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EPIPHYTIC BROMELIADS AS AIR QUALITY MONITORS IN SOUTH FLORIDA

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ABSTRACT. Three species of *Tillandsia* (Bromeliaceae) were surveyed at nine sites in south Florida to determine possible effects of air pollution. All three populations were healthy and reproductive. Most of the chemical elements examined in sampled foliage occurred at concentrations similar to those previously reported for the genus. However, one notable geographic trend was revealed: concentrations of S tended to be highest in mainland plants closest to the urbanized east coast. Continued use of these bromeliads and other Florida vascular epiphytes for air quality surveillance is recommended.

Vascular epiphytes, primarily members of *Tillandsia* (Bromeliaceae), have provided records of pollution, including exposures to SO_2 (Arndt & Strehl, 1989); technological and other metals (e.g., Martinez et al., 1971; Robinson et al., 1973; Shacklette & Connor, 1973; Sheline et al., 1976); and organic residues (Schrimpff, 1981). As with the more commonly used lichens (e.g., LeBlanc & Rao, 1975), these specialized higher plants are good air quality indicators because they lack contact with soil and accumulate a variety of nonnutritive substances from the atmosphere. Here we report the results of a survey conducted to identify possible effects of air contaminants during the early 1980's on three *Tillandsia* species and suggest why surveillance of these plants should continue.

MATERIALS AND METHODS

STUDY SUBJECTS. *Tillandsia balbisiana* Schultes and *T. paucifolia* Schlecht are labeled "atmospherics" or "air plants" because moisture and nutrient ions are acquired via trichomes that densely cover shoots (FIGURE 1); sparse root systems serve primarily to secure plants to trees. *Tillandsia utriculata* L. is a larger tank or phytotelm species that obtains nutrients through the activities of biota that process litter intercepted by overlapping foliage. Much is known about the biology of *Tillandsia,* including aspects of water balance, nutrition, and life history (Benzing, 1990). Distinguishing features of the more xerophytic species beyond the epiphytic habit are crassulacean acid metabolism (CAM), slow growth, and extraordinary abilities to scavage substances, including a variety of toxins, from the atmosphere (Benzing & Renfrow, 1980). Leaves that live for two or more years provide a time-averaged record of local air composition.

STUDY SITES. Collections were made at nine sites (FIGURE 2) chosen for location within boundaries of the Everglades or Biscayne National Parks (ENP and BNP respectively), proximity to the greater Miami metropolitan area, and the availability of suitable plant materials. Sites D, E, G, and H are protected by Class One status under the Prevention of Significant Deterioration provisions of the Clean Air Act; i.e., they occur on National Park land.

Modeling studies of south Florida source emissions conducted by the Environmental Science and Engineering, Inc. of Gainesville, Florida (Anonymous, 1981) indicated that of the nine sites, vegetation at locations A, C, and D experience the greatest exposure to SO_2 from the largest point source in Dade county, the Florida Power and Light Company (FPL) generating facility at Turkey Point (FIGURE 2). *Tillandsia balbisiana* occurred in six of the nine sites, *T. paucifolia* in five, and *T. utriculata* in four (TABLE 1). Bald cypress (*Taxodium distichum* (L.) Richard) was the most common host, but broad-leafed trees supported some of the sampled plants.

PLANT ANALYSIS. Samples were obtained during April 1983. Four to 15 mature leaf blades from two or more plants constituted a sample for *T. utriculata* and *T. balbisiana.* Collections of *T. paucifolia* consisted of 3–6 shoots approaching flowering size, with stems and roots removed. Materials were oven-dried for 48 hr at 85°C and ground in a Wiley mill. Total N content was determined by titrametric micro-Kjeldahl analysis following wet digestion of dried leaf tissue in selenium-H_2SO_4 (Benzing & Renfrow, 1971). Additional subsamples were sent to the Plant Analysis Laboratory at the Ohio State Agricultural Research and Development Center in Wooster, Ohio, where plant ash, obtained at

