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QUARTERLY JOURNAL OF THE FLORIDA ACADEMY OF SCIENCES

DEAN F. MARTIN, *Editor* BARBARA B. MARTIN, *Co-Editor*

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Biological Sciences

LANDSCAPE AND SEASONAL INFLUENCES ON ROADKILL OF WILDLIFE IN SOUTHWEST FLORIDA

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ABSTRACT: *Vehicle-related mortality (roadkill) of vertebrate wildlife was recorded during a 24-mo. survey along 48-km (30-mi.) of paved highway that traveled through urbanized, agricultural, and native landscapes in southwest Florida. We recorded 1,035 vertebrate roadkills, with mammals accounting for the greatest percentage (54%) of total roadkill and raccoons (*Procyon lotor*) and other medium-sized mammals being the most frequently recorded species. Roadkill of herptiles (15%), which primarily were snakes, and unidentified species (20%) were recorded at similar rates and birds (11%) had the fewest roadkills. Roadkill did not vary due to differences in traffic speed and volume, but did vary by land use with lowest roadkill recorded in urbanized areas and all rural land use categories having similar levels of roadkill. Roadkill varied by season for herptiles and unidentified species and corresponded to Florida's annual cycle of wet and dry seasons and the availability of standing water in roadside ditches and pasture wetlands. Landscape features associated with human-made structures at two locations along the route had significantly greater roadkill than expected. These included an area adjacent to a wildlife exclusion fence, where roadkill of herptiles and unidentified species was elevated, but the reasons for higher roadkill at this location were not clear. The greatest number of total roadkills, primarily mammals, was recorded in association with a canal crossing and included 12% of all mammal roadkills recorded during this study.*

Key Words: Bridges, roadkill, southwest Florida, waterways, wildlife fence

UNDERSTANDING the ecological effects of roads is becoming increasingly important as roads continue to spread throughout our human-dominated landscape (Forman, 2000; Hourdequin, 2000). Among other things, roads negatively influence wildlife populations through roadkill and by imposing limitations on animal movements (Forman and Alexander, 1998). The effects of roads on wildlife and other ecological parameters are influenced by traffic

TABLE 1. Location, land use, traffic volumes, and speed limits of roadkill survey route summarized by 5-km segments.

Survey segment	Land use	Traffic volume ($\bar{x}$ auto/day)	Speed limit (am/pm)
0–5 km US41–CR850	Mixed urban	30,000 (US41) 8,000 (CR850)	80/80 kph (50/50 mph)
6–10 km CR850	Mixed urban, forested	2,900	80/72 kph (50/45 mph)
11–15 km CR850	Forested	1,200	80/72 kph (50/45 mph)
16–20 km CR850	Forest/pasture	1,200	80/72 kph (50/45 mph)
21–25 km CR850	Forest/pasture	1,200	80/72 kph (50/45 mph)
26–30 km CR850	Forest/pasture, mixed rural	1,200	80/72 kph (50/45 mph)
31–35 km CR850	Mixed rural	1,200	80/80 kph (50/50 mph)
36–40 km CR850–SR82	Mixed rural	1,200 (CR850) 6,000 (SR82)	88/88 kph (55/55 mph)
41–45 km SR82	Citrus/agriculture	6,000	96/96 kph (60/60 mph)
46–48 km SR29	Citrus/agriculture	9,179	88/88 kph (55/55 mph)

volumes and speed, but also by landscape features such as habitats, land-use, and human-made structures (Clevenger and Waltho, 2000; Forman and Deblinger, 1998). Our objectives were to provide information on roadkill associated with landscape features and season along a 48-km survey route through various land uses in southwest Florida.

METHODS—We recorded vertebrate roadkills during weekday morning hours (0700–0830) along a 48-km (30-mi.) survey route from April 1996 to May 1998 in Lee (29 km) and Collier (19 km) counties in southwest Florida. Care was taken not to duplicate counts of the same animals during successive days. The rapid removal of roadkills by scavengers, particularly turkey vultures (*Cathartes aura*) and black vultures (*Coragyps atratus*), assisted in preventing duplicate counts. Mammals were recorded by species when possible, but all other vertebrates were pooled by major taxonomic group. Travel speed during surveys averaged approximately 80 kmh (50 mph), and only animals easily visible from the road were included in counts. Consequently, data represent the minimum number of vertebrates killed by vehicles.

The survey route was subdivided into 0.8-km (0.5-mi.) segments for data collection and analysis. We collected data for traffic volumes, speed limits, and defined 5 categories of land use to describe the survey route that, with exception of the initial 8 km, followed rural highways through a largely roadless region of agricultural and undeveloped lands (Table 1). Two human-made structural features of note occurred along the route. These included approximately 1 km of wildlife exclusion fence with underpass constructed to provide safe passage for wildlife through a forested wildlife corridor managed by the state, and a canal crossing over a canal that flows through mixed agricultural lands in proximity to the Corkscrew Regional Ecosystem Watershed conservation area (Fig. 1).

We used a general linear model (GLM) with log-transformed data to test effects of year

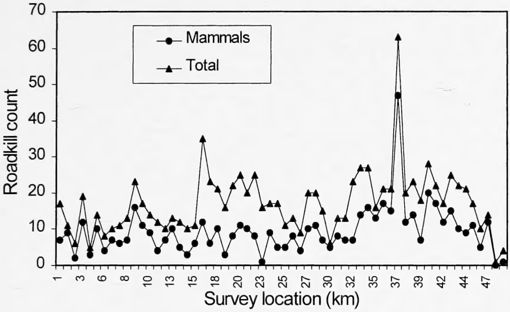

FIG. 1. Total roadkill (April 1996–May 1998) by 0.8 km (0.5 mi.) survey intervals.

of survey, land use, and a combined variable of speed limit and average traffic volume on total roadkill (data on traffic volume provided by the Florida Department of Transportation; Coggins, 2000). We created a combined variable of speed limit and average traffic volume (computational option of Statgraphics Plus version 2.1, Manugistics, Inc.) because speed limit varied little throughout the route and because traffic speed and volume operate synergistically on roadkill. We transformed the data based on inspection of residual plots of preliminary analyses (Sokal and Rohlf, 1981). Based on this analysis we tested effects of land use on roadkill using a one-way analysis of variance (ANOVA) with replication.

We tested for effects of season and taxonomic group (mammals, birds, herptiles, and unidentified wildlife) on roadkill with two-way ANOVA with replication. Interaction effects were interpreted by inspection of interaction plots between season and roadkill. We tested effects of season on roadkill separately within each taxonomic group using one-way ANOVA with replication. We tested for effects of location on roadkill for all 0.8 km segments along the survey route using one-way ANOVA with replication. Data were square root transformed for the two-way and one-way ANOVAs based on inspection of residual plots. All ANOVA tests used Fisher's least significant differences (LSD) method to make planned comparisons among means, Bartlett's test to check for compliance to assumptions of homogeneity of variance, and examination of skewness and kurtosis values to check for compliance to assumptions of normality. All GLM and ANOVA and associated tests were conducted with Statgraphics Plus version 2.1 (Manugistics, Inc.).

We combined data from both years of the survey and plotted roadkill along each km of the survey route for total roadkill and for mammals (Fig. 1). Based upon ANOVA results and visual examination of the graph, we identified two locations where roadkill appeared unusually high. These locations included km-16, which was located at the end of the wildlife exclusion fence, and km-37, which was located at the canal crossing on State Road 82 (Fig. 1). We used t-tests to compare roadkill at each of these locations against mean roadkill within each taxonomic group (Sokal and Rohlf, 1981:231). We excluded counts recorded from km-16 and km-37 when calculating sample means used in t-test comparisons.

RESULTS—We recorded 1,035 roadkills during 231 survey days in 1996–1997 (529 roadkills, 120 survey days) and 1997–1998 (506 roadkills, 111 survey days). Survey days per month averaged 10.0 (S.D. = 3.22) and 9.3 (S.D. = 2.49) during 1996–1997 and 1997–1998, respectively. Seasonal survey effort during 1996–1997 and 1997–1998 included 27 and 29 days during

TABLE 2. Multiple comparisons of means from analysis of variance (ANOVA) tests of land use, taxonomic group, and season on roadkill. Asterisks that do not align indicate significant differences among means within each respective test.

Test	Variable	Mean	S.E.	N	Homogenous groups
Total roadkill by land use (one-way ANOVA)	Urban	5.7	1.2	20	*
	Forested*	7.8	1.6	10	**
	Forest/pasture	9.7	1.0	30	*
	Citrus/agriculture	8.7	1.0	28	*
	Mixed rural	9.9	0.9	32	*
Total roadkill by taxonomic group (two-way ANOVA)	Birds	14.5	3.0	8	*
	Herptiles	19.5	3.0	8	**
	Unidentified spp.	24.0	3.0	8	*
	Mammals	70.0	3.0	8	*
Total roadkill by season (two-way ANOVA)	Dec–Feb	25.9	3.0	8	*
	Mar–May	30.0	3.0	8	**
	June–Aug	40.1	3.0	8	*
	Sept–Nov	33.4	3.0	8	**
Roadkill of herptiles by season (one-way ANOVA)	Dec–Feb	3.5	1.5	2	*
	Mar–May	22.0	5.0	2	**
	June–Aug	37.0	7.0	2	*
	Sept–Nov	15.5	9.5	2	**
Roadkill of unidentified species by season	Dec–Feb	11.5	1.5	2	*
	Mar–May	19.5	10.5	2	**
	June–Aug	43.5	5.5	2	*
	Sept–Nov	27.0	4.0	2	**

* Included some forested areas dominated by *Melaleuca quinquenervia,* an invasive exotic tree.

December–February, 30 and 26 days during March–May, 30 and 31 days during June–August, and 33 and 25 days during September–November, respectively.

Roadkill did not vary between years (F = 0.09, d.f. = 1, 117, P = 0.77) or due to differences in traffic speed and volume (F = 0.01, d.f. = 1, 117, P = 0.97), but did vary by land use (F = 3.38, d.f. = 4, 117, P = 0.01). Multiple comparisons among means revealed roadkill during the two-year period was significantly lower in the urbanized land use area along the initial portion of the survey route, but that roadkill in all other land use categories was similar (Table 2).

Total roadkill differed significantly among taxonomic groups (F = 49.54, d.f. = 3, 31, P < 0.01) and seasons (F = 6.71, d.f. = 3, 31, P < 0.01), with a significant interaction effect between these variables (F = 2.87, d.f. = 9, 31, P = 0.03). Examination of a plot of the interaction revealed the interaction was the result of similar but alternating levels of roadkill between herptiles and unidentified species during March–May and June–August. Multiple comparisons among means revealed mammals contributed the largest number of roadkills (54%), followed by unidentified roadkill (20%), herptiles (15%), and birds (11%) contributed the fewest roadkills

(Table 2). We recorded 16 species of mammals, most of which were mesomammals. Raccoons (*Procyon lotor,* 22%) and opossums *(Didelphis virginiana,* 14%) were the most frequently recorded species, with armadillos (*Dasypus novemcinctus,* 7%), cottontail rabbits (*Sylvilagus floridanus,* 4%), and otters (*Lutra canadensis,* 2%) less frequently observed. White-tailed deer (*Odocoileus virginianus*) exist at low densities in south Florida (Labisky et al., 1995; Smith et al., 1996) and were rarely (<1%) recorded during surveys. Snakes (11%) were the most frequently recorded herptiles. Most of the unidentified species were herptiles and small mammals.

Multiple comparisons among means revealed that seasonal differences in roadkill followed a pattern that mirrored the annual wet and dry seasons in Florida. Total roadkill was lowest during December–February, increased during March–May, was greatest during June–August, and declined during September–November as the rainy season came to an end (Table 2). Within taxonomic groups, roadkill did not differ significantly among seasons for either birds ($F = 1.55$, d.f. = 3, 7, $P = 0.33$) or mammals ($F = 1.27$, d.f. = 3, 7, $P = 0.40$). Both herptiles ($F = 5.20$, d.f. = 3, 7, $P = 0.07$) and unidentified species ($F = 3.94$, d.f. = 3, 7, $P = 0.11$) had P-values that suggested a seasonal effect. Multiple comparisons of means for herptiles and unidentified species revealed seasonal roadkill for both groups fluctuated according to seasonal rainfall patterns as did total roadkill, with the greatest number of roadkills recorded during June–August and the least number recorded during December–February (Table 2).

Total roadkill varied by location along the survey route ($F = 2.66$, d.f. = 59, 119, $P < 0.01$). Two locations, km-16 and km-37, had visible peaks in roadkill (Fig. 1). T-test comparisons of roadkill at location km-16 against survey means within each taxonomic group revealed significantly higher counts for total roadkill and roadkill of herptiles and unidentified species at this location (Table 3). Comparisons from location km-37 revealed significantly higher roadkill for total roadkill, mammals, and unidentified species (Table 3).

Discussion—The number of roadkills (1,035) recorded during this study must be considered a conservative estimate of the number of roadkills that actually occurred. Turkey vultures and black vultures, and to a lesser extent common and fish crows (*Corvus brachyrynchos, C. ossifragus*) and crested caracara (*Polyborus plancus*) rapidly scavenged roadkills, often dragging larger carcasses away from the road and carrying off smaller animals. Birds (11%) were the least and mammals (54%) were the most frequently recorded roadkills (Table 2), with medium-sized mammals (e.g., raccoons, opossums) accounting for 48% of total roadkill. Foster (1992) reported similar results along Interstate I-75 (Alligator Alley) in south Florida. That medium-sized mammals constituted the greatest percentage of recorded roadkills was presumably due both to the mixed rural landscape and roadside ditches that create habitat conditions conducive to generalist species such as raccoons

TABLE 3. Student's t-test comparisons of roadkill counts at locations km-16 and km-37 against survey means for each taxonomic group.

Survey location	Taxonomic group	Location roadkill	Mean roadkill	S.D.	t-statistic	d.f.	P
km-16 (end of wildlife exclusion fence)	Total roadkill	35	16.1	6.4	2.9	58	<0.01
	Mammals	12	8.6	4.4	0.8	58	0.43
	Birds	4	1.8	1.7	1.2	58	0.30
	Herptiles	11	2.7	2.7	3.1	58	<0.01
	Unidentified	9	3.2	2.0	2.3	58	0.03
km-37 (canal crossing)	Total roadkill	64	16.1	6.4	7.4	58	<0.01
	Mammals	47	8.6	4.4	8.6	58	<0.01
	Birds	5	1.8	1.7	1.8	58	0.08
	Herptiles	3	2.7	2.7	0.1	58	0.95
	Unidentified	9	3.2	2.0	2.8	58	<0.01

and opossums, as well as body size. Medium-sized mammals, such as raccoons, often are killed instantly by vehicles and possess sufficient body mass to remain relatively intact. Smaller animals may be rapidly removed by scavengers and larger animals, such as deer, may travel some distance from the road after being struck. Herptiles constituted 15% of total roadkill, of which 11% were snakes. High snake mortality also was recorded in other studies in south Florida (Foster, 1992; Bernardino and Dalrymple, 1992) and in Arizona (Rosen and Lowe, 1994). Unidentified species, which consisted primarily of herptiles and small mammals, contributed 20% of total roadkill.

Roadkill in this study was influenced by availability of wildlife habitat, season, and at least one human-made structure. Total roadkill was significantly lower along the urbanized portion of the survey route, but was similar among all other land use categories, which constituted a mix of different rural land uses (Table 1). That land use was lowest along the urban portion of the survey was presumably due to the scarcity of wildlife habitat and a corresponding scarcity of wildlife in that area. Although both speed and volume of traffic likely influence the ability of wildlife to safely cross roads, we found no significant effect of these variables on roadkill in this study. The lack of effect from traffic speed and volume was likely due to the fact that these variables did not differ greatly along the majority of the survey route, except in the most highly urbanized area (Table 1).

Seasonal patterns in roadkill followed the annual pattern of rainfall in southwest Florida (Table 2). Total roadkill was greatest during the rainy summer months of June–August, exhibited a declining trend during September–November as water in roadside ditches and flooded pastures subsided, was lowest during the dry winter months of December–February, and exhibited an increasing trend during March–May at the onset of the summer rainy season (Fig. 2). Not surprisingly, significant seasonal patterns within taxonomic groups were observed in herptiles and unidentified species, which were largely represented by herptiles, particularly amphibians (Table 2). Although not measured directly, the abundance of herptiles, particularly breeding amphibians and turtles, was observed to be greatly influenced by availability of water in roadside ditches.

