant species. The shaded areas indicate periods of cooling tower operation.

TABLE II
Palisades Drift Study: Mean chemical loadings for leaf tissue within 60 m of the cooling towers ($\mu g\ g^{-1}$ dry weight)*

	1974**	1975	1976	1977
		Calcium		
Q. rubra	9,570	8,375	10,500	12,900
S. albidum	9,600	7,730	7,200	14,170
S. stellata	10,200	10,550	11,450	13,700
		Sodium		
Q. rubra	100	150	300	670
S. albidum	100	525	450	870
S. stellata	100	300	850	1,100
		Sulfur		
Q. rubra	1,130	1,475	1,850	2,170
S. albidum	2,050	3,130	3,170	4,600
S. stellata	1,700	1,900	3,100	5,900

* These data constitute the <60 m curves in Figures 8, 9 and 10.

**Preoperational

vegetation damage; however, this is not probable. To explicitly identify the chemical(s) that is responsible for the vegetation damage, an experiment is presently in progress. The experiment is designed to spray simulated cooling tower water on plants under greenhouse conditions.

Copper in S. albidum leaves was the only other element examined that showed a definite increasing trend (significant at P = 0.05) throughout the study period for those plots less than 60 m from the cooling towers (Figure 11).

Figures 12 and 13 show soil calcium, sodium, potassium and sulfate-sulfur levels throughout the study period. These graphs are typical of all elements examined. Generally, little or no significant trends are evident except for an increase in soil sulfate-sulfur. The increase in soil sulfate-sulfur for the plots less than 60 m is significant at P = 0.05. The suspected leaching of soil cations (bases) by excess anions evidently is not occurring. Also noteworthy is the infertile nature of these sand dune soils as shown by the rather low levels of all soil elements.

SUMMARY

Observational and quantitative analyses show that drift emanating from the mechanical draft cooling towers at the Palisades Nuclear Plant has caused vegetation damage to the sand dune forests within 90 m of the towers. The damage has been the result of a combination of chemical deposition and icing. In the more severely impacted areas plant species diversity has been reduced by elimination or reduction of the shade tolerant species with an accompanying increase in density of the shade intolerant species.

The loadings of calcium, sodium, sulfur and copper in one species (S. albidum) have significantly increased in leaf tissue from the preoperational (1974) sampling period through the operational sampling periods (1975-1977), especially in those areas within 60 m of the cooling towers. Although calcium and sodium have increased significantly in leaf tissue, it is suspected that the high deposition rates of sulfate are responsible for the vegetation damage.

Only soil sulfate-sulfur appears to have increased significantly during the study period. Other elements show little or no change in soil.

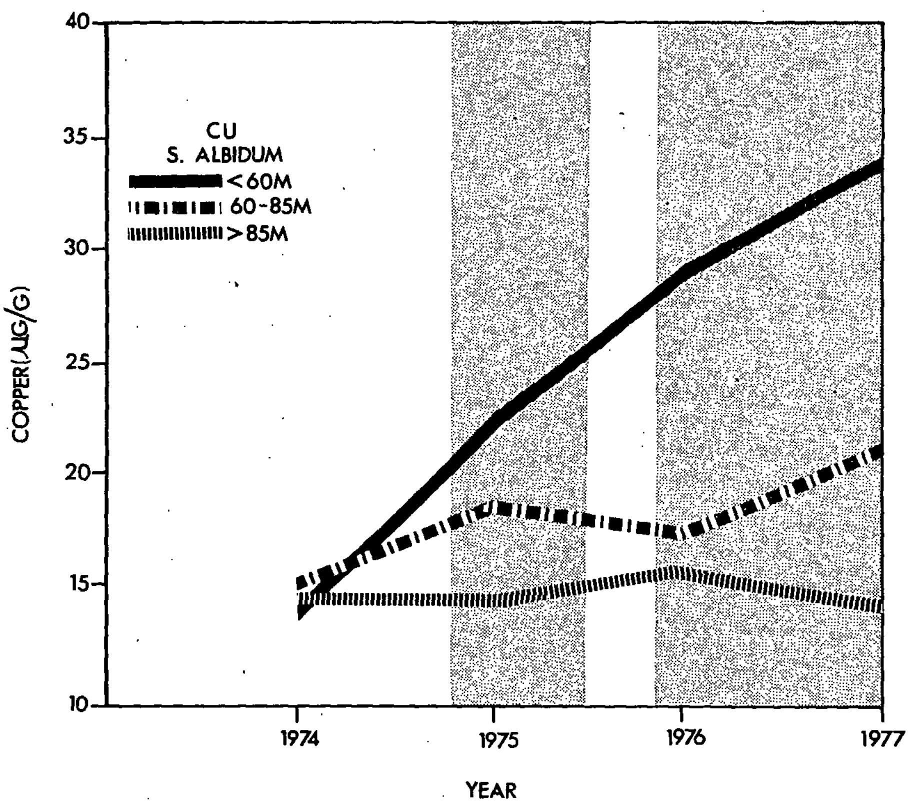

Figure 11. Annual variations in copper levels in Sassafras albidum leaf tissue. The shaded areas indicate periods of cooling tower operation.