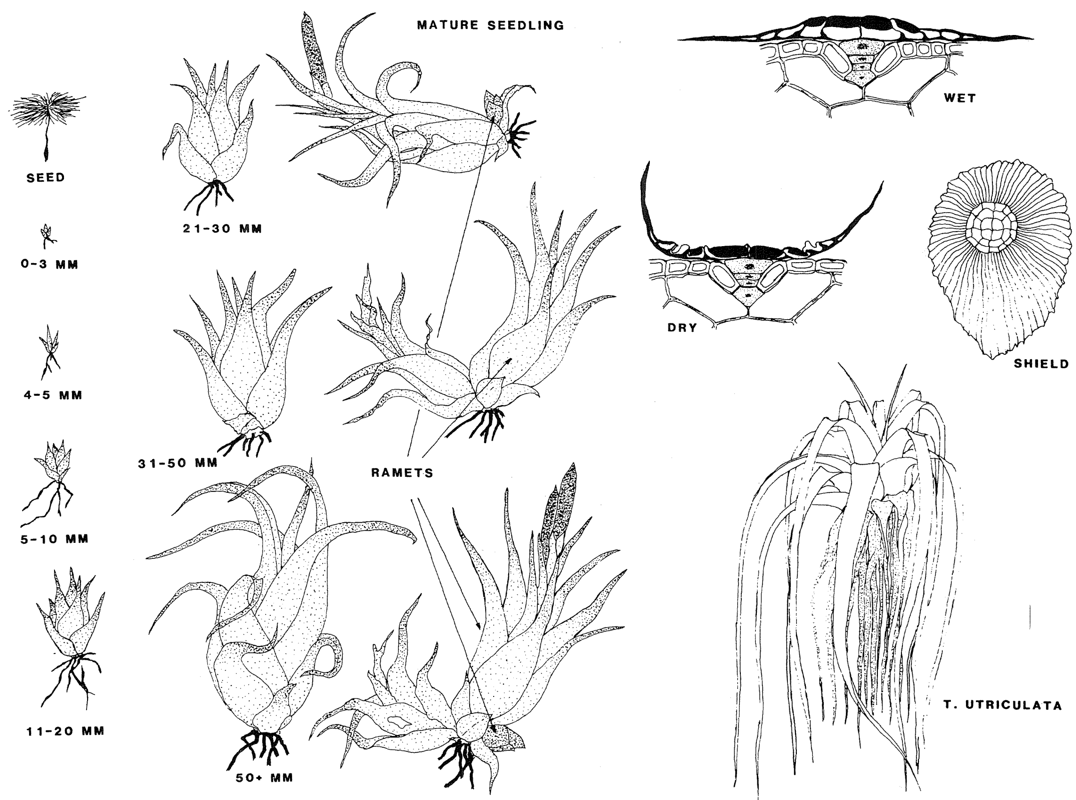

FIGURE 1. Age/size categories used for the demographic analysis of *Tillandsia paucifolia* on cypress trees in south Florida. Also illustrated is *T. utriculata* and an absorbing foliar trichome in the wet (absorbing) and dry (light-scattering) configurations.

500°C, was digested in 2.4 N nitric acid and analyzed for Al, Ca, K, P, Cu, Fe, Mn, Na, and Zn by inductively coupled argon-plasma-optical spectrometry. Total S was determined at the same facility by digesting dried material in nitric/perchloric acid and measuring SO_4^{-2} by turbidometry. Total reserve carbohydrate was determined in dried material after incubation for 12 hr at 30–40°C according to the enzymatic method of daSilveira et al. (1978) using amylase from Miles Laboratories, Inc.

LIFE TABLE ASSESSMENT. All living *T. paucifolia* specimens growing on 44 randomly chosen dwarfed cypress trees at sites A, C, and F were removed and brought to the laboratory for sorting into size/age categories (FIGURE 1).

GERMINATION TESTS. Seeds of *T. paucifolia* collected from plants maintained in the Oberlin College greenhouse were affixed in groups of four with Elmer's nonwater-soluble glue to trunks and limbs of dwarfed cypress at sites A, C, and F in late April 1983. As in a previous study (Benzing, 1978, 1981), intertwined coma hairs (FIGURE 1) were attached, leaving the seed itself free of adhesive. Two groups of 48 seeds were placed on 6–9 trees in each location. A single test group consisted of two vertical rows of 12 seed clusters forming a rectangle about 10 × 35 cm. An additional sample of 252 seeds arrayed similarly was anchored to lath strips and misted with tap water for 0.5 hr each day in the Oberlin Greenhouse. Surviving seedlings were recorded in late October 1983.