Total roadkill at two locations along the survey route was significantly greater than the survey mean (Table 3). These included km-16, which was located at the end of an approximately 1-km wildlife exclusion fence and underpass, and km-37, which was a canal crossing on SR82, a busy rural highway (Fig. 3). Wildlife exclusion fencing has been widely implemented in conjunction with wildlife underpasses in Florida (Land and Lotz, 1996), often for the purpose of protecting endangered species including the Florida panther (*Puma concolor coryi*; Maehr et al., 1991). Wildlife underpasses have been demonstrated to promote safe crossing of roads by wildlife (Clevenger and Waltho, 2000; Foster and Humphrey, 1995) and limit roadkill, an important source of wildlife mortality among many species (Cristoffer, 1991; Trombulak and Frissell, 2000). Location km-16 was at the end of the wildlife

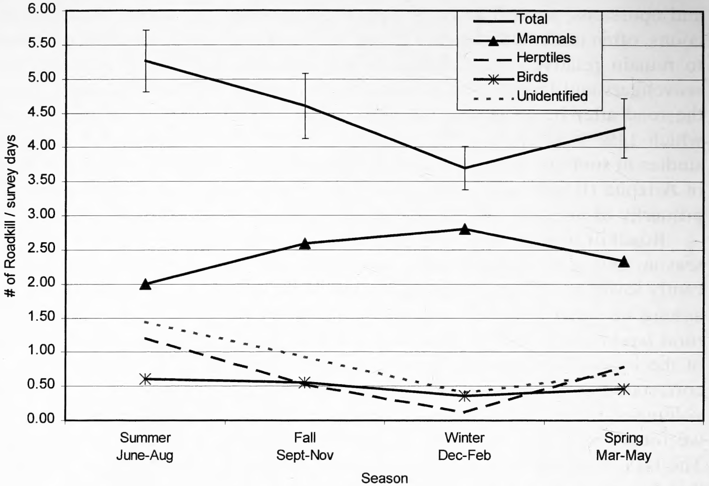

FIG. 2. Seasonal mean total roadkill/day with standard errors and mean roadkill/day by taxonomic group recorded along survey route during April 1996–May 1998.

exclusion fence, which terminated within the forested wildlife corridor. Our first suspicion, therefore, was that mammal crossings may have been concentrated at the end of the fence, but mammal roadkill did not differ significantly at this location (Table 3). Instead, the increased roadkill recorded at km-16 was due to increased roadkill of herptiles and unidentified species (Table 3). The reasons for elevated roadkill of herptiles (31% of total roadkill at km-16) and unidentified species (25% of total roadkill at km-16) was not clear. Snakes were the most commonly recorded roadkill at km-16 (23%) and although it is possible that the wildlife exclusion fence influenced where snakes crossed the road, this seems unlikely because snakes and most other herptiles could pass through the fence at any point.

Roadkill at the canal crossing (km-37) was more easily explained as a feature that concentrated wildlife crossings (Fig. 1). The canal crossing at this location was approximately 15 m wide and the canal travels through agricultural and undeveloped lands, including the 25,000 ha Corkscrew Regional Ecosystem Watershed conservation area. The canal serves as an important waterway and, apparently, as a landscape feature along which wildlife travel because roadkill was significantly higher at km-37 for mammals, unidentified species, and total counts (Table 3). Of particular note were the mammals, which included 8 species and constituted 73% of the total roadkill at this location and 12% of total mammal roadkill. Although raccoons (41%) and opossums (19%) were the most commonly recorded mammal roadkills at km-37, less frequently encountered species such as otter, bobcat (*Lynx rufus*), skunk (*Mephitis mephitis*), and the Big Cypress fox squirrel (*Sciurus niger*) also were recorded at this location. The lack of significance among roadkill of herptiles at km-37 was likely due to the fact that the canal crossing was elevated above the canal. The low P-value for birds (P = 0.08) at km-37 was interesting, but equivocal. A mature stand of slash pine (*Pinus elliottii*) exists along the road at km-37, but whether the pines or the canal influenced roadkill of birds at km-37 could not be determined. Our results, however, did indicate that the canal crossing at km-37 was an important landscape feature that concentrated wildlife crossings and increased roadkills, particularly among mammals.

Evaluating the effects of waterway crossings, other human-made structures, and natural landscape features that concentrate wildlife crossings will become increasingly important for reducing roadkill as new and busier roadways continue to be constructed and wildlife movements become increasingly concentrated due to declining habitat connectivity (Forman, 2000; Noss and Cooperrider, 1994). Waterways and other landscape features have been reported to concentrate the movement and crossing of roads by wildlife, thereby creating localized areas with high rates of roadkill, and identifying landscape features that concentrate wildlife crossings is the first step in identifying strategies to limit roadkill (Forman and Deblinger, 1998). Roadkill recorded during this study was significantly greater at a canal crossing on a busy rural highway, which suggests additional study of wildlife mortality at waterway crossings in Florida is warranted as is investigation of potential measures to reduce roadkill at these locations.

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USE OF PLANT CLIMATIC ENVELOPES TO DESIGN A MONITORING SYSTEM FOR EARLY BIOTIC EFFECTS OF CLIMATIC WARMING

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Abstract: *The climatic space within which a species survives and reproduces under natural conditions, i.e., its "climatic envelope," offers a relatively simple means for designing a system to monitor early biotic effects of climatic warming. The predicted loss of some part of a temperate plant species' climatic envelope from a certain area under a warming scenario identifies that area as a place where the species may be expected to lose fitness and eventually a part of its natural range. Monitoring fitness components of woody temperate species at sites within areas predicted to show large negative responses to 1°C annual warming provides an opportunity for early detection of negative impacts that may be greater with additional warming (e.g., 2°C). If a species is an ecologically important component of a major ecosystem, some potential loss of that ecosystem's integrity will also be expected. A number of sites where warming-induced envelope losses are predicted for one or more temperate species can then be identified as desirable parts of a monitoring system. An example involving six native, temperate, ecologically important, woody plant species, three 1°C annual warming scenarios, and a diverse group of major natural ecosystems is presented for Florida. In addition, monitoring sites for detection of warming induced increases in fitness of seven ecologically important, woody sub-tropical species are proposed, based on the northern boundaries of their current natural ranges. Florida's large and diverse system of conservation lands provides numerous protected areas in which selected species can be monitored over time for early indications of fitness change associated with a warming trend. Field inventories of these areas will be needed subsequently to select those most suitable for monitoring adequate stands and/or numbers of the proposed species.*

Key Words: Climatic envelope, climatic warming, monitoring, Florida, native trees

The climatic envelope of a plant species refers to the climatic bounds within which the species can grow and reproduce under natural conditions. The Florida Plant Species—Climatic Envelope Model, hereafter referred to as the Florida Model, establishes empirically determined climatic boundaries for 124 of the most common and/or characteristic native woody plant species in Florida (Box et al., 1993, 1999). These boundaries involve a number of potentially important temperature and precipitation variables for which long-term means can be obtained with relative ease from climatic databases. The

TABLE 1. Climatic envelope for *Magnolia grandiflora* L. (southern magnolia) in the Florida Plant Species–Climatic Envelope Model.

	TMAX	TMIN	DTY	TMMIN	TABMIN	PRCP	MI	PMIN
Maximum	28.5	17.5	28.0	20.0	17.5	*	*	*
Minimum	13.0	10.0	4.0	2.0	−20.0	600.0	0.92	30.0

The region of potential occurrence of a species is described by its climatic envelope which is defined by limiting maximum and minimum values for the following eight climatic variables:

TMAX	=	mean temperature of the warmest month (°C)
TMIN	=	mean temperature of the coldest month (°C)
DTY	=	annual range of monthly mean temperature (°C)
TMMIN	=	mean minimum temperature of the coldest month (°C)
TABMIN	=	absolute minimum temperature (°C)
PRCP	=	average annual precipitation (mm)
MI	=	annual moisture index (PRCP ÷ average annual potential evapotranspiration or PET), based on the Holdridge estimate of PET, which is obtained as TMEAN (mean annual temperature) × 58.93; (see Holdridge, 1959 and Box, 1986)
PMIN	=	average precipitation of the driest month (mm)

* Refers to unspecified and presumably unimportant (unattainable) limiting values.

Florida Model assumes a species can grow and reproduce at a site under natural conditions as long as none of the climatic variables at the site exceeds either its upper or lower limit for that species in the model (Table 1). The geographic range associated with the limiting climatic values for a species then becomes a prediction of the species natural range based only on climate. Thus, the predicted loss of some part of the climatic envelope of a woody temperate species in Florida, as a result of climatic warming, establishes the location of that envelope loss as a potentially useful area in which to monitor for early, negative biotic effects of warming on that species. The location of predicted gain in a woody subtropical species envelope could be used similarly to monitor for early, positive biotic effects of warming on that species, provided that the species was successfully moving into its newly expanded envelope. ("Subtropical" refers to the Florida range type of a certain species and is essentially synonymous with the "tropical" species designation of Little, 1978). In the present report, we use the locations of predicted climatic-envelope loss for 6 temperate tree species in the Florida Model to illustrate the basis for a monitoring system to detect negative biotic effects of climatic warming. The envelope losses are associated with three different 1°C annual warming scenarios. Additionally, we use existing main northern, natural range boundaries of 7 subtropical tree species as suggested locations for monitoring positive biotic effects of warming. Trees are especially useful organisms for monitoring climatic change because larger individuals are often easy to identify, not easily removed from protected areas such as those recommended for monitoring sites, and relatively long-lived.

The use of climatic-envelope models to locate terrestrial vegetation and plant taxa has been reviewed by Box and co-workers (1999). The method dates back at least to Holdridge (1947). Some more recent examples include the mapping of predicted changes in Holdridge life zones in Florida as a result of climatic change (Dohrenwend and Harris, 1975; Harris and Cropper, 1992); prediction of world vegetation structure and its sensitivity to climatic change (Box, 1981); prediction of worldwide shifts in Holdridge life zones based on climatic-change predictions for a 2 × CO_2 (equivalent doubling of global atmospheric CO_2 concentration) scenario (Emanuel et al., 1985a, b); and prediction of climatic envelopes for 15,148 native North American vascular plant species under a 3°C warming scenario (Morse et al., 1993). The relatively simple, geo-correlational approach of plant climatic-envelope modeling permits the simultaneous analysis of many species whose range-limiting mechanisms are poorly known. This, in turn, permits predictions of regional changes in species richness and important components of ecosystem structure (Crumpacker et al., 2001a,b). Confidence in the utility of any model depends on an understanding of its structure and the extent to which it provides rational and testable explanations of phenomena to which it applies. We therefore begin by presenting a reasonably detailed description of assumptions on which the Florida Model is based and results of a number of tests, some previously unpublished, that support its usefulness.

Model Assumptions, Limitations, and Supporting Evidence—The Florida Model is deterministic because it contains one set of climatic limits for each species and different model runs using these limits do not vary due to stochastic effects. It is an equilibrium model because, for a certain climatic-warming scenario, it predicts the location of a species climatic envelope after the climatic change has occurred and the new geographic dimensions of the envelope have been established and adjusted to by the species. The climate at all sites in the Florida Model is assumed to respond similarly to each warming scenario because Florida is a relatively small region in a typical global GCM (General Circulation Model) simulation of climatic change. GCM simulations were used as an aid in determining climatic-change scenarios to use with the Florida Model (Box et al., 1999).

Because equilibrium associated with a warming scenario is assumed in the Florida Model, predicted decreases in temperate species envelopes may be more useful to monitor than increases in subtropical species envelopes. This is because the former would involve only in-situ envelope contraction while the latter would also require successful movement of a subtropical species into its newly expanded envelope. Warming-associated fitness decreases in temperate species and increases in subtropical species might, however, be detectable in regions of predicted envelope loss or gain well in advance of their associated range losses or gains.

Due to its strongly empirical nature, the Florida Model should be used with warming scenarios which involve temperature and moisture changes that do not extrapolate beyond the range of these variables in the climatic database used to build the model. All sites in the Model except a few in

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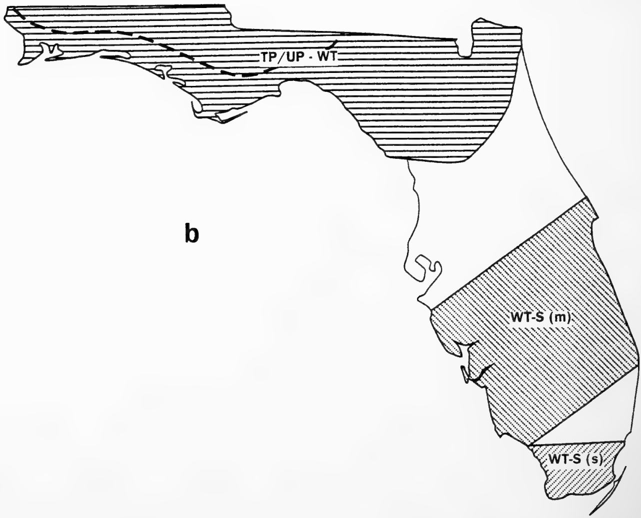

b

FIG. 1. Important boundaries and transition zones for natural range types of 112 native woody plant species in the Florida Plant Species—Climatic-Envelope Model (reproduced from Crumpacker et al., 2001b); these species are (1) not restricted to coastal areas, and (2) do not include the 5 Warm Temperate—Subtropical species listed on p. 164 of the present report (also see Box et al., 1999; Crumpacker et al., 2001c). Species natural range types, with numbers of species in parenthesis, are as follows: Temperate Panhandle and/or Upper Peninsula (TP/UP)—

south Florida (mostly the lower Keys) satisfy this requirement with respect to the scenarios used in this report.

Thirty-six sites located throughout Florida, each associated with a weather station, were used to provide baseline climatic data for building and testing the Florida Model (Box et al., 1993, Fig. 1). The sites were mostly elliptical, with an average area equivalent to that of a circle of radius 28 km around the weather station. The totality of sites covered most of the state. The model was found to predict baseline presence or absence of a species at 21 sites used to develop the model with a median accuracy of 87% per site (range of 98%–71%), and at 15 sites not used in development of the model, but held out for testing, with a median accuracy of 85% (range of 92%–60%). The median accuracy of prediction to within 100 km of a site was 96% (range of 100%–84%) for sites used to develop the model and 97% (range of 100%–87%) for those used in testing it. Conversely, the ability of the model to predict natural ranges of individual species in terms of correct presence or absence of 44 species of special ecological importance gave a median prediction accuracy of 88% per species (range of 100%–67%) and of 100% to within 100 km of a site (range of 100%–67%). Additional analyses of discrepancies between predicted species ranges and those mapped by Little (1978) indicated that many discrepancies were close to agreeing with Little, when using the criterion of "accurate to within 100 km of a site" (Box et al., 1993). Maps used in subsequent reports were, therefore, divided into 100 km grid cells to provide a generally accurate scale of reference for cartographic presentation of predicted envelope changes.

As with other types of models for relating plant or vegetative taxa to predicted climatic change, it is impossible to achieve unambiguous validation of climatic-envelope models. This could only be done by first providing enough time for development of the full ecosystem response to climatic change, including slow-responding, nonlinear mechanisms that may domi-

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extending from the north southward into parts or all of the Florida panhandle and/or upper peninsula (28); Warm Temperate (WT)—extending from the north southward into much or most of Florida but usually not significantly south of Lake Okeechobee (53); Subtropical (S)—extending from the Keys and Caribbean Islands northward into parts or all of the lower to central peninsula (31).

(a) Southern range boundaries of TP/UP species (see Appendix to Crumpacker et al., 2001b for list of species and Little, 1978 for range maps).

(b) TP/UP—WT species transition zone shown in the northern horizontally barred area, with the broken line designating the area of maximum southern range boundary concentration of TP/UP species; transition zone portion above the broken line is similar to Southern Mixed Hardwood Forest Zone of Greller (1980), clayhill portion of high pine zone of Myers (1990), and Mixed Hardwood and Pine ecological community of the USDA Soil Conservation Service (1981). Major (m) and secondary (s) WT-S species transition zones (Crumpacker et al., 2001c) shown in the southern hatched areas.

nate long-term behavior. Instead, Rastetter (1996) has suggested that confidence in models of ecosystem response to global change "has to be built through the accumulation of fairly weak corroborating evidence rather than through a few crucial and unambiguous tests." The real importance of such a model derives from its internal consistency, and its ability to be consistent with, and synthesize, all empirical sources of relevant evidence. In this way, a climatic-envelope model can become an important part of an overall evaluation of the response of species and ecosystems to global change.

The above-described assessment of the Florida Model's ability to predict species locations based on climatic values at sites used to construct the model is a type of internal consistency test which checks the Model's ability to reconstruct the species-climatic associations on which it is based. The assessment of ability to predict species presence or absence at sites not used in developing the Model, but which have climatic values within the range of the model's climatic database, provides a more stringent test. Other types of evidence also provide support for the Model's usefulness. While it predicts that warming without drying will usually constrict temperate and enlarge subtropical species envelopes, most exceptions have rational explanations. Temperate species which exhibit less envelope constriction in the Model under disproportionately greater winter warming than under seasonally equal warming are often evergreen or semi-evergreen, and thus adapted to some extent for winter growth. Temperate species which show some envelope increase with warming that includes drying tend to be those which are adapted to the dry soils of central Florida. The Model predicts that five species referred to by Little (1978) as temperate will undergo some envelope increase with warming. Additional investigation indicated that most relatives of these species have tropical or subtropical range types. These species, which were subsequently reclassified as "warm temperate—subtropical," include *Cyrilla racemiflora* L., *Erythrina herbacea* L., *Cliftonia monophylla* (Lam.) Britton, *Sabal palmetto* (Walt.) Lodd., and *Serenoa repens* (Bartr.) Small.

Up to 2°C warming, with no change in the baseline moisture index, MI (ratio of average annual precipitation to average annual potential evapotranspiration; see Table 1), the Florida Model predicts a northward rate of movement of 100 km per 1°C increase for (1) the major Warm Temperate—Subtropical transition zone of native plant species in the southern half of the Florida peninsula (Fig. 1), and (2) the mean northern boundary of 6 important subtropical coastal species along the Atlantic Coast (Crumpacker et al., 2001c). The major Warm Temperate—Subtropical transition zone is based on 112 species whose natural ranges are not restricted to coastal locations. This predicted northward movement agrees well with the approximate rate of mean northward cooling in the United States of 1°C per 98 km that occurs from Texas to North Dakota (which, like the south-north gradient along much of the interior Florida peninsula, allows elevation and moisture to be held relatively constant). This shows that the Model can associate

TABLE 2. Scenarios used with the Florida Plant Species–Climatic Envelope Model to develop the monitoring system (see Box et al, 1999 for more details, and other scenarios used with the Model).