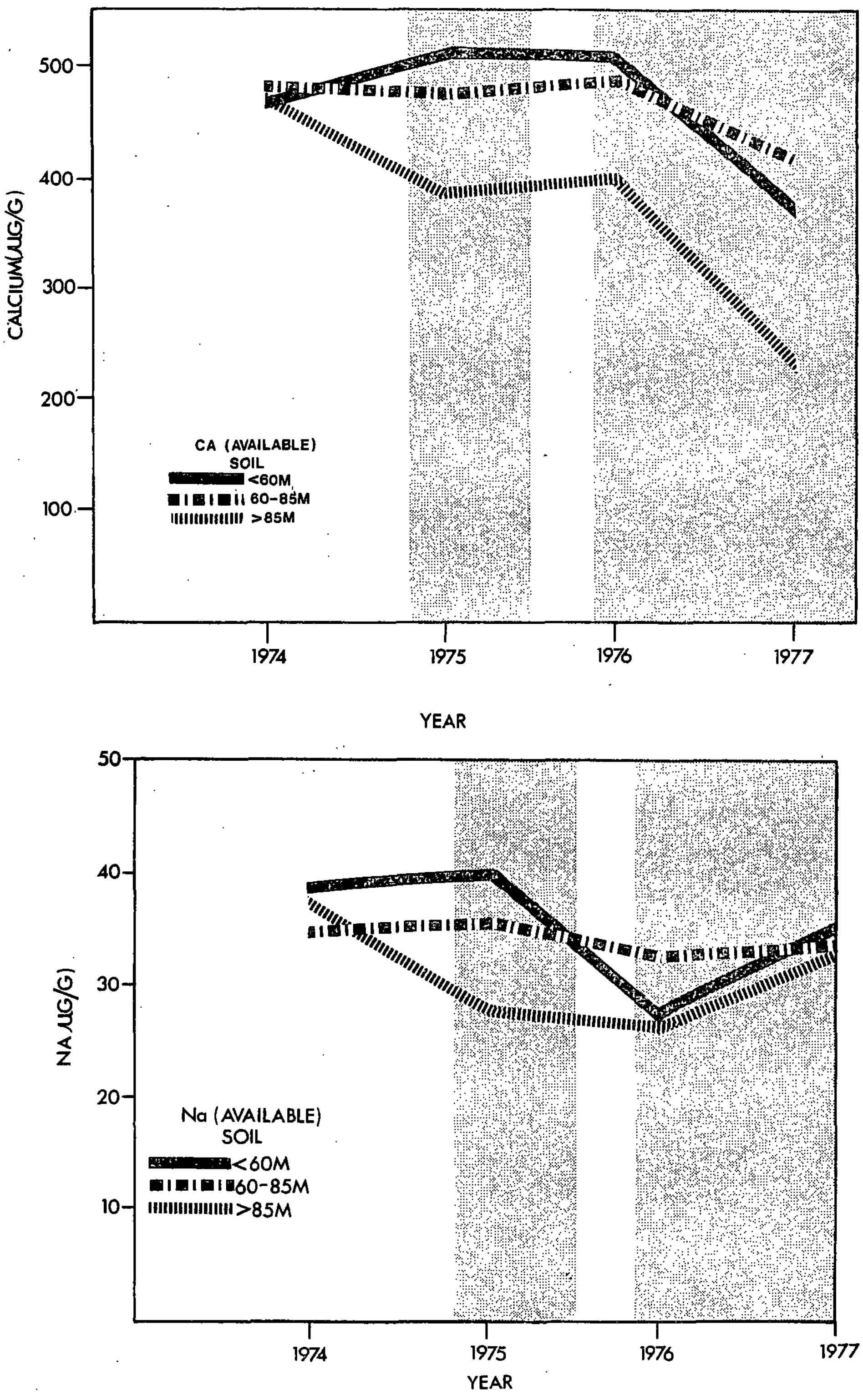

Figure 12. Annual variations in available soil calcium and sodium. The shaded areas indicate periods of cooling tower operation.