RESULTS

LEAF COMPOSITION. Assayed elements were present in leaves in concentrations (TABLE 2) approximating those reported for *T. paucifolia* and several other *Tillandsia* spp. in south Florida (Benzing & Renfrow, 1971; Benzing & Davidson, 1979; Benzing, 1990). Foliar N, P, and K levels were lower, whereas Ca, Mg and the trace elements occurred within ranges expected for soil-

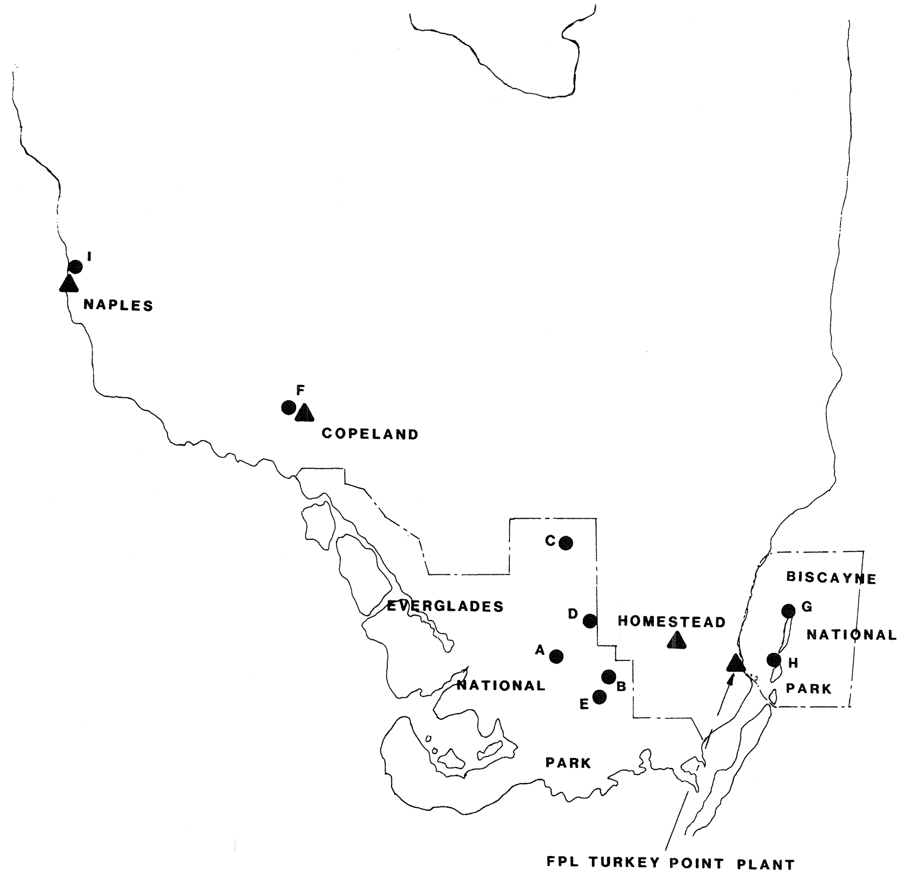

FIGURE 2. Map of south Florida showing locations of collection sites, park boundaries, Turkey Point, and other pertinent landmarks.

rooted vegetation (Epstein, 1972). Sodium concentrations were generally elevated for non-halophytes, but highest in samples from sites G and H that were only a few meters from the ocean, and at site C in the ENP.

Sulfur, an element that has received little attention in studies of bromeliad nutrition, exhibited a noteworthy distribution. Remarkably low values for vascular plants were recorded in *T. utriculata* taken at site F, about 120 km northwest of Homestead, Florida. Sulfur in shoots of *T. balbisiana* and *T. paucifolia* was also lowest at this remote rural location. Closer to the urbanized east and west coasts, particularly along

TABLE 1. Host tree identity and approximate canopy exposure levels at nine sites in south Florida.