Scenario	Comments
T	Baseline mean annual temperature; obtained mostly from climatic data over the first 2/3 of the 20th century; used as a standard for all other scenario comparisons;
T + 1	1°C increase in mean annual temperature applied equally to each month, with a 5% increase in average annual precipitation to hold the baseline climatic moisture balance or "moisture index" (MI in Table 1) approximately constant;
T + 1w	Same as T + 1 but with disproportionately more winter and less summer warming (i.e., winter-enhanced warming, as indicated by the w);
T + 1 (80)	Same as T + 1 but with only 80% of average annual precipitation (i.e., with a lower MI).

species locations with temperature, and then predict species movements under warming that agree with a well established, relatively analogous, climatic gradient.

The Florida Model predicts the general types of woody species and vegetation for two sites that are, respectively, outside the spatial and temporal database used to construct the Model. These situations are relatively similar to the "space-for-time" and "reconstruction of the past" tests that can be used to help evaluate models of ecosystem response to global climatic change (Rastetter, 1996). In the first situation, the Model predicts that a 1°C rise in temperature accompanied by only 80% of average annual precipitation, i.e. scenario "T+1 (80)" (Table 2), will cause the Key West area to lose 92% of its model species whose ranges are not restricted to coastal areas; this compares with no loss under the T+1 scenario which maintains the baseline moisture balance between average annual precipitation and temperature by allowing precipitation to rise with temperature (Crumpacker et al., 2001a, Fig. 2). This loss occurs because T+1 (80) causes the MI (moisture index) value at Key West to fall below its lower limit for nearly all model species. The T+1 (80) scenario produces a droughtier climate at Key West than exists anywhere north of that point in Florida. However, the Dry Tortugas, a group of small Florida islands approximately 109 miles farther west, provides a "space-for-space" (somewhat similar to a "space-for-time") substitution. These islands have an annual precipitation that is 13% less than Key West [from a calculation based on precipitation values provided by Davis (1942) who also noted that the temperature difference between the two sites is "much less significant"]. This indicates a drier and possibly warmer situation in the Dry Tortugas than currently exists at Key West and provides an approximation to the T+1 (80) scenario for Key West. Davis described the native vegetation of the Dry Tortugas as predominately herbaceous except for some stands of mangroves and a few subtropical

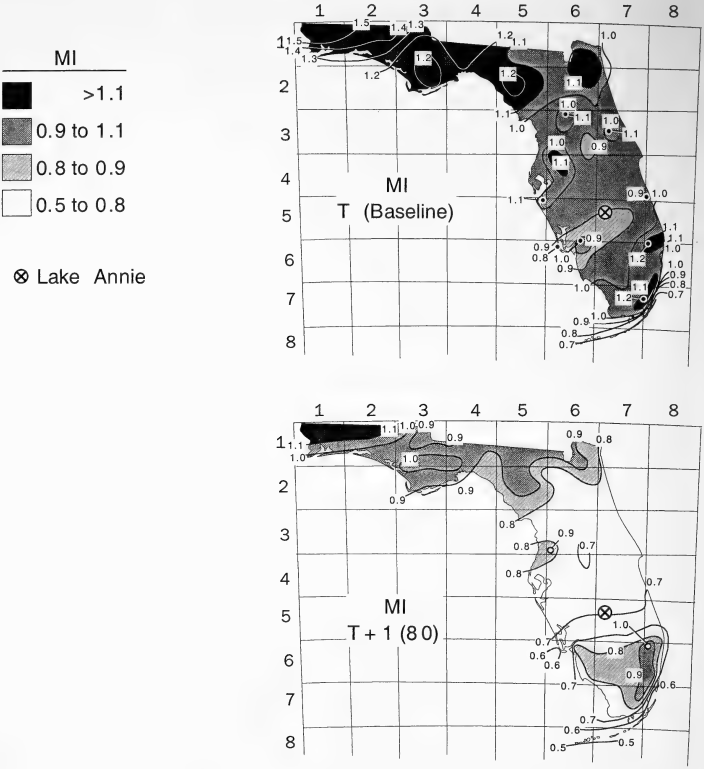


FIG. 2. Florida moisture index (MI) values for the T (baseline) and T+1 (80) scenarios (see Table 1 for definition of MI and Table 2 for explanation of scenarios). Maps are divided into 100 km × 100 km grid cells. Predicted association of range of MI values with major vegetation types is as follows: MI > 1.1, closed forest; from 0.9 to 1.1, open to closed forest, depending on substrate; from 0.8 to 0.9, open woodland or savanna forest; from 0.5 to 0.8, scrub or savanna (values are adapted from Box, 1987, are based solely on climate, and require adjustment for special topo-edaphic, topo-hydrologic, and pyric conditions). Lake Annie is the location of Watts' 1975 analysis of pollen deposits from the the earlier part of the Holocene, described on p. 167 of the present report.

shrubs [which species were not analyzed in the Florida Model for drier scenarios such as T+1 (80)]. Davis noted further that the drier conditions for plants in the Dry Tortugas, due both to low rainfall and coarse soils, probably prevents the development of hammock (forest) vegetation. His report is, therefore, consistent with the virtual absence of woody vegetation predicted by the Florida Model for Key West under the T+1 (80) scenario.

A "reconstruction of the past" test is provided by comparing the vegetation type and flora predicted by the Florida Model for the vicinity of Lake Placid in south-central Florida with an independent prediction for the same general location by Watts (1975), who analyzed pollen deposits from Lake Annie for the earlier part of the Holocene (from 13,010 BP to 4,715 BP). The T+1 (80) scenario is again of special interest because the global mean temperature may have been 1°C higher in the earlier part of the Holocene than it is today (Webb and Wigley, 1985, cited in Webb, 1992; also cf. Florida part of 9 ka, 6 ka, and 0 ka mean January and July temperature maps in Fig. 5.4 of Webb, 1992 for an indication of previously warmer conditions 6,000 years ago). In addition, the mean annual precipitation may have been about 15% less (cf. Florida part of 9 ka, 6 ka, and 0 ka mean January and July precipitation maps in Fig. 5.4 of Webb, 1992). Watts' prediction for the earlier part of the Holocene of an "upland oak scrub and prairie" in the area around Lake Annie fits well with the Florida Model's prediction of "scrub or savanna" under the T+1 (80) scenario (Fig. 2). Watts' 1975 report of pollen data for woody plants indicated a relatively high amount of oak compared to pine for the middle part of the period between 13,010 BP and 4,715 BP. For scenario T+1 (80), the Florida Model's prediction of 5 *Quercus*: 1 *Pinus* species is consistent with Watts' report of a preponderance of oak compared to pine pollen. The Florida Model predicts a current or "baseline" ratio of 3 *Quercus*: 1 *Pinus* in the vicinity of Lake Placid, which agrees well with the modern species ranges depicted in Little (1978). Thus, the Florida Model predicts a vegetative and floristic situation in the south-central Florida peninsula that is consistent with the current climatic situation and with a palynological analysis of what was probably a warmer and dryer climate 6,000 to 9,000 years ago.

METHODS—The earliest detection of warming effects on temperate species might be expected to occur near their southern range boundaries where the increased temperatures would generally be highest. Several Florida areas which contain concentrations of southern range boundaries of native temperate species are shown in Fig. 1. If, however, a temperate species contains temperature-sensitive ecotypes along a north-south gradient, warming induced fitness losses may occur simultaneously throughout its range. That is, an ecotype adapted to the cooler northern part of its species range might be just as sensitive to a 1°C increase that occurs throughout the species range as a "southern" ecotype. Although good evidence of such ecotypic variation is generally lacking for Florida plant species, the state has an approximate 11°C north-south, nighttime winter temperature gradient (Box et al., 1999, Fig. 2), and there is strong empirical evidence for an association between environmental and genetic heterogeneity in natural plant populations (Linhart and Grant, 1996). Furthermore, photoperiodic ecotypes of many woody species along north-south gradients are known (Kozlowski et al., 1991). Relatively rapid change in temperature at a site that is not accompanied by change in a related photoperiodic cue could, therefore, cause higher temperatures to occur during processes such as flowering and dormancy.

Natural range types, together with climatic envelopes predicted by the Florida Model for

6 temperate species under the baseline scenario (T) and three 1°C climatic-warming scenarios, are shown (Fig. 3). These species are suggested as components of a monitoring system to detect biotic effects of warming for the following reasons:

First, they involve different temperate species range types and have southern range boundaries that, collectively, represent each of the various areas of maximum southern range boundary concentration of Florida Model species shown in Figure 1;

Second, as discussed under Results, each species is predicted to undergo some of the largest climatic-envelope losses among the species in its range type, with respect to the type of 1°C warming with which it is paired (see Fig. 4 in Results).

Third, each species is ecologically important, and some are physiognomically dominant, in at least some stages of one or more major vegetated ecosystems of Florida (Crumpacker et al., 2001b).

With respect to the first reason above, the locations of predicted envelope loss of the six species suggest an array of monitoring sites, each of which occurs near the southern range boundary of one or more of the species, where the highest temperatures and the most pronounced effects of warming on those species might occur. With respect to the second reason, the relatively large areas of predicted envelope loss for these species, in regard to their respective range types, offer additional sites for monitoring (discussed under Results). If temperature and/or photoperiod ecotypes do, in fact, commonly occur in Florida woody species, the large predicted range of north-south envelope loss for *Magnolia grandiflora* L. and *Taxodium distichum* (L.) Rich., under the respective scenarios with which they are paired (in Fig. 4 in Results), provides opportunities to detect negative impacts of warming at monitoring sites along an extensive north-south gradient. With respect to the third reason, detection of negative warming effects in any of the 6 species-scenario combinations (see Fig. 4 in Results) would be a warning that more extensive, negative impacts to one or more major ecosystem types might also be expected to occur. Examples of such important species-ecosystem associations are as follows: *Pinus echinata* Mill. (shortleaf pine) and *Magnolia grandiflora* L. (southern magnolia) in Mixed Hardwood and Pine; *M. grandiflora* in Upland Hardwood Hammocks, Wetland Hardwood Hammocks, and North Florida Coastal Strand; *Salix nigra* Marsh (black willow) and *Quercus michauxii* Nutt. (swamp chestnut oak) in Bottomland Hardwoods; *Quercus laevis* Walt. (turkey oak) in Longleaf Pine—Turkey Oak Hills; and *Taxodium distichum* (bald cypress, including *T. distichum* var. *nutans*) in Cypress Swamp, Swamp Hardwoods, and Scrub Cypress. Relationship of these ecosystems, which are based primarily on the USDA Soil Conservation Service's 1981 classification, to other Florida ecosystem classifications is discussed in Crumpacker et al. (2001b).

Temperate species such as the gymnosperms *Torreya taxifolia* Arn. and *Taxus floridana* Nutt., that are endangered or threatened endemics in the upper Apalachicola River bluffs and ravines of the Florida Panhandle (Ward, 1979), might also be useful for monitoring biotic effects of climatic warming. Rare species such as these could be good monitoring candidates if they were among the first species to lose fitness in situ and move north with warming. Because our original intent was to consider common native species in the Florida Model, only a few rare species were included. Only one, *Kalmia latifolia* L. is temperate and it occurs commonly in other parts of the eastern U.S. The others are subtropical palms whose populations have been largely removed as a result of human development activities in south Florida. Rare temperate endemics may, however, be strongly limited by other factors less directly related to climate, such as disease (e.g., *T. taxifolia;* see Ward, 1979). Thus, they may be unable to undergo significant fitness increases and northward range extensions under relatively rapid warming. They also do not provide extensive spatial opportunities to detect ecotypic responses to warming or an increased potential for impending, major negative impacts to whole ecosystems.

Some of the more common subtropical Model species, such as *Bursera simaruba* (L.) Sarg., *Coccoloba diversifolia* Jacq., *Ficus aurea* Nutt., and *Eugenia axillaris* (Sw.) Willd. in Florida Tropical Hammocks, are important species to monitor for warming-induced fitness increases in one or both of the warm-temperate—subtropical transition zones (Fig. 1).

Use of 1°C scenarios (Table 2) provides an opportunity to detect biological responses to

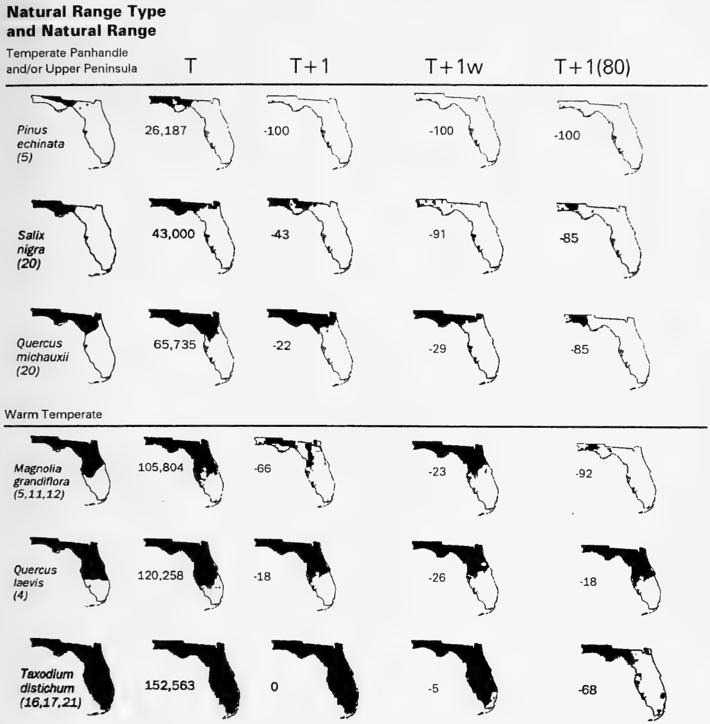
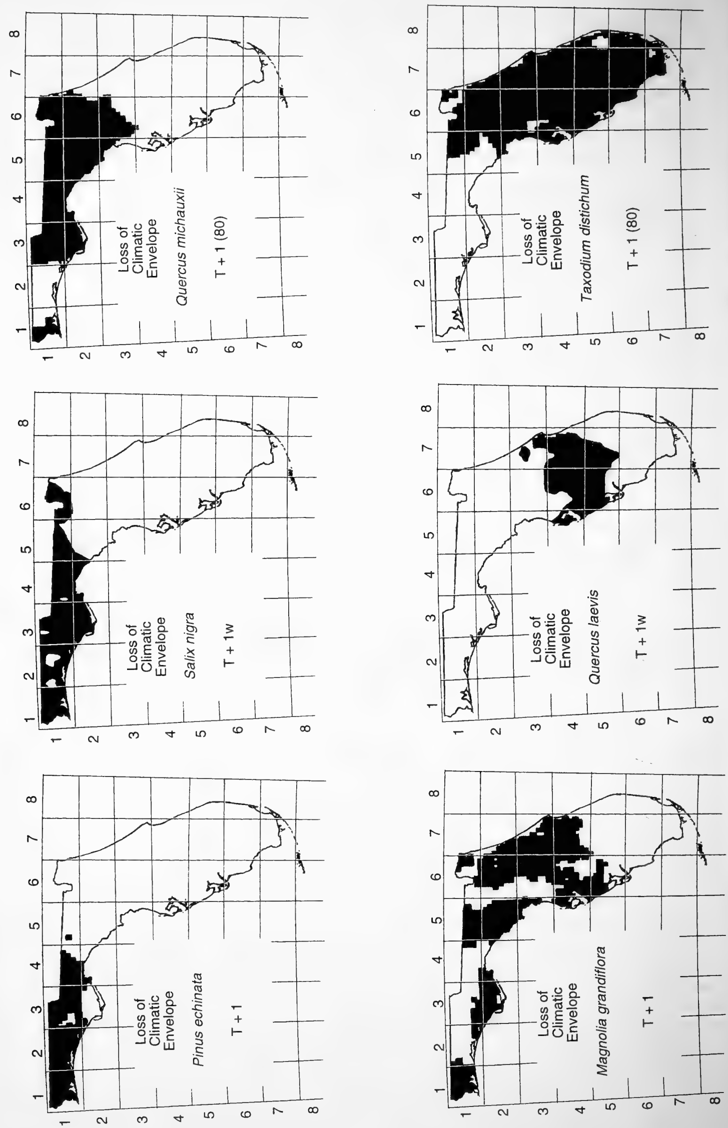


FIG. 3. Effects of three 1°C warming scenarios, T+1, T+1w, and T+1 (80), on climatic envelopes of 6 ecologically important temperate species, as predicted by the Florida Plant Species—Climatic Envelope Model. See legend to Fig. 1 for definition of species natural range types and Table 2 for explanation of scenarios. Adapted partly from Fig. 4 and Table III of Box and co-workers (1999). Black areas are species natural ranges in maps of the left-most column (from Little, 1978), and predicted climatic envelopes in maps of the remaining columns. Parenthetical numbers in the left-most column refer to the major plant communities in which each species is ecologically important, as described by the UDSA Soil Conservation Service (1981) and explained further by Crumpacker et al. (2001b). Numbers in the T column are areas in square kilometers for "baseline" species climatic envelopes in Florida predicted by the Florida Model, using only baseline climatic information. The baseline envelopes are in general agreement with the species natural ranges, as discussed in the text. Numbers shown with each species-scenario map represent predicted % change in area from the T scenario. For example, scenario T+1 reduces the baseline Florida climatic envelope of *P. echinata* by 100% (from 26,187 to 0 sq. km.), and that of *S. nigra* by 43%.