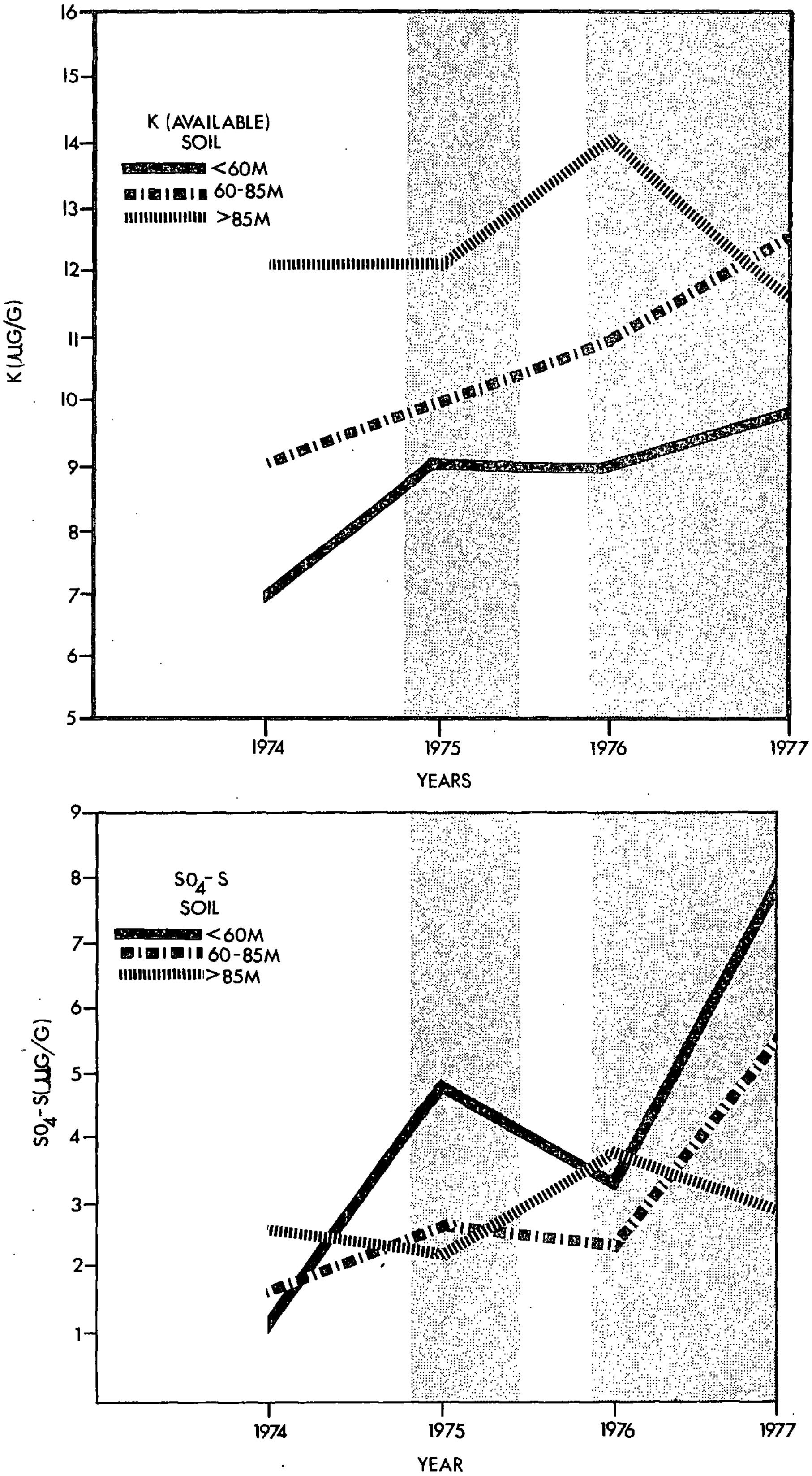

Figure 13. Annual variations in available soil potassium and sulfate-sulfur. The shaded areas indicate periods of cooling tower operation.