	Site			
	A	B	C	D
Tillandsia balbisiana	*Taxodium,* high exposure		*Taxodium,* high exposure	Various hardwoods, low exposure
Tillandsia paucifolia	*Taxodium,* high exposure		*Taxodium,* high exposure	
Tillandsia utriculata		Various hardwoods, low exposure		Various hardwoods, low exposure

the eastern boundaries of the ENP, S was more abundant in leaf tissue—up to four times in *T. utriculata*, 3.5 times for *T. balbisiana* and 2.5 times for *T. paucifolia* than at site F. Even the highest S concentrations, however, remained well below the 0.1% concentration deemed sufficient for a number of crops (Epstein, 1972). Nitrogen was most abundant in *T. balbisiana* at site C and in *T. paucifolia* at A and C. Nitrogen composition varied less among subsets of *T. utriculata*.

Sizable variation was recorded for several additional elements. Phosphorus was severalfold more concentrated in the unusually robust *T. paucifolia* specimens growing in the low mangrove woodland that borders Sands and Taten Keys in the BNP compared to samples from the mainland. Values were more uniform in the other two species. Potassium ranged about fourfold in *T. paucifolia* with the lowest values recorded at site F. Manganese was higher than usual in the foliage of *T. utriculata* at site I, as was Cu in this taxon at site D. At locations G and H, *T. paucifolia* contained relatively more B.

Carbohydrates were abundant in all sampled plants, although differences occurred among species and within species at different locations (TABLE 2). Collections from site F consistently yielded the highest values. Differences among species covaried with two other leaf characteristics; the epiphyte with the lowest starch content, *T. balbisiana*, possesses stiff, fibrous foliage. The softer texture and higher fresh/dry weight ratio may explain why the same reserves were up to twice as concentrated in *T. paucifolia* leaves. Starch concentrations in *T. utriculata* were more similar to those of *T. balbisiana*, as was leaf water content and texture.

A one-way ANOVA comparing concentrations of foliar elements and starch and site for each species revealed significant heterogeneity ($P < 0.005$) among samples relative to collection location in all cases except for Cu, Fe and Mg in *T. balbisiana*. A Scheffe Multiple Range test demonstrated overlap among rank-ordered sites for each element in all three subjects (TABLE 3). For instance, Cu in *T. balbisiana* was statistically indistinguishable among populations at six sites, whereas *T. utriculata* growing at location D contained significantly more of this trace element than did conspecifics at the other three collection sites. Iron exhibited a similar pattern except that *T. utriculata* specimens from site F carried greater concentrations of this metal than either of the other species. Plants collected at site F consistently exhibited the lowest S contents among conspecifics.

STATUS OF POPULATIONS. All four of the censused *T. paucifolia* colonies were healthy and reproducing by seeds and ramets (FIGURE 3). Year-old juveniles were usually present on a tree if at least one adult epiphyte had fruited there the season before. Conversely, cypress trees that supported few or no first-year seedlings tended to lack potential parents for those progeny. Two factors apparently accounted for the abundance of intermediate-sized plants: steady mortality and accelerated growth as seedlings matured. Categories 3–5 each contained members of several cohorts. Category 8 also included plants of diverse age, but longevity could not be calculated because spent ramets eventually rot away.

GERMINATION TESTS. Seed success on cypress trees at sites A, C, F1, and F2 approached or exceeded performances in the greenhouse (20.0%, 42.4%, 22.2%, 40.8% respectively vs. 26.8%; TABLE 4). Survivors were well-distributed; only two test patches, one at site F1 and another at site A, were completely barren six months after seeds were sown. Survival on a few test patches exceeded 50%. A Kruskal-Wallis one-way ANOVA indicated significant differences between seedling survival among sites ($p < 0.001$), but paired comparisons of survivorship (Mann-Whitney *U*-test) revealed that seed success at sites A and F1 and C and F2 were indistinguishable ($p > 0.79$, $p > 0.67$).

TABLE 1. Extended.

Site				
E	F	G	H	I
Taxodium, high exposure	*Fraxinus, Taxodium*, medium exposure			*Quercus*, high exposure
	Taxodium, high exposure	*Conocarpus*, high exposure	*Conocarpus*, high exposure	
	Fraxinus, Taxodium, medium exposure			*Quercus*, high exposure

TABLE 2. Means and standard deviations for concentrations of 13 elements and total reserve carbohydrates in dried foliage of *Tillandsia balbisiana, T. paucifolia* and *T. utriculata* collected at nine sites in south Florida.