Loss of Climatic Envelope
Quercus michauxii
T + 1 (80)
Loss of Climatic Envelope
Taxodium distichum
T + 1 (80)
Loss of Climatic Envelope
Salix nigra
T + 1w
Loss of Climatic Envelope
Quercus laevis
T + 1w
Loss of Climatic Envelope
Pinus echinata
T + 1
Loss of Climatic Envelope
Magnolia grandiflora
T + 1
1
2
3
4
5
6
7
8

warming at the low end of the range of global mean surface warming estimates provided by the Intergovernmental Panel on Climate Change or "IPCC" (+1°C to +3.5°C by the year 2100, Houghton et al., 1996; subsequently amended to +1.4°C to +5.8°C; see Intergovernmental Panel on Climate Change, 2001). If warming were to increase gradually to 2°C or more, early detection of 1°C warming effects might provide time and impetus for implementation of mitigations before more serious impacts to biodiversity occurred. In this respect, the Florida Model generally predicts much larger envelope loss of temperate species under +2°C than under otherwise similar +1°C scenarios (Box et al., 1999, Fig. 4 and Table III). A disproportionately larger envelope loss is also predicted in the later stages of drying between scenarios T+1 and T+1 (80) (Crumpacker, Box, and Hardin, unpublished). The above mentioned mitigations for warming might include protection of critical landscape linkages, prescribed burning to reduce fuel accumulation, curtailment of land drainage and natural vegetation removal, and control of non-native species introductions and invasions (for additional examples, see Crumpacker et al., 2001a, b, c).

Support for scenario T+1w comes from two of the three General Circulation Model (GCM) projections for an equivalent doubled CO_2 or "2xCO_2" climate in the southeastern United States, as surveyed by Smith and Tirpak (1989) and, more generally, from the IPCC's tentative conclusion that global warming will lead to a decrease in winter days with extremely low temperatures (Kattenberg et al., 1996). Higher minimum temperatures have subsequently been projected for nearly all land areas (Intergovernmental Panel on Climate Change, 2001).

Support for T+1 (80) is derived from the following sources:

(1) the same three GCM projections from Smith and Tirpak referred to above; each of these projections indicated a drier average, annual climate for the southeastern U.S. and one indicated a 16% decrease in average summer precipitation;

(2) preliminary results of Neilson and Marks (1994) which suggest that, under a 2xCO_2 climate, eastern North America would be one of two global areas most sensitive to drought-induced forest decline; and

(3) linkage of the BIOME2 model (which simulates geographic distribution of major vegetation types based partly on climatic variables such as temperature, moisture, and light) to the GFDL R30 GCM (which provides climatic scenarios that can be used with biome models), under a $2 \times C0_2$ climate; this linkage predicts conversion of temperate peninsular Florida from a warm-temperate forest biome to a more arid mixture of grassland and forest biomes (Melillo et al., 1996); and

(4) the Canadian Climate Centre's 21st Century Model which predicts decreased precipitation in most of Florida, combined with a temperature increase (National Assessment Synthesis Team, 2000).

Continued conversion of natural landscapes to urban and agricultural lands may alter future weather patterns to cause even more drying. Average summer rainfall in south Florida may have decreased by as much as 11% from such causes over the past 100 years (Pielke et al, 1999).

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FIG. 4. Maps showing predicted loss of species climatic envelopes from Florida for 6 combinations of ecologically important temperate species and 1°C annual climatic warming scenarios. These combinations were selected from the 18 possible species—climatic-warming scenario combinations in Fig. 3 because they involve some of the largest % losses for their respective range types in different parts of Florida, as discussed in the text. *The envelope losses are shown in black, as opposed to white in Fig. 3, for easier use in locating the losses and, hence, potential monitoring sites.*

RESULTS—Predicted losses in baseline (T) climatic envelopes of the temperate species suggested previously for monitoring are shown in Figure 4 for 6 combinations of species and 1°C warming scenarios. Each scenario represents a change from the mean annual baseline temperature scenario, T. The black areas in each of the maps represent those parts of a species' climatic envelope which are predicted (Fig. 3) to be lost under one of the 3 scenarios. In the upper left-hand map of Figure 4, e. g., T+1 is predicted to remove those parts of the baseline envelope of *P. echinata* that are shown in black in the 100 km × 100 km grid cells 1,1; 1,2; 1,3; 1,4; 1,5; 2,2; 2,3; and 2,4 (where 1,2 refers to row 1, column 2, etc.). Comparison of these black areas with the baseline (T) map for *P. echinata* in Fiure 3 shows that scenario T+1 has removed the entire baseline envelope of *P. echinata.* A similar comparison of the black areas in Figure 4 for *T. distichum* under scenario T+1 (80) with the T map of *T. distichum* in Figure 3 shows that T+1 (80) has removed almost all of the peninsular part of that species' envelope which presently covers all of Florida except the Keys.

For purposes of this report, the most important significance of the black areas in the Figure 4 maps is that they represent locations where various monitoring sites for species might be located. In addition, they represent areas of predicted loss in integrity (Crumpacker et al., 2001b) for important parts of major ecosystems in which the species are ecologically important. The maps in Figure 4 can be used in conjunction with the Landsat landcover and proposed strategic habitat conservation area maps in Cox and co-workers (1994), various ecosystem maps listed in Crumpacker and co-workers (2001b), and the maps and descriptions of Florida conservation lands by Jue and co-workers (2001). Together, these maps and descriptions of conservation lands can be used to suggest examples of sites for inclusion in a comprehensive system to monitor for biotic effects of climatic warming. The subsequent choice of actual sites would require field investigations to determine if stands and/or numbers of individuals of species suitable for monitoring occur in the conservation lands cited below. Privately owned lands protected by conservation easements or other suitable management agreements, but not included in Jue and co-workers' 2001 list of Florida conservation lands, might also provide useful long-term monitoring sites (see Discussion).

In Florida, *P. echinata* and *S. nigra* are located at the southeastern boundary of their extensive U.S. ranges (Little, 1971). Their southern natural range boundaries in Florida (Fig. 3) lie in or near the area of maximum range boundary concentration of species in the Temperate Panhandle and/or Upper Peninsula—Warm Temperate transition zone in the Florida panhandle (Fig. 1). This is a probable tension zone if warming occurs, as Warm Temperate species lose fitness less rapidly and gain at least a temporary competitive advantage over Temperate Panhandle and/or Upper Peninsula species such as *P. echinata* and *S. nigra* (Crumpacker et al., 2001b). Possible monitoring sites for *P. echinata* in this area, with managing agencies in parentheses, include Torreya State Park (Florida Division of Recreation and Parks), Lake Talquin State Forest (Florida Division of Forestry), and Tall Timbers Research Station (Tall Timbers Research, Inc.); for *S. nigra,* Lower Escambia River Water Management Area (Northwest Florida Water Management District), Blackwater River State Forest (Florida Division of Forestry), Eglin Air Force Base (U.S. Air Force), and Choctawhatchee River Water Management Area (Northwest Florida Water Management District).

The southern natural range boundary of *Quercus michauxii* in Figure 3 coincides with the southern boundary of the Temperate Panhandle and/or Upper Peninsula—Warm Temperate transition zone (Fig. 1). Examples of potential monitoring sites for *Q. michauxii,* from west to east along this boundary, include Waccasassa Bay Preserve State Park and San Felasco Hammock Preserve State Park (Florida Division of Recreation and Parks), and Timucuan Ecological and Historic Preserve (U.S. National Park Service).

The southern natural range boundaries of *Magnolia grandiflora* and *Quercus laevis* in Figure 3 lie along or near the northern boundary of the major Warm Temperate—Subtropical transition zone in the central Florida peninsula (Fig. 1). Some monitoring sites from west to east along this potential tension zone of warming-induced weakness of Warm Temperate species, with possible encroachment of Subtropical species, might include Hillsborough River State Park (*M. grandiflora* only—Florida Division of Recreation and Parks), Withlacoochee State Forest (Florida Division of Forestry), Green Swamp (Southwest Florida Water Management District), Disney Wilderness Preserve (The Nature Conservancy), and Rock Springs Run State Reserve (Florida Division of Recreation and Parks).

Taxodium distichum (including bald cypress and pond cypress) occurs throughout much of the southeastern coastal plain from Texas to Florida and north to the Delmarva peninsula (Little, 1971). Its natural range in Florida includes all of the Florida peninsula (Fig. 3 and Little, 1978) and extends about 300 km south of its southernmost boundary in Texas. The main part of *T. distichum*'s southern range boundary in Florida is approximately the northern portion of the secondary Warm Temperate—Subtropical transition zone in Figure 1. Potential warming-related tensions in this area have been discussed by Crumpacker and co-workers (2001c). Everglades National Park and the southern part of Big Cypress National Preserve (U.S. National Park Service) offer a number of potential monitoring sites for *T. distichum* within this transition zone.

The extensive north-south axes of predicted climatic-envelope loss for *M. grandiflora* and *T. distichum* under scenarios T+1 and T+1 (80), respectively (Fig. 4), suggest a number of monitoring sites that could be used to detect losses in both individual-plant fitness and stands of temperature or photoperiod ecotypes (if they occur within these species). Additional sites for *M. grandiflora* north of those mentioned previously for its southern range boundary might include Silver River and Fort Clinch State Parks (Florida

Division of Recreation and Parks), and the connecting complex of Mike Roess Gold Head Branch State Park (Florida Division of Recreation and Parks), Camp Blanding Military Reservation (Florida Department of Military Affairs), Jennings State Forest (Florida Division of Forestry), and Cecil Field Conservation Corridor (City of Jacksonville). Just north of the secondary Warm Temperate—Subtropical transition zone, some suggested monitoring sites for *T. distichum* are Corkscrew Swamp Sanctuary (Audubon of Florida), and Arthur R. Marshall Loxahatchee National Wildlife Refuge (U. S. Fish and Wildlife Service). Increasingly farther north, monitoring sites for *T. distichum* might include Avon Park Air Force Range (U.S. Air Force), Disney Wilderness Preserve (The Nature Conservancy), Graham Swamp Conservation Area (St. Johns River Water Management District), Waccasassa Bay Preserve State Park (Florida Division of Recreation and Parks), Tiger Bay State Forest (Florida Division of Forestry), Santa Fe Swamp Conservation Area (Suwannee River Water Management District), and Osceola National Forest (U.S. Forest Service).

Florida's average annual precipitation increases from approximately 1200 mm on the northeast coast to 1700 mm in the western panhandle (Box et al., 1999, Fig. 2). This provides an east-west gradient along which *M. grandiflora* and *Q. michauxii* could be monitored for potential moisture ecotypes. Using the black areas on the species-scenario maps in Figure 4 to locate sites of predicted climatic-envelope loss under warming, and moving west from the complex of climatically drier sites involving Camp Blanding Military Reservation (see preceding paragraph), two potential monitoring sites for *M. grandiflora* in the more moist western panhandle are Blackwater River State Forest (Florida Division of Forestry) and Lower Escambia River Water Management Area (Northwest Florida Water Management District). Climatically drier and more moist monitoring sites for *Q. michauxii* might include, respectively, Timucuan Ecological and Historic Preserve (U.S. National Park Service) and Lower Escambia River Water Management Area.

The above suggestions for temperate species and potential monitoring sites are summarized by site in Table 3. This gives an indication of the degree of monitoring efficiency in terms of the number of suggested species per site that could be monitored simultaneously for evidence of response to warming over time. The overall number and type of these ecologically important temperate species, across sites that exhibit negative individual plant or stand effects when monitored, could also be used to infer the potential, future magnitude of warming impacts on important ecosystem types (for determination of ecological importance, see Crumpacker and coworkers, 2001b).

Figure 5 shows natural ranges for 6 ecologically important subtropical hardwood and 1 subtropical softwood species. "Subtropical" refers to the Florida natural range type of these species, as discussed in Figure 1 (in other usages, they are more generally referred to as tropical). The softwood species, *Pinus elliottii* var. *densa* Little and Dorman (south Florida slash pine)

TABLE 3. Conservation lands suggested as monitoring sites for climatic warming responses of ecologically important native tree species in Florida. Sites are near southern natural range boundaries of certain temperate (T) species and northern range boundaries of certain subtropical (S) species. For a few temperate species, additional sites are suggested that may be useful in monitoring responses of ecotypes along environmental gradients. Parenthetical names of managing agencies for conservation lands listed by Jue and co-workers (2001) have been simplified; e.g., Florida Department of Environmental Protection, Division of Recreation and Parks, and Florida Department of Agriculture and Consumer Services, Division of Forestry, are referred to, respectively, as Florida Division of Recreation and Parks, and Florida Division of Forestry.

Location/Species
Arthur R. Marshall Loxahatchee National Wildlife Refuge (U.S. Fish and Wildlife Service)
T: *Taxodium distichum*
Avon Park Air Force Range (U.S. Air Force)
T: *Taxodium distichum*
Big Cypress National Preserve (U.S. National Park Service)
T: *Taxodium distichum*
S: *Bursera simaruba, Coccoloba diversifolia, Eugenia axillaris, E. foetida, Ficus aurea*
Blackwater River State Forest (Florida Division of Forestry)
T: *Magnolia grandiflora, Salix nigra*
Camp Blanding Military Reservation (Florida Department of Military Affairs)
T: *Magnolia grandiflora*
Castellow Hammock (Miami-Dade County)
S: *Bursera simaruba, Coccoloba diversifolia, Eugenia axillaris, E. foetida, Ficus aurea, Metopium toxiferum*
Cayo Costa State Park (Florida Division of Recreation and Parks)
S: *Bursera simaruba, Eugenia axillaris, E. foetida, Ficus aurea*
Cecil Field Conservation Corridor (City of Jacksonville)
T: *Magnolia grandiflora*
Charles Deering Estate (Miami-Dade County)
S: *Bursera simaruba, Coccoloba diversifolia, Eugenia axillaris, E. foetida, Ficus aurea, Metopium toxiferum*
Choctawhatchee River Water Management Area (Northwest Florida Water Management District)
T: *Salix nigra*
Collier-Seminole State Park (Florida Division of Recreation and Parks)
S: *Bursera simaruba, Coccoloba diversifolia, Eugenia axillaris, E. foetida, Ficus aurea*
Corkscrew Swamp Sanctuary (Audubon of Florida)
T: *Taxodium distichum*
Disney Wilderness Preserve (The Nature Conservancy)
T: *Magnolia grandiflora, Quercus laevis, Taxodium distichum*
Eglin Air Force Base (U.S. Air Force)
T: *Salix nigra*
Everglades and Francis S. Taylor Wildlife Management Area (Florida Division of Wildlife)
S: *Bursera simaruba, Coccoloba diversifolia, Eugenia axillaris, E. foetida, Ficus aurea*
Everglades National Park (U.S. National Park Service)
T: *Taxodium distichum*
S: *Bursera simaruba, Coccoloba diversifolia, Eugenia axillaris, E. foetida, Ficus aurea*
Fakahatchee Strand Preserve State Park (Florida Division of Recreation and Parks)
S: *Bursera simaruba, Coccoloba diversifolia, Eugenia axillaris, Ficus aurea*
Fort Clinch State Park (Florida Division of Recreation and Parks)
T: *Magnolia grandiflora*
Fort DeSoto Park (Pinellas County Park Department)
S: *Ficus aurea*
Fort Pierce Inlet State park (Florida Division of Recreation and Parks)

TABLE 3. Continued.