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COOLING TOWER
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PROCEEDINGS

A SYMPOSIUM ON ENVIRONMENTAL EFFECTS OF COOLING TOWER EMISSIONS

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ERRATA

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ERRATA

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Page Number	Nature of Correction
I-12	Figure 5: new copy enclosed: current reproduction cannot be read.
I-15	Figure 8: ordinate should be g, not mg.
I-16	Figure 9: ordinate should be g, not mg.
I-106	Table 1: a new page is enclosed with corrections in the surface texture column.
I-119	Figure 1: LSD = 20.8 instead of 5.2
I-120	Figure 2: LSD = 20.8 instead of 5.2
I-121	Figure 3: LSD - 20.0 instead of 5.0
I-122	Figure 4: LSD = 20.0 instead of 5.0
I-123	Figure 5: LSD = 37.2 instead of 9.3
I-124	Figure 6: LSD = 37.2 instead of 9.3
I-125	Figure 7: Units on EC reported should be µMHOS/cm instead of MMHOS/cm
I-126	Figure 8: Units on EC reported should be µMHOS/cm instead of MMHOS/cm
I-127	Figure 9: Units on EC reported should be µMHOS/cm instead of MMHOS/cm
I-128	Figure 10: Units on EC reported should be µMHOS/cm instead of MMHOS/cm
I-129	Figure 11: Units on EC reported should be µMHOS/cm instead of MMHOS/cm
I-130	Figure 12: Units on EC reported should be µMHOS/cm instead of MMHOS/cm
II-28	Figure 9: Dash line is for K = 3.69 instead of 2.97 and dash-dot line is for K = 2.97 instead of 3.69
II-34	Table 1: Number of afternoon visible plumes observed should be changed from 125 to 175 in "Characterization of Cooling Tower Plumes from Paradise Steam Plant"

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Errata cont.

III-3 2.1 Mathematical Modelling, 4th line:
park, $1 \leq M \leq 10$ uncoupled systems consisting...

11th line: ......the two components v_z and v_x of...

2nd equation:

$$\mu_1 = (K_1 v_z{}^2/v^2 + K_2 v_z v_x{}^2/v^3 + K_4 F)/R + K_3 \Delta\rho g/\rho v^2$$

4th line after the equations:

initially had no vertical momentum (μ)

III-4
$$\frac{da}{ds} = (0.5\ \mu_1\ a - \theta_1 + K_y/av)/(1 + \alpha/(1 - W))$$

$$\frac{da}{ds} = (0.5\ \mu_1\ b - \theta_2 + K_z/bv)/(1 + \beta/(1 - W))$$

III-5 page center:

This method delivers N_K Gaussian plumes for the N_K cooling towers which are then superposed point by point in the space downwind of the plant.

3rd line from bottom:

.....the plume of tower j and $\alpha - \beta = (1 - W \frac{dW}{ds})$. Fig. 2

III-13 2nd line:

.....due to the drift droplets but - mainly in the case of

III-119 2nd paragraph, lines 9 and 10:

"1.2 x 10^3 Kg/Km-Month" and "0.60 x 10^3 Kg/Km-Month" rather than "1.2 x 10^6 Kg/Km^2-Month" and "0.60 x 10^6 Kg/Km^2-Month".

III-122 2nd paragraph, line 11: same corrections as above.

III-123 Table 2: "total at range" values should be "10^3" not "10^6" and have units "Kg/Km-Month".

III-125 Table 3: footnote should be "*Kg/Km-Month multiplied by 10^{-3}".

III-162 Add reference:

Thompkins, D. M. (1976) Atmospheric dispersion and deposition of saline water drops, Master of Science Thesis, Graduate Program in Meteorology, University of Maryland, College Park, Md., 69 pp.