	Percent dry weight								ppm					
Site	N	P	K	Mg	Ca	S	Carb.	Na	Mn	Fe	Cu	B	Zn	Al
							Tillandsia balbisiana							
A	0.58 ±0.14	0.018 ±0.004	0.27 ±0.08	0.17 ±0.04	0.51 ±0.10	0.045 ±0.011	5.14 ±0.70	0.54 ±0.13	25.1 ±4.9	62.1 ±11.6	4.2 ±1.2	4.5 ±0.7	10.7 ±2.1	75.3 ±20.1
C	0.78 ±0.12	0.020 ±0.004	0.37 ±0.08	0.19 ±0.29	0.55 ±0.11	0.070 ±0.013	5.99 ±0.54	0.59 ±0.10	20.4 ±3.5	77.0 ±10.3	7.7 ±4.1	9.1 ±3.2	19.0 ±2.7	86.4 ±20.3
D	0.66 ±0.16	0.038 ±0.004	0.48 ±0.16	0.21 ±0.02	0.39 ±0.06	0.042 ±0.011	7.16 ±0.58	0.56 ±0.07	25.0 ±6.6	56.6 ±14.4	3.4 ±0.5	7.7 ±1.5	12.2 ±1.9	58.9 ±14.5
E	0.64 ±0.10	0.027 ±0.006	0.25 ±0.07	0.21 ±0.06	0.42 ±0.09	0.022 ±0.019	5.83 ±0.56	0.49 ±0.07	19.7 ±5.2	81.0 ±15.6	7.7 ±10.2	7.1 ±0.8	13.1 ±2.8	101.9 ±23.1
F	0.59 ±0.09	0.044 ±0.013	0.46 ±0.13	0.17 ±0.02	0.79 ±0.19	0.020 ±0.015	8.86 ±1.28	0.40 ±0.07	14.6 ±3.7	76.1 ±22.4	7.5 ±4.0	4.4 ±1.1	11.1 ±2.3	95.6 ±23.3
I	0.33 ±0.06	0.029 ±0.003	0.37 ±0.08	0.20 ±0.04	0.33 ±0.05	0.059 ±0.012	6.46 ±0.81	0.58 ±0.05	39.7 ±17.1	87.4 ±24.9	2.9 ±0.2	5.9 ±1.0	22.9 ±4.0	66.2 ±8.4
							Tillandsia paucifolia							
A	0.78 ±0.07	0.023 ±0.011	0.30 ±0.09	0.17 ±0.03	0.41 ±0.05	0.099 ±0.016	9.10 ±1.20	0.71 ±0.14	27.6 ±8.0	77.4 ±19.0	5.7 ±2.9	8.6 ±1.8	17.8 ±9.3	95.7 ±20.1
C	0.72 ±0.10	0.025 ±0.010	0.42 ±0.09	0.19 ±0.02	0.52 ±0.08	0.097 ±0.014	10.08 ±0.68	0.91 ±0.13	37.7 ±6.3	74.6 ±16.7	7.3 ±2.2	9.7 ±1.3	19.0 ±2.8	97.7 ±21.7
F	0.37 ±0.04	0.019 ±0.002	0.20 ±0.05	0.14 ±0.02	0.50 ±0.06	0.040 ±0.012	16.00 ±1.69	0.48 ±0.06	33.9 ±5.2	75.9 ±9.1	3.2 ±0.4	6.7 ±0.7	17.6 ±3.8	181.4 ±133.3
G	0.37 ±0.07	0.055 ±0.020	0.53 ±0.11	0.21 ±0.03	0.18 ±0.04	0.058 ±0.017	14.69 ±3.30	0.83 ±0.13	13.4 ±1.7	35.2 ±12.2	2.1 ±0.3	29.0 ±5.7	9.6 ±1.8	50.5 ±17.4
H	0.45 ±0.13	0.064 ±0.018	0.78 ±0.18	0.26 ±0.05	0.24 ±0.04	0.050 ±0.006	10.96 ±1.82	1.06 ±0.40	29.4 ±9.2	46.8 ±9.1	2.2 ±0.4	31.6 ±8.5	11.4 ±1.9	83.3 ±21.7
							Tillandsia utriculata							
B	0.43 ±0.03	0.048 ±0.010	1.31 ±0.26	0.24 ±0.04	0.67 ±0.12	0.049 ±0.015	6.29 ±2.25	0.27 ±0.07	22.7 ±5.8	35.6 ±5.2	4.9 ±1.7	11.8 ±3.8	14.7 ±3.8	17.3 ±6.1
D	0.64 ±0.14	0.056 ±0.18	0.91 ±0.15	0.28 ±0.05	0.63 ±0.12	0.040 ±0.032	6.73 ±1.50	0.40 ±0.07	36.8 ±7.9	55.8 ±7.1	9.6 ±4.0	10.8 ±2.4	23.8 ±8.5	37.9 ±10.8
F	0.50 ±0.06	0.042 ±0.007	0.69 ±0.16	0.25 ±0.04	0.60 ±0.17	0.011 ±0.003	11.85 ±1.42	0.39 ±0.03	32.0 ±9.7	104.7 ±13.6	2.9 ±1.0	10.6 ±1.2	15.0 ±2.2	56.1 ±28.6
I	0.35 ±0.10	0.036 ±0.009	0.70 ±0.27	0.22 ±0.04	0.38 ±0.06	0.039 ±0.016	8.99 ±1.36	0.49 ±0.18	104.6 ±40.5	50.1 ±9.8	1.9 ±0.3	4.9 ±1.5	28.4 ±7.0	32.9 ±6.2