Location/Species
S: *Bursera simaruba, Eugenia axillaris, E. foetida, Ficus aurea*
Graham Swamp Conservation Area (St Johns River Water Management District)
T: *Taxodium distichum*
Green Swamp (Southwest Florida Water Management District)
T: *Magnolia grandiflora, Quercus laevis*
S: *Pinus elliottii* var. *densa*
Gumbo Limbo Environmental Complex (City of Boca Raton)
S: *Bursera simaruba, Coccoloba diversifolia, Eugenia axillaris, E. foetida, Ficus aurea, Metopium toxiferum*
Hillsborough River State Park (Florida Division of Recreation and Parks)
T: *Magnolia grandiflora*
Jennings State Forest (Florida Division of Forestry)
T: *Magnolia grandiflora*
Kissimmee Prairie Preserve State Park (Florida Division of Recreation and Parks)
S: *Ficus aurea*
Lake Talquin State Forest (Florida Division of Forestry)
T: *Pinus echinata*
Lower Escambia River Water Management Area (Northwest Florida Water Management District)
T: *Magnolia grandiflora, Quercus michauxii, Salix nigra*
Madira Bickel Mound State Archaeological Site (Florida Division of Recreation and Parks)
S: *Bursera simaruba, Eugenia axillaris, E. foetida, Ficus aurea*
Mike Roess Gold Head Branch State Park (Florida Division of Recreation and Parks)
T: *Magnolia grandiflora*
Ocean Ridge Hammock (Palm Beach County)
S: *Bursera simaruba, Coccoloba diversifolia, Ficus aurea, Metopium toxiferum*
Osceola National Forest (U.S. Forest Service)
T: *Taxodium distichum*
Rock Springs Run State Reserve (Florida Division of Recreation and Parks)
T: *Magnolia grandiflora, Quercus laevis*
San Felasco Hammock Preserve State park (Florida Division of Recreation and Parks)
T: *Quercus michauxii*
Santa Fe Swamp Conservation Area (Suwannee River Water Management District)
T: *Taxodium distichum*
Silver River State Park (Florida Division of Recreation and Parks)
T: *Magnolia grandiflora*
Tall Timbers Research Station (Tall Timbers Research, Inc.)
T: *Pinus echinata*
Tiger Bay State Forest (Florida Division of Forestry)
T: *Taxodium distichum*
Timucuan Ecological and Historic Preserve (U.S. National Park Service)
T: *Quercus michauxii*
Torreya State Park (Florida Division of Recreation and Parks)
T: *Pinus echinata*
Waccasassa Bay Preserve State Park (Florida Division of Recreation and Parks)
T: *Quercus michauxii, Taxodium distichum*
S: *Pinus elliotti* var. *densa*
William Beardall Tosohatchee State Reserve (Florida Division of Recreation and Parks)
S: *Ficus aurea, Pinus elliottii* var. *densa*
Withlacoochee State Forest (Florida Division of Forestry)
T: *Magnolia grandiflora, Quercus laevis*

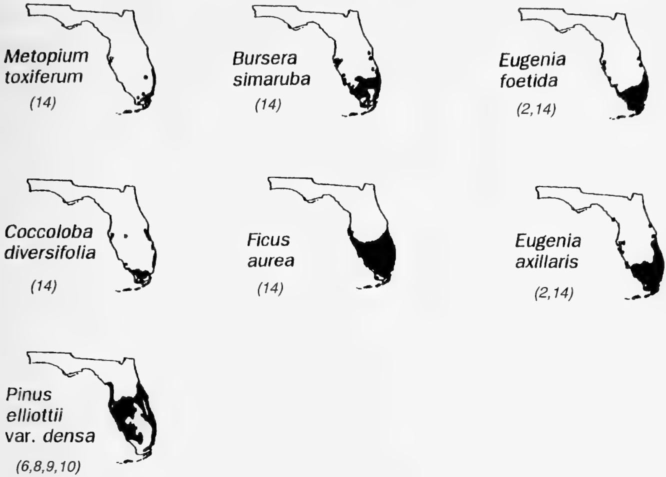

FIG. 5. Natural range maps from Little (1978), shown in black for 7 ecologically important subtropical species. Parenthetical numbers refer to the 1 or more major plant communities in which each species is ecologically important. See USDA Soil Conservation Service (1981) for a key to community names and Snyder et al. (1990) for assignment of each species to ecosystem types in different parts of South Florida.

is treated in the Florida Model as a separate species from its temperate counterpart, *P. elliottii* Engelm. var. *elliottii,* slash pine. Increases in climatic-envelope size, and hence potential range expansion, have been predicted for all 7 of these subtropical species under scenarios T+1, T+1w, and T+1 (80) (Box et al., 1999, Fig. 4 and Table III). However, monitoring for increased fitness in the vicinity of their main current, northern range boundaries and a few other sites is all that is suggested in the present report. Only limited warming induced northward movement of subtropical woody species in Florida over the next 50 years would be expected, due to their relatively long generation times, extensive habitat fragmentation by human activities, and, for some species and locations, lack of suitable soils (Crumpacker et al., 2001a).

The six subtropical hardwood species occur commonly in Tropical Rockland Hammock ecosystems of the Florida Keys (Little, 1978; Snyder et al., 1990). Occurrences of Tropical Hammocks associated with tree islands in the more northern parts of Everglades National Park and southeastern Big Cypress National Preserve (U.S. National Park Service), and in Everglades and Francis S. Taylor Wildlife Management Area (Florida Division of Wildlife) are suggested monitoring sites where some of the earliest effects of climatic warming on all of the subtropical hardwood species except *M. tox-*

iferum (L.) Krug and Urban (Florida poisontree, or poisonwood) might be detected. All 6 of the subtropical hardwoods occur together at Castellow Hammock and Charles Deering Estate (Miami-Dade County) (Hammer, 2001); these are some of the northernmost sites of the South Florida Rockland ecosystem (Snyder et al., 1990). The natural range of *Metopium toxiferum* does not include the southwest Florida Peninsula. However, the remaining 5 subtropical hardwoods occur west of Big Cypress at Collier-Seminole State Park and 4 of them, i.e., excluding *Eugenia foetida* Pers. (boxleaf or spanish stopper), are found in Fakahatchee Strand Preserve State Park (from plant lists, Florida Division of Recreation and Parks).

The warming effect of the Gulf Stream on Florida's Atlantic Coast has permitted the natural range of all hardwood species in Figure 5 except *Metopium toxiferum* to extend, at least intermittently, north to Brevard County (Little, 1978). *M. toxiferum*'s range extends intermittently to at least Martin County on the Atlantic Coast. Hardwood hammocks in Palm Beach County that contain these species might provide opportunities for simultaneous monitoring of their potential warming-induced fitness increases on the Atlantic Coast. For example, all 6 of the subtropical hardwood species in Figure 5 occur at Gumbo Limbo Environmental Complex (City of Boca Raton) in Palm Beach County (Bass, 2001), and at least 4 occur at Ocean Ridge Hammock (Palm Beach County), along with additional possibilities of *Eugenia axillaris* (Sw.) Willd. (white stopper) and *E. foetida* (Atkinson, 2001). A mature, diverse hammock at Fort Pierce Inlet State Park (St. Lucie County) contains *Bursera simuraba* (L.) Sarg. (gumbo limbo), *E. axillaris, E. foetida,* and *Ficus aurea* Nutt. (Florida strangler fig) (from plant lists, Florida Division of Recreation and Parks).

Coastal hammocks on the Gulf of Mexico contain disjunct populations that represent northern range extensions of *B. simaruba, E. axillaris* and *foetida,* and *F. aurea.* All 4 of these species could apparently be monitored simultaneously at Cayo Costa State Park and Madira Bickel Mound State Archaeological Site in Lee and Manatee Counties, respectively (from plant lists, Florida Division of Recreation and Parks).

Natural ranges of the subtropical species *F. aurea* and *P. elliottii* var. *densa* extend both inland and northward to the middle of the Florida peninsula (Fig. 5). These northern locations are near the northern boundary of the major Warm Temperate—Subtropical transition zone (Fig. 1). Across the central Florida peninsula, *F. aurea* occurs in various sites (Hilsenbeck, 2001). From west to east, this species could be monitored at Fort DeSoto Park (Pinellas County Park Department), and at Kissimmee Prairie Preserve State Park and William Beardall Tosohatchee State Reserve (Florida Division of Recreation and Parks). The northernmost natural range extensions of *P. elliottii* var. *densa* near the Gulf and Atlantic Coasts respectively (Abrahamson and Hartnett, 1990, Fig. 5.5), suggest this species could be monitored for warming-induced fitness increases at Waccasassa Bay Preserve State Park and William Beardall Tosohatchee State Reserve (Florida Division of Recreation and Parks), with a more central site at Green Swamp (Southwest Florida Water Management District).

All of the above suggestions for subtropical species monitoring sites are summarized by site, along with those for temperate species, in Table 3. Besides indicating where monitoring efficiency in terms of number of species per site might be greatest, some sites offer opportunities for simultaneous monitoring of negative warming impacts on temperate species and positive warming impacts on subtropical species.

DISCUSSION—We used the predicted responses of 6 native temperate, woody species to 1°C climatic warming to propose an initial group of 30 Florida sites where early biotic effects of warming might be monitored. Most sites are near the southern natural range boundaries of their respective species. We chose these species because they are ecologically important in different major ecosystems and are predicted to show negative, *in situ* warming responses (loss of plant fitness and possibly stands) throughout significant portions of their current natural ranges. Different pairs of these species are predicted to show especially large negative responses to certain types of 1°C warming. If 1°C warming occurs uniformly throughout the year with no change in the moisture balance (scenario T+1), then the large % envelope losses predicted for *Pinus echinata* and *Magnolia grandiflora* within their natural ranges will offer some of the best opportunities for detecting associated fitness losses. If 1°C annual warming occurs disproportionately during the winter (scenario T+1w), the almost complete envelope loss predicted for *Salix nigra* should provide a better opportunity for detecting response than the smaller % envelope loss for *Quercus laevis,* although both are predicted to experience some of the highest percentages of negative response for their respective natural range types. If 1°C uniform annual warming is accompanied by a 20% loss in average annual precipitation [scenario T+1(80)], both *Q. michauxii* and *T. distichum* are predicted to undergo some of the largest % envelope losses within their respective range types. Choice of the above species for monitoring is, then, intended to increase the opportunity to detect 1°C annual warming, regardless of which of the above types of 1°C annual warming occurs.

We also used the main northern range boundaries of 7 ecologically important subtropical woody species to suggest 17 sites at which they could be monitored for *in situ* increases in fitness associated with climatic warming. Four of the sites are identical to those mentioned above for 1 or more temperate species, giving 43 monitoring sites in all (Table 3), or approximately 3.5% of the 1220 separate conservation lands listed in Jue and coworkers (2001).

Opportunities for monitoring more than 1 temperate species are provided at 6 of the 30 temperate species sites (20%) and, for more than 1 subtropical species, at 13 of the 17 subtropical sites (76%). The much higher efficiency involved in simultaneous monitoring of 2 or more subtropical species is related to their common co-occurrence in the Tropical Hammocks ecosystem of south Florida. Other opportunities for monitoring additional temperate or subtropical species at various sites in Florida do, of course, occur. However, they would not necessarily involve ecologically important species and might often include species stands that are not located near their respective southern or northern range boundaries. Nor would they necessarily be species that have been predicted to undergo large, warming-associated changes in fitness.

Besides the increased efficiency involved with monitoring several species (especially subtropicals) simultaneously at certain locations, other efficiencies can be inferred for temperate species from inspection of Figure 4. For example, monitoring of *P. echinata* in grid cell 1,3 (Torreya State Park, Lake Talquin State Forest, and Tall Timbers Research Station), *Q. laevis* in cell 4,6 (Green Swamp and Disney Wilderness Preserve), and *Taxodium distichum* in cell 6,7 (Big Cypress National Preserve and Everglades National Park), in a well replicated experiment, would have the advantage of monitoring simultaneously for three different kinds each of 1°C warming, species, and regions of Florida. *S. nigra* and *Q. michauxii* occur as ecologically important "pairs" in the riverine Bottomland Hardwoods ecosystem in cell 1,1, which would increase monitoring efficiency at Lower Escambia River Water Management Area.

All potential monitoring sites should be field checked to ensure they contain adequate stands and/or numbers of each species proposed for monitoring. Even though all locations in Table 3 are potentially important monitoring sites based on their locations and on predictions of species responses to warming, only a subset of sites may meet the above requirements. Stands and individual trees should also be in good present condition and located in protected areas where long-term monitoring can be assured. Monitoring sites proposed in the present report are, therefore, based on the extensive list of Florida Conservation Lands in Jue and co-workers (2001).

Additional monitoring sites on private lands might be added by contacting the Florida Fish and Wildlife Conservation Commission. The Commission is actively involved in assessing and prioritizing privately owned "strategic habitat conservation areas" (SHCAs) needed to maintain key components of Florida's biodiversity (Cox et al, 1994; Kautz and Cox, 2001). Figure 1 of Cox and co-workers (1994) indicates that the largest concentration of SHCAs falls within the major Warm Temperate—Subtropical transition zone in our Figure 1 and the second largest is located near the southeast boundary of the Temperate Panhandle and/or Upper Peninsula—Warm Temperate transition zone in our Figure 1. Both of these locations are important areas for monitoring potential responses to climatic warming of certain groups of woody species in the Florida Model. SHCAs for monitoring should be in low-intensity land uses on well managed lands, where prospects for continued conservation are secured by long-term conservation easements or other legally binding management agreements. The State's recently extended, major land acquisition program, now called "Florida Forever," involves a much greater emphasis than previously on use of easements for land protection (Hoctor et al., 2000).

Replicates of species stands and/or individuals, within and between monitoring areas, will be needed, not only to provide statistical precision for analysis but also in case some stands are effectively lost due to natural or other disturbances. Permission to monitor will be needed for both publicly and privately owned lands. Ideally, monitoring should begin before, or as early as possible during a warming trend, in order to provide options for future mitigations. Potential changes in tree fitness components expected to precede and accompany climatic-envelope loss or gain, including seed production, seedling establishment and viability, and vegetative reproduction, should be monitored on an individual-plant basis within species. Association of fitness decreases in temperate species with disease and insect outbreaks might provide early evidence of more general ecosystem damage.

Occurrence of subtropical seedlings in areas without reproductively active plants of the same species would provide evidence of successful immigration, and of possible climatic envelope expansion of subtropical species. *Metopium toxiferum* is an especially important subtropical candidate for envelope expansion under each of the three +1°C scenarios, as is *Coccoloba diversifolia* under T+1 (80) and T+1w, based on predicted warming responses in Figure 4 and Table III of Box and coworkers (1999).

The warming involved in each of the Florida Model scenarios is projected to reach its +1°C value over the 110-year period from 1990 to 2100, as a result of approximate doubling of the atmospheric equivalent CO_2 concentration of the global environment (Houghton et al., 1996). Even if the Florida Model's predictions of temperate species envelope loss are reasonably accurate for this time period, equivalent range losses may not result. Some CO_2 enrichment and various acclimations of individual trees, accompanied by selection for heat and/or drought-resistant ecotypes, might occur (Loehle and LeBlanc, 1996; National Assessment Synthesis Team, 2000; Crumpacker et al., 2001b), as well as persistence of long-lived individuals at lowered fitness. Alternatively, increased influence of warming-induced insect, pathogen, and weedy plant outbreaks, more intense wildfires, and other warming-related environmental perturbations could interact to weaken entire forested ecosystems (Loehle and LeBlanc, 1996; National Assessment Synthesis Team, 2000; Crumpacker et al., 2001a, b, c). Extensive stand degradation and range loss might then accompany individual-plant fitness loss.

A more comprehensive monitoring system could be designed by including the 13 other ecologically important temperate species in Figure 4 and Table III of Box and co-workers (1999). Predicted amount and location of envelope loss is available for these species under each of the three +1°C scenarios (except predicted *location* of loss for +1°C under T+1w, which could be obtained from the authors). Other species, both native and non-native, and rare as well as common, could be added to monitoring sites as desired.

A wide array of ownership and management is involved in the small subset of 43 Florida conservation lands proposed for monitoring in Table 3. Managing agencies or organizations are distributed as follows: 7 federal (16%), 27 state (63%), 4 county (9%), 2 "municipal", i.e., city or town (5%), and 3 private (7%). Together with the potential for future increases in privately owned and mananged conservation lands, this is yet another example of the complexity of conservation area systems. Extensive cooperation and coordination among public agencies, private organizations, and individuals will be needed to maintain Florida and U.S. biodiversity in the 21st century. This will be especially true if the present climatic-warming trend continues.

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CHARACTERIZATION OF A GOPHER TORTOISE MORTALITY EVENT IN WEST-CENTRAL FLORIDA

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ABSTRACT: *A significant gopher tortoise (*Gopherus polyphemus*) mortality event was documented in June 1998 at a 150-ha mitigation park established for tortoise protection. Shell surveys throughout the park were conducted between June 1998 and September 1999. The greatest concentration of dead tortoises, as determined by shells and remains, occurred on a 28-ha portion of the park, where 104 individual shells were recovered. Tortoise age class and sex were recorded, with results indicating 68% of shells were of adult males. In an attempt to estimate time since death, shells were assigned to one of 6 condition classes, based on degree of disarticulation. Burrow surveys conducted as a means of obtaining tortoise density estimates showed major declines in population size between December 1994 and June 1998 in the area of highest mortality. Potential causes of death and management implications are discussed.*

Key Words: Gopher tortoise, *Gopherus polyphemus*, upper respiratory tract disease, tortoise mortality

UNUSUALLY high mortality in gopher tortoise (*Gopherus polyphemus*) populations has been noted at several locations in Florida (McLaughlin, 1997; J. Berish, 1998; M. Barnwell, 1999). In June 1998, we documented a significant mortality event at Oldenburg Mitigation Park (OMP) in Hernando County, Florida, with the number of dead tortoises (shells) counted representing 87 individuals (3.1/ha) in the area of greatest mortality. Additional shells were found during subsequent surveys of the same area (Site A, Fig. 1) in December 1998 and September 1999 bringing the total count to 104.

Post-hoc efforts were made to determine when the mortality event began. No unusual mortality on Site A was noted during a prescribed burn in June 1994, nor during tortoise burrow surveys in December 1994. Tortoise mortality first became apparent in October 1996 when private contractors

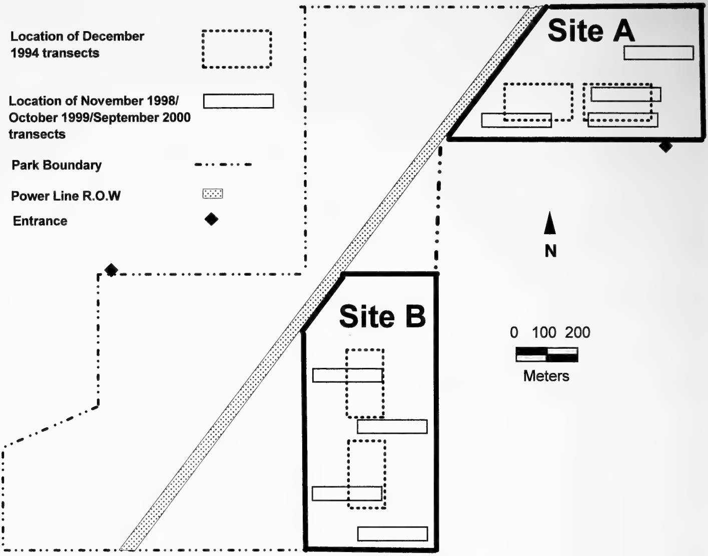

FIG. 1. Location of Sites A and B, and approximate locations of tortoise burrow transects at Oldenburg Mitigation Park in Hernando County, FL.

were surveying the park for exotic plant infestations. Eight tortoise shells were observed at that time.