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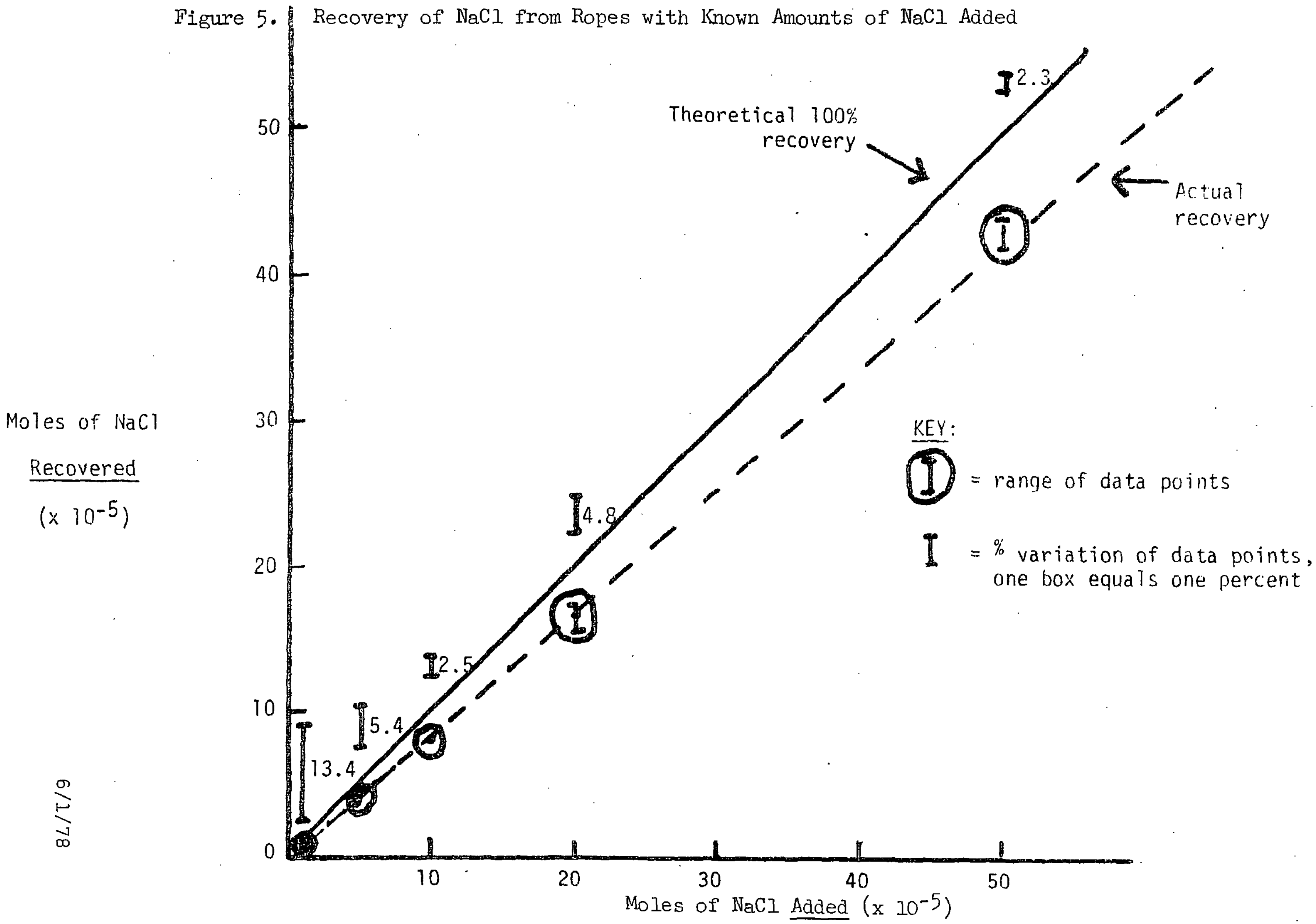
Figure 5. Recovery of NaCl from Ropes with Known Amounts of NaCl Added



6/1/78

Table 1. Classification and partial chemical and physical characterization of the soils at the Chalk Point research sites.

Location with Respect to Cooling Tower		Soil	Surface	Physical Analysis*			Chemical Analysis*						
							Extractable					Organic	
Distance	Direction	Series	Texture*	Sand	Silt	Clay	Mg	P	K	Ca	Na	Matter	pH
-- km --				------ % -------			------ µg/g -------					-- % --	
1.6	north	Lakeland	fine sand	90	3	7	67	61	22	57	17	0.9	5.1
	east	Lakeland	fine sand	90	7	3	23	51	45	236	20	0.9	6.5
	south	Mattapex	loam	45	45	10	28	19	71	50	19	1.5	5.5
	west	Sassafras	fine sandy loam	73	21	6	62	12	51	96	18	0.8	5.8
4.8	north	Sassafras	fine sandy loam	75	19	6	29	24	59	152	20	0.9	5.8
	east	Woodstown	fine sandy loam	76	15	9	64	50	83	210	22	1.9	5.4
	south	Sassafras	fine sandy loam	68	25	7	50	5	31	245	20	0.6	5.9
	west	Westphalia	loamy fine sand	83	12	5	24	65	48	24	18	1.3	6.0
9.6	north	Sassafras	sandy loam	54	34	12	67	53	70	102	22	2.3	5.6
	east	Matapeake	loam	45	45	10	73	6	31	404	22	1.1	5.9
	south	Galestown	fine sandy loam	71	24	5	37	46	93	344	17	1.1	6.1
	west	Woodstown	loamy sand	78	17	5	53	4	28	164	21	1.0	6.0

* All values are reported for samples collected at a depth of 0-15 cm.

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