TABLE 3. Site-to-site overlap of leaf constituents in three epiphytic bromeliads at the 95% confidence level determined by the Scheffe Multiple Range test.

	Tillandsia balbisiana						*Tillandsia utriculata*				*Tillandsia paucifolia*				
Sulfur	F	E	D	A	I	C	F	I	D	B	F	H	G	C	A
Phosphorus	A	C	E	I	D	F	I	F	B	D	F	A	C	G	H
Nitrogen	I	F	E	A	D	C	I	B	F	D	G	F	H	C	A
Potassium	E	A	C	I	F	D	F	I	D	B	F	A	C	G	H
Calcium	I	D	E	A	C	F	I	D	B	F	G	H	A	F	C
Magnesium	A	F	C	I	D	E	I	B	F	D	F	A	C	G	H
Iron	D	A	F	C	E	I	B	I	D	F	G	H	C	F	A
Manganese	F	E	C	D	A	I	B	F	D	I	G	H	A	F	C
Sodium	F	E	A	D	I	C	B	F	D	I	F	A	G	C	H
Zinc	A	F	D	E	C	I	B	F	D	I	G	H	F	A	C
Copper	I	D	A	F	C	E	I	F	B	D	G	H	F	A	C
Boron	F	A	I	E	D	C	I	F	D	B	F	A	C	G	H
Aluminum	D	I	A	C	F	E	B	I	D	F	G	H	A	C	F
Reserve carbohydrates	A	E	C	I	D	F	B	D	I	F	A	C	H	G	F

DISCUSSION

Sulfur and nitrogen oxides are more abundant today over south Florida than 30 years ago, although concentrations of these gases stabilized somewhat following implementation of the energy economies prompted by the fuel crisis that began in the early 1970's (Brazonik et al., 1980, 1983; Anonymous, 1986, 1988). Heavier automobile use, greater industrial activity, and additional demand for electric power on Florida's southeast coast are primarily responsible for reducing local air quality in recent decades. The power-generating facility at Turkey Point alone emitted on average about 8,000 metric tons of S per year during the early 1980's, an output three to four orders of magnitude greater than that generated naturally in estuaries within three to eight km of the power plant (Gough et al., 1986). Nevertheless, stack emissions have had no substantial regional influence on the chemical composition of tested vegetation. Stable S isotope ratios indicated minor impact on plants within three to eight km of the generators. Possible modest longer range (at 26.5 and 37 km distances) transport and deposition of trace metals from the power plant were recorded in soils and soil-rooted *Casuarina* spp. and *Schinus terebinthifolius* Raddi plants that may have lower affinities for airborne substances than the epiphytes examined in this survey.

Although the tested bromeliads exhibited no signs of injury from airborne toxins, the S data suggest anthropogenic influence. Differences in foliar S are consistent with projections produced by an atmospheric dispersion model (Anonymous, 1981) employed to evaluate potential environmental consequences should the two FPL fossil fuel steam generators at Turkey Point be fired with oil containing 2.5% S. According to that model, prevailing southeastern air currents assure that vegetation at sites A, B, C, D, and E are most exposed to stack emissions whereas sites G and H (only 10–20 km east and northeast of the power generators), and sites F and I (120 and 170 km to the northwest) are less affected. Bromeliads at site I occur just a few km north of the city of Naples, a possible source of the additional S in the foliage of local *T. balbisiana* and *T. utriculata* which was elevated compared to populations of the same species at sites F, G, and H.