The purpose of this study was to assess the extent of the tortoise mortality event and to estimate time since death based on the condition of shells observed. Dodd (1995) monitored shell disarticulation rates for several turtle species, including gopher tortoises. He wrote detailed descriptions of each disarticulation stage and noted considerable variation in disarticulation rate within a species. We conducted shell surveys between June 1998 and September 1999, using a shell condition classification system similar to, but less detailed than, that developed by Dodd (1995).

OMP is one of several facilities established under the Florida Fish and Wildlife Conservation Commission's (FWC) Mitigation Park Program within the Office of Environmental Services. These parks were established to provide an off-site alternative whereby development impacts are mitigated through the acquisition and management of suitable habitat that supports existing populations of gopher tortoises and other upland listed species. Rules prohibit use of these parks as recipient sites for relocation efforts for gopher tortoises or other species; however, actions by well-intentioned people concerned about the fate of individual tortoises on roadways and proposed building sites likely result in the translocation of some tortoises to this park.

MATERIALS AND METHODS—Study site-OMP is located approximately 10 km north of Brooksville, Hernando County, Florida (28° 37′N, 82°20′W). The park encompasses about 150 ha. Approximately 73% of the park is in longleaf pine-turkey oak (*Pinus palustris-Quercus laevis*) sandhill, and 19% is hardwood hammock dominated by live oak (*Quercus virginiana*) and/or laurel oak (*Quercus hemisphaerica*). An oldfield dominated by bahiagrass (*Paspalum notatum*) is being colonized by hardwoods and makes up about 3% of the site. A power line right-of-way, consisting of pasture grasses and scattered shrubs, covers 3% of the area and runs diagonally through the property. A small ephemeral pond dominated by maidencane (*Panicum hemitomon*) and other grasses occupies about 2% of the site.

Acquisition of OMP by the FWC began in 1989 and was completed in 1995. Selective timber cuts, moderate cattle grazing and longleaf pine reforestation practices occurred in the past at OMP. Based on heavy fuel accumulation and oak hammock encroachment prior to acquisition, it does not appear that OMP was subjected to a regular prescribed burn regime. As FWC acquired parcels, periodic prescribed fires were conducted. OMP is surrounded by 0.8- to 2-ha residential tracts on the east, northwest, and south sides. Property to the north is in public ownership. The park is open to the public for passive, nature-based recreation, including hiking and wildlife viewing.

Study efforts focused primarily on Site A, the area of greatest gopher tortoise mortality, and Site B, an area of low mortality (Fig. 1). Each of these sites is approximately 28 ha in size.

Gopher tortoise densities—Tortoise density estimates were derived by counting active and inactive tortoise burrows using a belt transect method (Cox et al., 1987) and the criteria and correction factor developed by Auffenberg and Franz (1982). Counts were conducted throughout the park in December 1994 and again in June 1998 (Fig. 1). Permanent transects were established for subsequent counts conducted on Sites A and B in November 1998, October 1999, and September 2000. Approximately 14–16% of Site A and Site B was covered during each burrow survey. Each transect was 250 m long × 20 m wide (0.5 ha). Two to four observers covered parallel transects by walking the transect centerline and counting all active and inactive burrows within, or partially within, the belt transect 10 m either side of the centerline. Within a transect set, observers were spaced approximately 30 meters apart so that there was a distance of at least 10 m between transects.

Density estimates were calculated (Eqn. 1):

$$\text{Tortoise Density/ha} = \frac{\text{Active} + \text{Inactive Burrows}}{(0.5\ \text{ha})(\text{No. of Transects})} \times (\text{Correction factor of } 0.614) \qquad (1)$$

Tortoise shell surveys—In October 1996, private contractors working in the northeast part of OMP noted 8 tortoise shells at various locations. Subsequently, FWC biologists began to note the presence of more shells. In June 1998, a complete survey of shells was conducted on Site A. Three observers, spaced approximately 15 to 20 m apart, traversed parallel lines searching for tortoise shells. Whenever possible, carapace length (CL) and width (CW) (± 2.0 mm) of shells were measured using tree calipers. The following characteristics of each shell were also noted: sex (based on concavity of the plastron, with males exhibiting a higher degree of concavity than females-McRae et al., 1981a), position (carapace up vs. carapace down), and condition (degree of disarticulation). Condition classes of shells, based on modifications of Dodd's (1995) disarticulation stage classification, were as follows:

Class A (Dodd's Stage 1 and 2)-all scutes attached with some skin and/or appendages attached;

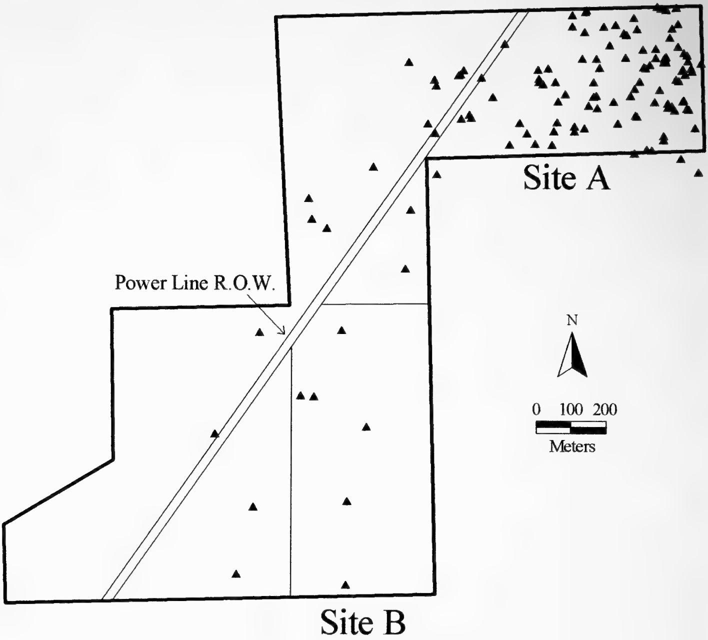

FIG. 2. Locations of tortoise shells found at Oldenburg Mitigation Park, Hernando County, FL, during surveys conducted between June 1998 and September 1999.

Class B (Dodd's Stage 3)-≥50% of scutes attached;

Class C (Dodd's Stage 4)- >0 to <50% of scutes attached; sutures may be beginning to separate;

Class D (Dodd's Stages 4 and 5)-no scutes attached but shell still intact, sex determinable and CW and CL measurable;

Class E (Dodd's Stages 6 and 7)-no scutes attached, shell collapsing (disarticulating), sex determinable and/or CW measurable; CL not measurable; and

Class F (Dodd's Stages 8 and 9)-no scutes attached, shell completely disarticulated.

Shell surveys were subsequently conducted throughout OMP, using the techniques described above. Locations of shells were recorded using a GARMIN Model 48 Global Positioning System (GPS) unit to show the geographical extent of mortality within OMP (Fig. 2).

RESULTS—*Gopher tortoise densities*—A comparison of tortoise density data on Site A showed a decline from 5.5 to 1.0 tortoises per ha between December 1994 and June 1998, whereas density on Site B, an area of low tortoise mortality (a total of 6 shells for all surveys combined), increased from 2.5 to 3.3 tortoises per ha (Fig. 3). Transects were sampled again in November 1998 on Site A and yielded estimates of 1.7 tortoises per ha.

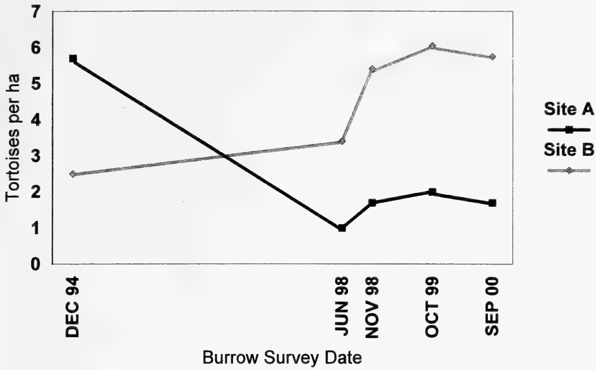

FIG. 3. Tortoise densities (tortoises/ha) of Site A and Site B, Oldenburg Mitigation Park, Hernando County, FL, based on burrow surveys conducted between December 1994 and October 1999.

Density estimates on Site B also were higher in November 1998 (5.2 tortoises per ha) compared to June 1998 (3.3 tortoises per ha). To minimize variability due to seasonal differences, more emphasis should be placed on comparisons between December 1994 and November 1998. These data indicate a 70% decline in tortoise numbers on Site A, and a 108% increase in tortoise density on Site B. From November 1998 to September 2000, densities appear to be stable for both sites (Fig. 3).

Tortoise shell surveys—A total of 87 shells was observed during a complete survey of Site A in June 1998. Data from these shells were used to establish time-since-death estimates. GPS locations were recorded on 83 of these shells (Fig. 2). None showed signs of human or animal depredation.

A majority of shells found were males. Of 72 shells examined for sex determination, 55.6% were males and 27.8% were females. Sex could not be reliably determined for approximately 17% of shells based on plastron concavity alone and because several shells were highly disarticulated. Age class was based on size and sex with males of CL ≥177 mm being considered sexually mature adults. Females of CL ≥ 225 mm were considered to be sexually mature adults (Berish, unpubl. data). Of 57 shells where both sex and size class could be determined, 39 (68.4%) were adult males, 16 (28.1%) were adult females, and 2 (3.5%) were subadult females. No subadult males were found in this sample. No juveniles of either sex were found.

Carapace length was measured for 76 shells. Average CL was 244.8 mm (± 30.0 mm) and ranged from 178 to 320 mm. For shells where both sex and age class could be determined, shells of adult males averaged 244.6 mm (± 20.6 mm) and shells of adult females averaged 261.7 mm (± 19.7 mm).

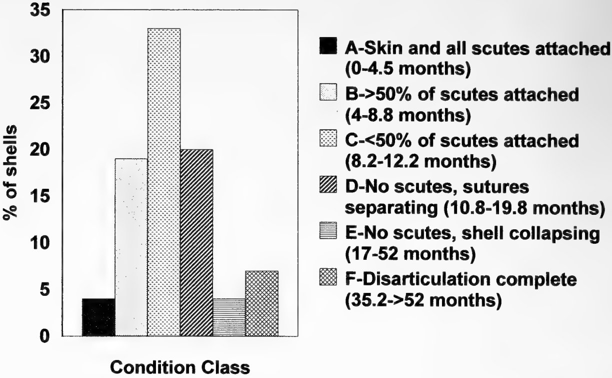

FIG. 4. Percent of tortoise shells observed within 6 condition classes on Site A, and elapsed time since death (in months), Oldenburg Mitigation Park, Hernando County, FL, in June 1998.

Positions of 84 shells were as follows: 32 (38%) were carapace-side-up, 50 (60%) were carapace-side-down, and 2 (2%) were on their side. Three shells were too disarticulated and scattered to determine orientation.

All 87 shells were evaluated for carcass and shell disarticulation stage. Four shells (4.6%) were in Class A, 19 (21.8%) were in Class B, 33 (37.9%) were in Class C, 20 (23.0%) were in Class D, 4 (4.6%) were in Class E, and 7 (8.0%) were in Class F (Fig. 4).

To approximate elapsed time since death, condition class data were compared to disarticulation stages discussed by Dodd (1995). Although the six condition classes we used are defined more broadly than the nine classes developed by Dodd, basic similarities allow an estimate of elapsed time since death. However, some differences exist. To minimize extraneous variance, Dodd purposely placed tortoise shells in an open, sandy area exposed to direct sunlight, whereas a number of shells found in this study were in shady, oak hammocks. Dodd's work was conducted during drought; this study's June 1998 shell survey was preceded by several months of above average rainfall due to an El Nino event. Disarticulation rates may be faster during wet periods (Dodd, 1999). Additionally, Dodd placed all tortoise shells in a right-side-up (carapace up) position for his study. He noted that plastrons remained articulated for a longer time than carapaces. We were concerned that position (carapace up vs. carapace down) might affect disarticulation rate. Therefore, only data from shells observed in a carapace-up position in our study were analyzed to estimate elapsed time since death, but frequency data by class are shown for all shells (Fig. 5). Figure 5 (excluding data for Class F) shows that percent of shells found within a given condition class

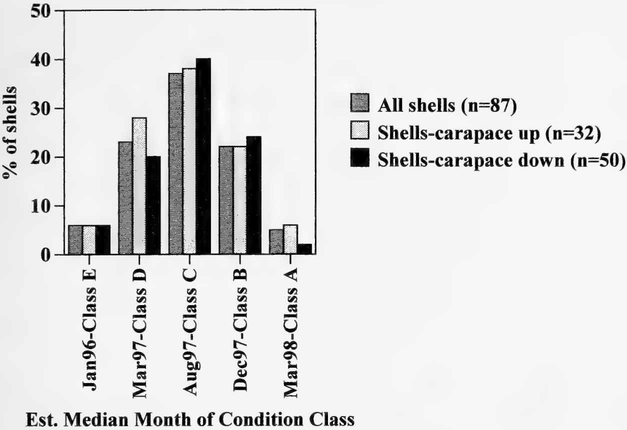

FIG. 5. Percent of shells (total shells vs. shells-carapace up vs. shells-carapace down) by estimated median month of each condition class, Oldenburg Mitigation Park, Hernando County, FL, June 1998.

in the carapace-up position closely approximated the percentage of shells in the carapace-down position (n = 50) and total shells (carapace up, down, or on side) (n = 87). This was especially true for shells in classes B, C, and E.

Dodd (1995) calculated the mean duration (in months) taken to progress from one shell disarticulation stage to the next stage. We took the mean duration for Dodd's Stage 2 to progress to Stage 3 (2.9 months) as the midpoint of our Class A. We then took the mean for the next change (Stage 3 progressing to Stage 4 = 3.5 months) and added it to the mean for the first change (2.9 months) as the midpoint for our Class B (6.4 months), and so on. To estimate a range of months within which a given tortoise (based on shell condition class) might have died, we used the midpoint with Dodd's calculated standard deviation for that stage and counted back from our June 1998 survey. We could then approximate elapsed time since death for each of our classes (Table 1). Clearly, as indicated by Dodd (1995), the latter disarticulation stages are more variable in their length, with a distinctive change in rate between Classes D (Dodd's Stages 4/5) and E (Dodd's Stages 6/7), when shell sutures begin to separate. There is considerable overlap in time intervals for Classes E and F. The midpoint of Class E was calculated by taking the mean duration of Dodd's Stages 6–7 and 7–8 and taking the average (28.6 months). Greater variability in the duration of the latter stages of Class E resulted in an extended range of months that a shell could be categorized as such.

TABLE 1. Elapsed time-since-death estimates of gopher tortoises at OMP, Hernando County, Florida, based on shell condition class, in June 1998.

Class	Characteristics	Approx. time-since-death, months	Midpoint, months
A	all scutes, and some skin and/or appendages attached	0.0–4.5	2.9
B	≥50% scutes attached	4.0–8.8	6.4
C	<50% scutes attached	8.2–12.2	10.2
D	no scutes attached, shell intact, can determine sex, carapace width, and carapace length	10.8–19.8	15.3
E	no scutes attached, shell disarticulating, can determine sex and/or carapace width	17.0–52.0	28.6
F	shell completely disarticulated, cannot determine sex or carapace width	35.2–≥52.0	40.3

Estimated peak times of death appeared to be between June 1997 and October 1997, with an increase in mortality beginning as early as October 1996 (Fig. 6). Sixty-six percent of those shells in Classes A, B, and C had an estimated elapsed time since death of 12 months. Ninety-seven percent of those shells in Classes A, B, C, and D had an estimated elapsed time since death of about 20 months.

Additional complete surveys of Site A yielded eight shells in December 1998 and nine in September 1999, indicating that mortality had continued. No new shells were found during September 2000 surveys. Complete sur-

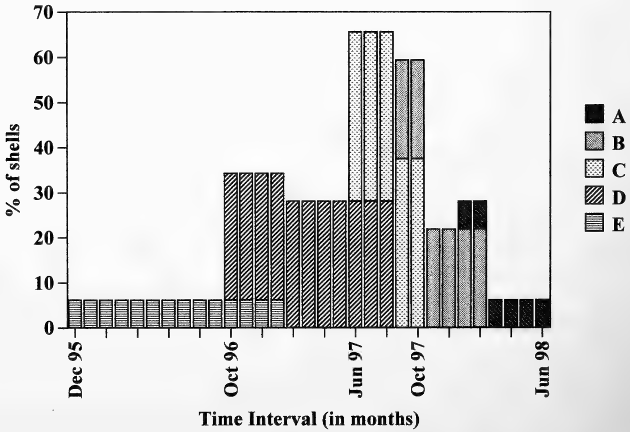

FIG. 6. Percent of shells by time interval (range of months) among 5 condition classes, Oldenburg Mitigation Park, Hernando County, FL, June 1998.

veys of Site B yielded five shells in October 1998 and one shell in October 1999. Only three shells in subsequent surveys showed signs of animal or human depredation. One shell from Site A had been damaged or cut, as with a saw; another shell showed signs of apparent canid predation. On Site B, a juvenile shell also showed signs of canid predation. Ultimately, complete shell surveys were conducted throughout OMP between March 1999 and September 1999. Tortoise shells were noted at low densities in all but the two management compartments located farthest from Site A, the area of highest mortality (Fig. 2). No shells were observed in the extreme southwest corner of the park. For all surveys throughout OMP combined, a total of 127 shells was found.