CONCLUSIONS

We conclude that the sampled epiphytic bromeliads had not been adversely affected by air pollution at the time of collection. However, continued surveillance of these populations is advisable and will be useful for three reasons: 1) identity of the subjects as vascular rather than nonvascular species, hence greater similarity to dominant native vegetation and crops than li-

TABLE 4. Survivorship of *Tillandsia paucifolia* seedlings approximately six months after sowing on cypress trees at three locations (two at site F). Most trees supported two test patches (A and B) of 48 seeds each.

	Tree number																	
	1		2		3		4		5		6		7		8		9	
Site	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
F_1	6	14	4	17	0	9	2	5	26	—	18	16	—	—	—	—	—	—
F_2	29	25	32	18	15	27	16	26	6	7	26	28	—	—	—	—	—	—
A	1	6	5	3	20	12	9	19	0	4	24	11	8	14	4	4	19	—
C	21	22	24	25	28	27	19	17	13	16	22	16	27	31	7	2	17	32

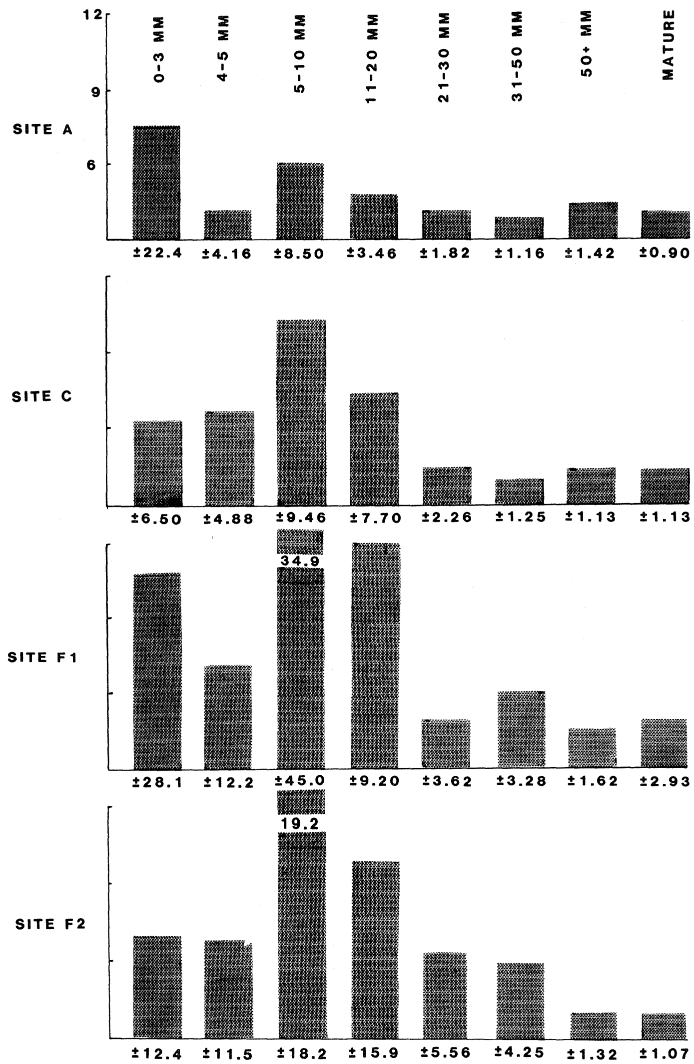

FIGURE 3. Life table distributions of *Tillandsia paucifolia* colonies in 10–13 cypress tree crowns at each of the three sites in south Florida. Numbers below bars are standard deviations.

chens; 2) biological equivalence to a number of rare and endangered epiphytic orchids and air plants in the ENP and the Big Cypress National Preserve; and 3) the likelihood of increased urbanization in south Florida. Data presented here constitute a reference for future assessments of air quality and related effects on important flora in subtropical Florida.

Acknowledgments

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