Discussion—Gopher tortoise colonies on Site A suffered major declines in numbers between December 1994 and June 1998 as shown by the 87 shells found within this 28-ha area. Based on shell disarticulation rate estimates, the mortality event may have begun during the late summer or fall of 1996 and peaked between June 1997 and October 1997. These data should be interpreted with caution, however, for a number of reasons:

First, many of the shells were found in shady, oak hammocks, whereas all of Dodd's shells were placed in open, exposed areas. While humidity may have been higher in oak hammocks at OMP, shells in these areas may have been exposed to less direct mechanical abrasive action from heavy rainfall than that to which shells in Dodd's study were subjected.

Secondly, overall weather patterns (drought vs. above-average rainfall) may have differed between Dodd's study area and OMP and between the two study periods, thereby affecting decomposition and disarticulation rates.

Thirdly, the presence of the gopher tortoise moth caterpillar (*Ceratophaga vicinella*), which builds silk feeding tubes and feeds on scute keratins (Deyrup and Deyrup, 1999), may affect disarticulation rate. Feeding tubes were found on over 85% of the shells from Site A in this study, although Dodd also noted the presence of feeding tubes on some of the shells he monitored (Dodd, 1999).

Burrow counts are not precise; however, they likely provide a useful index of trends for a given site. Broad application of the Auffenberg and Franz (1982) correction factor for estimating tortoise densities has been disputed and several researchers have reported the need for development of site-specific correction factors (Breininger et al., 1988, 1994; McCoy and Mushinsky, 1992); however, a declining trend in tortoise numbers on Site A is evident. Burrow counts indicated a substantial drop in tortoise density on Site A between December 1994 and June 1998. It is important to note that burrow transect sampling was conducted during different seasons—winter of 1994 and summer of 1998. Tortoises are generally less active in winter as compared to other seasons (Douglass and Layne, 1978; McRae et al., 1981b; Diemer, 1992). However, drought prior to and during June 1998 also may have led to reduced tortoise activity; although burrow numbers had increased slightly on Site B, numbers on Site A had dropped drastically by June 1998. A comparison between December 1994 and November 1998 burrow count data may be more appropriate to reduce seasonal variation. Moler and Berish (unpubl. report) compared total burrow counts at different seasons for two sites in north Florida. They found that the total of active plus inactive burrows increased dramatically between spring and late summer/fall.

Estimated tortoise numbers (based on burrow counts) on Site A appeared to drop 70% between surveys conducted in December 1994 and November 1998. Conversely, tortoise numbers on Site B increased 108%. The increase reported for Site B may be the result of several factors. Transects sampled on Site B during the 1994 survey included a slightly higher proportion of less suitable tortoise habitat compared to transects sampled during subsequent surveys. Perhaps some animals had moved from Site A to Site B. Indeed, the power line right-of-way provides open, grassy habitat attractive to tortoises and may function as a travel route to other parts of the property. However, we would have expected a higher level of mortality on Site B, comparable to that on Site A. Additional clearing and development of adjacent home sites may have driven some tortoises to seek more suitable habitat on Site B. Habitat conditions on Site B are somewhat better than on Site A. Gates (unpubl. data) noted similar total canopy cover between the two sites, but wiregrass cover was higher on Site B (68%) than on Site A (36%). However, it seems unlikely that the influence of these potential factors combined would result in such a dramatic increase in tortoise numbers on Site B.

Juveniles were conspicuously absent from both Site A and Site B; except for one juvenile shell with evidence of predation, no other juvenile shells were found, nor were any juvenile-sized burrows observed during burrow surveys. It is possible that juvenile shells or burrows were overlooked due to their smaller size, although most transect sites were fairly open (i.e., sparse to moderate vegetation cover) with good visibility. Predators (including avian species and raccoons) quickly carry off shells of smaller tortoises (Dodd, 1999). Softer juvenile shells also would be expected to decompose and disarticulate more rapidly than adult or subadult shells.

Cause of death is open to speculation, and we offer three possible explanations for the observed mortality event; 1) illegal release of sick or stressed tortoises; 2) a severe disease event brought about by upper respiratory tract disease (URTD) singly or in combination with another unknown pathogen; or 3) a loss of carrying capacity induced by a reduction in habitat quality.

Shell surveys indicated that more than 80% of the observed mortality occurred on <20% of the total park acreage (Site A). The number of tortoises dying within a 1- to 3-year period at Site A, coupled with its proximity to the original park entrance, raises the possibility that sick tortoises may have been released at the site. It is not known how many tortoises may have died underground in burrows, nor were any surveys conducted to determine if notable levels of tortoise mortality occurred on adjacent lands. Thus, the mortality event may have covered a more extensive area than revealed by our survey data. Unfortunately, it is not possible to verify whether or not the release of a large number of tortoises occurred.

Another possibility is that the mortality event was related to factors on-site that adversely impacted the resident population of tortoises. This is supported to some degree by the large decline in tortoise numbers observed on Site A based on burrow counts. Counts of active and inactive burrows provide only an indirect estimate of tortoise density and should be viewed with caution. However, burrow survey data suggest a loss of 4.0 tortoises per ha, or 112 animals, between December 1994 and November 1998. Observed mortality based on shell counts was 104 tortoises.

A high incidence of URTD has been documented in the OMP gopher tortoise population (Berish et al., 2000). This disease has been implicated in the mortality of 90% of the adult desert tortoise (*G. agassizii*) population of the Desert Tortoise Natural Area in California (Berry, 1997). Twenty-two of 29 individuals (76%) tested at OMP in July 1998 were seropositive, indicating that they had been exposed to *Mycoplasma agassizii,* a causative agent of URTD, and had developed a detectable immune response to this bacterium (Berish et al., 2000). Males suffered the highest proportion of observed mortality; 68% of the shells observed were adult males, as opposed to 28% females. If the mortality event is associated with a disease agent, it is not surprising that a higher proportion of males than females perished, as males generally have larger home ranges, disperse more widely in search of mates, and are more likely to engage in combat with other male tortoises (McRae et al., 1981b; Douglass, 1990; Diemer, 1992; Smith et al., 1997). In studies of URTD in tortoises at various locations, Berish and co-workers (2000) and Smith and co-workers (1998) found higher numbers of seropositive males than females. Seropositive individuals were found throughout OMP, including areas where no significant mortality was observed. Other disease organisms may be involved as well (Wendland, 1999).

Finally, the amount of herbaceous cover is considered an important indicator of habitat suitability for gopher tortoises. Auffenberg and Iverson (1979) found that areas with herbaceous cover ≥80% supported 5–20 times more tortoises than areas with <35% herbaceous cover. Herbaceous cover is very low on Site A. Gates (unpubl. data) estimated that non-wiregrass (*Aristida* spp.) herbaceous cover is as low as 11–21%, with wiregrass cover ranging from 28–38%. This explanation seems the least plausible because gopher tortoises are capable of moving to more suitable habitat and sudden, massive mortality events due to poor habitat quality have not been previously reported. However, McLaughlin (1997) suggested that poor habitat quality may contribute to stress, thereby rendering animals more susceptible to URTD.

CONCLUSIONS—Monitoring of the gopher tortoise population at OMP will continue. Managers should conduct annual shell surveys on Site A and Site B to determine if mortality is continuing at a significant rate and, if so, what portions of the population are most affected. As part of a larger study being conducted at four locations in Florida, 15 tortoises tested for antibodies to *M. agassizii* were fitted with radiotransmitters in July 1998 so that they could be recaptured and re-tested to follow the progression of URTD and its potential impact on tortoise mortality (Berish, unpubl. data). This disease has been implicated in large-scale mortality events in desert tortoise populations, but it cannot be determined definitively to be the cause of the mortality event at OMP.

Managers will continue periodic prescribed burns throughout the site to enhance foraging and nesting conditions for tortoises. Mechanical and chemical methods to reduce oak canopy cover in overgrown hammocks also are being considered. It is hoped that improving habitat conditions will encourage recruitment from adjacent lands. Also, managers will initiate a public education effort to discourage relocation of tortoises to the park.

Finally, resource managers should be aware of potentially significant tortoise mortality events at other sites. If more than a few shells are encountered, managers should 1) note disarticulation class of each shell to estimate time-since-death, 2) note sex and age class characteristics, 3) note occurrence of gopher tortoise moth caterpillar feeding tubes on shells, 4) conduct periodic burrow surveys to estimate and track population trends, 5) record shell locations to determine geographic extent and spatial relationship of shells, and 6) test surviving tortoises in an effort to determine if exposure to URTD-causing agents has occurred or if active *Mycoplasma* spp. infection exists in the population.

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DISTRIBUTION OF *AEDES ALBOPICTUS* (DIPTERA: CULICIDAE) IN INDIAN RIVER COUNTY, FLORIDA—*Lawrence J. Hribar*[1], Indian River Mosquito Control District, 5655 41st Street, Vero Beach, FL 32967. [1]Current address: Florida Keys Mosquito Control District, 506 106th Street, Marathon, FL 33050

ABSTRACT: *The distribution of* Aedes albopictus *in Indian River County, Florida, was determined by larval and pupal collections. This mosquito is found in the eastern and central parts of the county, with the western portion free of infestation. Possible explanations for this distribution include sanitation, restricted public access, and St. John's Marsh serving as a barrier to movement.*

Key words: *Aedes albopictus,* mosquito, Indian River County

THE EXOTIC mosquito *Aedes albopictus* (Skuse) was first discovered in the continental United States in Memphis, Tennessee in 1983 (Reiter and Darsie, 1984). The first major infestation was detected in Harris County, Texas, in 1986 (Sprenger and Wuithiranyagool, 1986). This species reached Jacksonville, Duval County, Florida in 1986 (Peacock et al., 1988) and within four years it had reached Indian River County, Florida (O'Meara et al., 1993). The introduction of this mosquito into Florida has affected the distribution of *Aedes aegypti* (Linnaeus) in several areas of the state and it has become a species of some concern to mosquito control agencies in Florida (Betts, 1994; Hornby and Opp, 1994a, 1994b; O'Meara et al., 1993; Sibal, 1994; Vargas and Prusak, 1994). *Aedes albopictus* is remarkable in its ability to utilize almost any container that can hold water as a larval habitat (Bonnet, 1947). In late 1996 and early 1997, the Indian River Mosquito Control District received a number of complaint calls regarding container-breeding mosquitoes. This survey was conducted to determine the distribution of *Ae. albopictus* in Indian River County, Florida.

METHODS—Surveillance was conducted in Indian River County from March to July 1997. After that time, St. Louis Encephalitis activity necessitated termination of the survey and redirection of activities. Although the majority of effort was confined to areas that are part of the Indian River Mosquito Control District, some time was spent in other parts of the county in order to determine the extent of infestation. Most containers were located at illegal dump sites throughout the county. Other containers were inspected as they were located in neighborhoods or along roadsides. A sample of water was taken and returned to the laboratory where mosquito larvae, if any, were identified.

RESULTS AND DISCUSSION—*Aedes albopictus* was found in the cities of Fellsmere, Indian River Shores, Orchid, Sebastian, and Vero Beach; and in the unincorporated communities of Gifford, Oslo, Roseland, Vero Lake Estates, Wabasso, Wabasso Beach, and Winter Beach. One hundred sixty-one sites were visited, one hundred ninety-six containers were sampled, and 119

(60.7%) were positive for *Ae. albopictus.* Tires most often harbored *Ae. albopictus* (n = 75), followed by cemetery vases (n = 14) and buckets (n = 8). Other mosquito species were collected during this study: *Culex nigripalpus* Theobald, *Cx. quinquefasciatus* Say, *Cx. salinarius* Coquillett, and *Wyeomyia* spp. *Corethrella* sp. (Diptera: Corethrellidae) larvae also were collected. These species were most commonly collected from tires (n = 19) and buckets (n = 8). Two collections revealed *Cx. quinquefasciatus* cohabiting with *Ae. albopictus,* and three times *Cx. salinarius* co-occurred. Only 17 natural containers were sampled: 9 bromeliads; 6 tree holes; one banana leaf and one rock hole. *Wyeomyia* spp. larvae were the only mosquitoes collected from bromeliads. *Aedes aegypti* was not found in any of the containers sampled during this investigation.

The western part of Indian River County appears to be free of *Ae. albopictus.* Collections were taken at a fish camp *ca.* 18.4 mi west of Vero Beach. No *Ae. albopictus* were found, although other mosquitoes were collected there. Collections along SR 60 west to the Osceola County line revealed no *Ae. albopictus.* Attempts to locate *Ae. albopictus* along the northwestern border of Indian River and Brevard Counties were unsuccessful. The extreme southwestern quadrant of Indian River County, adjacent to Okeechobee County, was not well-explored but no containers were found. This area is private property owned by St. John's Water Management District, with restricted public access. The St. John's Marsh occupies a large portion of western Indian River County, and may serve as a barrier to westward movement of *Ae. albopictus.* Studies of adult mosquitoes would be helpful to determine what role, if any, the marsh plays in distribution of *Ae. albopictus.* The small number of artificial containers found in the western part of the county more probably explains the distribution of this species. Almost all the *Ae. albopictus* collected during this survey were found in artificial containers. Only five times were collections were made from natural containers, three from tree holes, and one each from a rock hole and a banana leaf. This reinforces the idea that sanitation is an important part of mosquito control, and that the public can contribute to the control of pest mosquitoes.

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IN VITRO PROPAGATION OF *CONRADINA ETONIA*

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Abstract: *Conservation institutions worldwide such as the Royal Botanical Gardens at Kew (U.K.) have frequently used* in vitro *propagation (micropropagation) as a valuable tool to support the conservation of some threatened and endangered species. Although many of the endemic species of Florida's scrub ecosystem are extremely rare, they have not been widely researched using tissue culture techniques. In this paper, the amenability of* Conradina etonia, *an endangered scrub mint species, to* in vitro *growth and propagation was investigated using shoot tips. Callus formed and grew rapidly in the presence of both cytokinins and auxins. Rhizogenesis from callus occurred in both the presence and absence of growth regulators. Induction of axillary shoots from the main explant stem occurred on media containing 3.0 mg/L 6-[γ,γ-dimethylallylamino]purine + 0.3 mg/L indole-3-acetic acid. When excised and placed on fresh media, these shoots produced three to four adventitious shoots each. Subculturing the adventitious shoots onto media devoid of growth regulators resulted in stem elongation, leaf production, and occasionally root formation. The results suggest that micropropagation may be an option for the propagation of this species.*

Key Words: Organogenesis, micropropagation, *in vitro* propagation, *Conradina,* Florida native plants, conservation

The genus *Conradina* (family Lamiaceae) consists of six allopatric species of minty aromatic shrubs (*C. canescens, C. brevifolia, C. etonia, C. glabra, C. grandiflora,* and *C. verticillata*), characterized by dense hairs on their lower leaf surfaces and by a sharply bent corolla tube in the flowers (USFWS, 1993). Five of the species are endemic to Florida, and one (*C. verticillata*) is endemic to north-central Tennessee and Kentucky. Five of the six species are threatened or endangered (USFWS, 1993), with the most rare considered to be *C. etonia.*

Conradina etonia was discovered in the Etonia Scrub in Putnam County, Florida by Robert McCartney in September 1990. Its entire known range is within a subdivision containing streets and a few residences (Kral and McCartney, 1991). There are no known individuals on protected lands, and its two existing populations are on land slated for development (USFWS, 1994). The U.S. Fish and Wildlife service listed *C. etonia* as endangered in July, 1993 (USFWS, 1993).

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Current efforts are underway at botanical gardens and institutions associated with The Center for Plant Conservation (CPC) to understand and conserve *Conradina etonia.* The Florida plant conservation process encompasses research, education, philanthropy, government, and resource management (including *in situ* and *ex situ* activities) in its long term goals (CPC, 1995). One type of *ex situ* approach, *in vitro* plant propagation (micropropagation), is being increasingly recognized worldwide as a valuable method for augmenting conservation strategies (Krogstrop et al., 1992). Micropropagation uses a stem tip or other plant material to generate numerous plantlets on culture media containing the proper nutrients and plant growth regulators. This technique is becoming increasingly important in conservation because it has a minimum impact on existing populations, can yield as many as a million plantlets a year (Dodds and Roberts, 1995), can be used to propagate species whose seeds are recalcitrant (Fay, 1992), can restore fertility to infertile lines (Bramwell, 1990), can generate pathogen-free plants to rescue diseased collections (Fay and Muir,1990), and can provide a good source of plant tissue for long-term storage of germplasm (Bramwell, 1990). Although tissue culture has so far been applied to very few Florida native plants, it has already been used successfully for propagation (Kent et al., 2000), and has the potential to be of great value to Florida's conservation and restoration efforts.

The objectives of the recovery plan for *Conradina etonia* include research on its biology and the propagation of sufficient numbers of individuals for introduction on protected lands (USFWS, 1994). To date, very few biological data have been reported for *C. etonia,* and its seeds are recalcitrant to conventional propagation (Race, 1997). The objective of our research was to determine the response of *C. etonia* explants to various growth regulators that might support a micropropagation protocol. It is our hope that the development of a successful micropropagation protocol may serve to support the conservation of this species.

MATERIALS AND METHODS—Seventy apical cuttings were excised from a *Conradina etonia* shrub (accession # Ce119353) in an outdoor plot located at Bok Tower Gardens, Lake Wales, Florida, during the period from June 1996–September 1996. Cuttings were briefly immersed in isopropanol and rinsed in distilled water prior to storage at approximately 4° C until further treatment. Each apical cutting was trimmed to one 1.5 cm long section containing one node, and was surface sterilized in a laminar flow hood by a five minute immersion in 70% ethanol, followed by exposure to aqueous 1% benomyl + 1% captan + 0.1% mercuric chloride for 10 minutes, and then were soaked in 20% bleach + Tween™ 20 for 15 minutes. Explants were rinsed in sterile distilled water between each sterilization step and prior to transfer vertically onto MS-CIM media. Cultures were maintained in 30 mm Pyrex™ tubes filled with 25 ml media and fitted with Bellco™ caps. Cultures were incubated at 25°C under a cool white 40W fluorescent bulb with 16 hours of light followed by eight hours of darkness. The following media were based on Linsmaier and Skoog's (1965) modification of Murashige-Skoog (1962) medium: MS is growth regulator-free and supplemented with 10 μg/l $NiSO_4$, MS-CIM contains 2.0 mg/L α-naphthaleneacetic acid (NAA) with 0.3 mg/l kinetin, and MS-RM contains 0.3 mg/l indole-3-acetic acid (IAA) with 3.0 mg/l 6-[γ,γ dimethylallylamino]purine (2-IP). The follow-

FIG. 1. 59-day old culture of *Conradina etonia* on MS-RM with its callus base and two axillary shoots.

ing media were based on Lloyd and McCown's (1980) Woody Plant Medium: WPM is growth regulator-free and supplemented with 10 μg/l $NiSO_4$, WPM-CIM contains 2.0 mg/l NAA with 0.3 mg/l kinetin, and WPM-RM contains 0.3 mg/l IAA with 3.0 mg/l 2-IP. The pH of MS-based media was adjusted to 5.6, the pH of WPM-based media was adjusted to 5.2, and all media were solidified with 0.8% TC™ agar and autoclaved for 15 minutes at 121°C.

RESULTS—*Culture establishment*—Internal contaminants overran all but one initial culture. In the surviving culture, a 1.5 cm long stem section, positioned vertically into MS-CIM, formed an approximately 3/4 cm diameter brown friable callus at the stem/media interface within two weeks. After two more weeks, the entire callus was subcultured onto fresh MS-CIM because of significant media browning that accompanied callus growth. After another two weeks, the callus was divided into four 0.75 cm diameter segments. Two segments were subcultured onto WPM-CIM and one onto MS-CIM. The fourth segment, which included the original explant, was subcultured onto MS-RM to observe any effects resulting from a shift in exogenously applied plant growth regulators.

In 10 days an axillary shoot emerged from one side of the initial explant, and a second axillary shoot emerged on the other side seven days later (Fig. 1). When evaluated two weeks later, no further changes were evident.

Callus cultures—Callus on MS-CIM grew faster than on WPM-CIM. When callus diameter reached 2.5 cm, one half of each callus was subcultured onto fresh MS-CIM, and the other half was subcultured onto MS. Callus growth was somewhat slower on MS. Continued browning of the media accompanied new callus growth on each media. Subculturing the calli onto fresh media at 1–2 week intervals eliminated all browning within 6 weeks. Calli which were generated on MS were subcultured onto either MS-CIM, MS-RM, or MS containing only IAA, 2-IP, or 6-benzylaminopurine

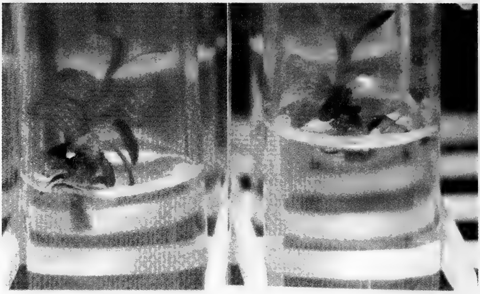

FIG. 2. Continued dedifferentiation of shoot base tissue into callus in an *in vitro* generated adventitious shoot of *Conradina etonia* on MS-RM, 7 days following transfer from MS-RM.

(BAP). With the exception of MS + 2-IP, callus growth occurred on all media tested. The morphology of all calli, except those on MS + 2-IP, was medium to dark brown and friable, with the darkest calli developing on MS-RM and MS + IAA. New surface growth of calli on MS-RM occasionally appeared green, though these areas turned brown within a week. Calli on MS + 2-IP became flat, shiny and brown-black, and no growth was observed. Some calli developed roots within two weeks of incubation. This rhizogenesis occurred most frequently with calli on MS-CIM or MS, and less frequently with calli on WPM or MS-RM. Most rhizogenesis was in the form of numerous short aerial roots with infrequent occurrences of additional long roots extending below the media surface.

Shoot cultures—The two axillary shoots that developed from the initial surviving explant were excised and transferred to fresh MS-RM. Each shoot grew rapidly; within two weeks, one shoot developed three adventitious shoots at its base and the other developed four. When each additional shoot attained a length of 1.5 cm, it was excised and transferred to fresh MS-RM, and subcultured at 2 week intervals. Following three subcultures, the basal tissue of each shoot began to rapidly dedifferentiate into callus (Fig. 2). Excising the remaining shoot tissue and transferring it to media without growth regulators eventually resulted in a cessation of callus formation. The response of shoots to growth regulator-free media included stem elongation, leaf formation, and in some cases, root formation, resulting in the production of entire plantlets (Fig. 3) (the number of shoots with this response was limited to 12 from one initial explant, because of fungal contamination in the remainder of cultures at the conclusion of this study).

DISCUSSION—*Conradina etonia* is the most rare of the six *Conradina* species. No *in vitro* work has previously been reported on any member of

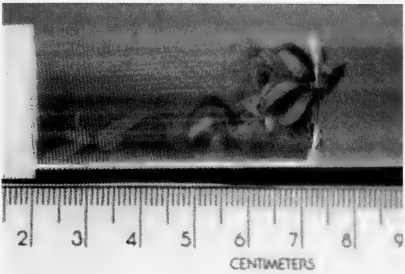

FIG. 3. An *in vitro* generated adventitious shoot of *Conradina etonia* developing into an entire plantlet with roots, stem and leaves on MS, 50 days after excision from shoot explant on MS-RM.

this genus. Knowledge about the *in vitro* response of threatened and endangered plant species enhances our ability to propagate and to culture them in order to study their unique cell biology and biochemistry, including possible valuable secondary metabolites, without disturbing sensitive wild populations.

Bacteria and fungi may be present on the inside of field plants, and surface sterilization procedures may fail to eradicate them. Accordingly, culture contamination is a frequent occurrence in the initiation of tissue cultures from field explants, and the percentage of axenic initial cultures can be quite low. Contamination may also occur at any time during tissue culture propagation, for various reasons. In many cases, the number of initial cultures may be increased simply by collecting large numbers of explants (hundreds, for example) for culture initiation. This is usually not feasible or desirable to do with an endangered species. Nonetheless, if as few as one culture is successfully initiated, an infinite number of sub-cultures can potentially be derived from it.

The medium developed by Murashige and Skoog (1962) for tobacco (*Nicotiana tabacum*) is widely used for many plant cultures. The reduced salinity level of Woody Plant Medium, developed by Lloyd and McCown (1980) for mountain laurel (*Kalmia latifolia*), is preferable for many woody plant cultures. In this study, Woody Plant Medium did not appear to be superior to MS medium, as modified, for the cultures of *C. etonia,* although it is a woody plant.

Callus is an amorphous mass of undifferentiated cells that are often rapidly dividing. Callus occurs in nature following tissue damage, and can be induced experimentally with a combination of media and growth regulators appropriate for the species. Callus production is important in tissue culture, because callus can differentiate into organized structures such as roots (rhizogenesis), stems (caulogenesis), and somatic embryos, and can also produce valuable secondary products such as flavors, fragrances, and drugs.

Conradina etonia callus was readily initiated in this study. The callus cultures gave rise to roots but not shoots. Callus media contained auxins (IAA and NAA), cytokinins (kinetin, 2-IP, BAP), cytokinins plus auxins, or were growth regulator-free. In culture, auxins typically promote cell growth and root initiation, whereas cytokinins promote cell division and shoot initiation. Root formation only occurred in the presence of both auxins and cytokinins, and on medium devoid of growth regulators.

All callus growth occurring within six subcultures of the initial callus culture was accompanied by significant media browning. Although the reason for the browning was not determined, one possibility is the production of phenolic compounds by the callus cells. Plant polyphenol oxidase and tyrosinase are activated by tissue injury, such as the excision of a stem tip for use as an explant. These enzymes oxidize phenolic compounds, resulting in the presence of dark colored compounds in the media that can be inhibitory to growth (Dodds and Roberts, 1995). Repeatedly subculturing onto fresh media at two week intervals eliminated all browning.

Peterson (1998) reported that calli derived from *in vitro* grown leaves appeared to be rapidly growing, were light green, friable, and had white crystalline surface areas. These calli were morphologically distinct from the calli generated from the initial *in vivo* grown shoot tip explant, which were medium to dark brown. None of the callus cultures derived from *in vitro* grown leaves exhibited evidence of media browning. Because callus of *Conradina etonia* forms, grows readily, and demonstrates organogenesis, this species may be amenable to further tissue culture research which includes a callus stage.

Axillary shoots were readily induced from the main *Conradina etonia* explant. Repeated subculturing of these shoots resulted in the repeated production of several adventitious shoots at their bases. When subcultured onto MS-RM, the shoot base tissue began dedifferentiating into callus. When subcultured onto MS without growth regulators, no dedifferentiation occurred, and shoot initiation occurred at a reduced rate. When transferred to MS, these shoots responded with vigorous stem elongation and leaf production. Therefore, subculturing newly regenerated shoots from MS-RM onto growth regulator-free MS permitted continued shoot growth while avoiding basal tissue dedifferentiation. In addition, root formation was observed in these shoot cultures on MS. In this way, cultures of *C. etonia* with the appearance of entire plantlets were produced *in vitro,* demonstrating that this species may indeed be amenable to successful micropropagation. Although this first step has been achieved, many challenges remain before plantlets can be routinely produced *in vitro,* acclimated to field conditions, and established in safe field habitats.

Described here for the first time is the amenability of a *Conradina* species, *C. etonia,* to callus formation and micropropagation. Callus grew well on MS-CM and MS-RM, and demonstrated the capability for organogenesis. Axillary shoots were produced from stem tip explants on MS-RM, multiplied through the formation of adventitious shoots, and developed into full plantlets on MS. It should now be possible to develop a successful micropropagation protocol for this species which may be applicable to the other threatened or endangered *Conradina* species.

ACKNOWLEDGMENTS—We thank Margaret Hames, who first brought the genus *Conradina* to our attention, and Tammara Race, Curator of Endangered Species at Bok Tower Gardens in Lake Wales, Florida, for providing access to her plots for sample collection and for her expertise and generosity.

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SEASONAL DISTRIBUTION OF MANATEES, *TRICHECHUS MANATUS LATIROSTRIS*, IN DUVAL COUNTY AND ADJACENT WATERS, NORTHEAST FLORIDA

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Abstract: *Aerial surveys of manatees (*Trichechus manatus latirostris*) were conducted between March 1994 and May 1998 to assess temporal trends in counts and activities of manatees in the Lower St. Johns River (LSJR) and Atlantic Intracoastal Waterway (ICW). More manatees were observed in the LSJR compared to the ICW. Most (50–79%) manatees in LSJR were engaged in resting activity, followed by traveling (17–21%) and feeding (11–21%), with few observed cavorting (4–10%). In the ICW, manatees engaged in traveling (8–76%) and resting (18–89%) predominantly, with little feeding (0–11%) and no cavorting. This suggested that the ICW was used primarily as a travel corridor for seasonal north/south migrations. Seasonal analysis revealed that manatees were distributed throughout most of the study area except in winter months, when manatees congregated at industrial sites that discharge warm-water (information about manatee usage of these sites is also discussed). Manatee seasonal distribution was correlated with high concentrations of tape grass (*Vallisneria americana*) which is a preferred food source for manatees. Most manatees were distributed within 91 m from shore and used the protected areas near lines of private and commercial docks to rest, feed, travel and cavort.*

Key Words: Aerial survey, endangered species, Duval County, Florida, Florida manatee, distribution, abundance, behavior, *Trichechus manatus latirostris*, West Indian manatee

Florida manatees (*Trichechus manatus latirostris)* occur in the St. Johns River, Duval County, in northeastern Florida and are considered one of the most endangered marine mammals in the U.S. (Garrott et al., 1994). Watercraft collisions have been identified as the largest human-related contributor to manatee mortality (Ackerman et al., 1995; Wright et al., 1995; Marmontel et al., 1997). Regulations governing the speed of watercraft have been the main mechanism used by conservation agencies to minimize the effect of watercraft on manatees. Manatees are protected as endangered species by state and federal laws because mortality rates throughout Florida are considered too high for successful recovery of manatee populations (Marmontel et al., 1997). In 1989, the State of Florida identified 13 counties in which high rates of manatee mortality had occurred. These counties were required to develop conservation measures to reduce manatee mortality (Department of Natural Resources, 1989). Duval County ranked fourth highest among these counties in number of manatee deaths from 1974 to 1998 (Florida Department of Environmental Protection, Bureau of Protected Species Management. Unpubl. Data). Prior manatee studies in northeastern Florida include Irvine and Campbell (1978), Hartman (1979), Rose and McCutcheon (1980) and Kinnaird (1985). Data from these studies did not represent a continuous record and published information on manatee populations in Duval County was limited in that respect (Valade, 1991). Kinnaird (1985) flew a comprehensive survey of northeast Florida (July 1982–June 1983) encompassing Duval, St. Johns, Flagler, and Volusia Counties and Valade (1991) flew a two-year study covering Duval County waters (May 1988–April 1990).

The City of Jacksonville was required by the State of Florida to develop a Manatee Protection Plan. A database of manatee statistics was compiled, including habitat use, water quality, occurrence at over-wintering sites, and use of travel corridors. As a part of that research, aerial surveys were conducted to assess the distribution of manatees in Duval County and adjacent waters.

Aerial surveys have been used to monitor Florida manatees since 1967 (Hartman, 1979). Methods for mapping manatee distribution have undergone many changes in an effort to accurately document population size and movements. Aerial surveys are still considered the most cost-effective method for estimating numbers and location of manatees in large areas like Duval County (Irvine, 1982; Ackerman, 1995). Lefebvre and co-workers (1995) have reported that accuracy in estimating trends in manatee population size is limited because of visibility and sampling biases. As a result, counting manatees from a plane is considered to be a conservative estimate of manatee numbers and distribution. Surveys provide a snap-shot record of spatial distribution and habitat use and have been used in support of conservation efforts (Ackerman et al., 1995).

METHODS—Aerial surveys consisted of two flight routes within Duval County: (1) the Atlantic Intracoastal Waterway (ICW) covering the area from just north of Nassau Sound to Palm Valley, including the mouth of the St. Johns River at Mayport, Blount Island, and extending inland to the mouth of the Trout River (Fig. 1); (2) the Lower St. Johns River (LSJR) and associated tributaries from the Trout River to Julington Creek, including Doctor's Lake. We attempted to do both surveys on the same day but this was not always possible. In some cases surveys were separated by two or three days because of unfavorable weather conditions or aircraft mechanical problems. Survey altitude averaged 152 m and air speed was maintained at about 138 km/hr. Time was spent circling around marinas and warm-water effluents to obtain the most accurate count. Aerial surveys were conducted on an average of twice each month (Table 1) similar to methods used by researchers in the past (Kinnaird, 1985; Packard, 1985; Ackerman, 1995). Surveys used a Cessna 172 high-wing aircraft. Pilots were experienced in low-altitude, slow-speed flight that required doing circles over areas where groups of manatees were observed or likely to be observed. The primary observer occupied a front seat in the aircraft and used polarized sunglasses to reduce glare reflecting from the water surface.

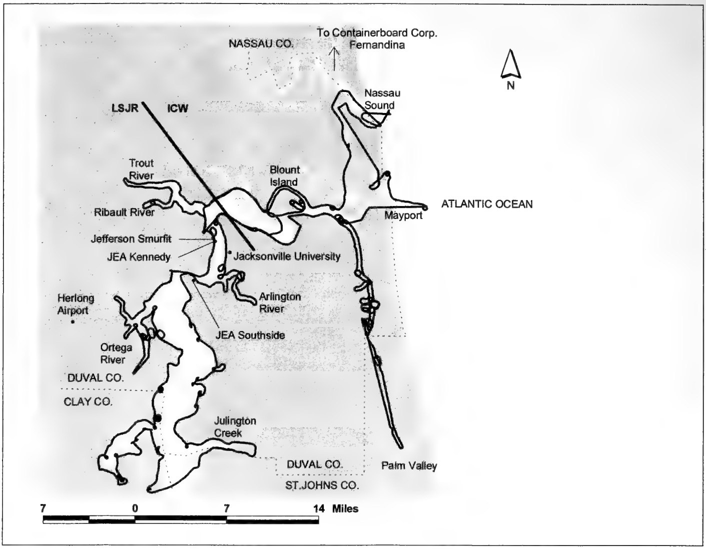

FIG. 1. Map of the study area showing the location of St. Johns River and Intracoastal Waterway flight paths, Duval County, Florida.

TABLE 1. Summary of the total number of aerial surveys in which manatees were observed, and single highest day counts by year (1994–1998).

Year	No. of surveys	Adults	Calves	Total	% Calves	SHDC[1]
			LSJR			
1994[2]	19	783	67	850	7.88	113
1995	22	583	36	619	5.82	76
1996	21	706	92	798	11.53	124
1997	23	1113	89	1202	7.40	136
1998[3]	9	62	1	63	1.59	—
			ICW			
1994[2]	12	74	7	81	8.64	21
1995	23	79	6	85	7.06	21
1996	23	84	11	95	11.58	16
1997	24	73	10	83	12.05	20
1998[3]	9	9	2	11	18.18	—

[1] SHDC = Single Highest Day Count.
[2] March to the end of December.
[3] January to the end of May.

We recorded water temperature (°C) each week at the Jacksonville University dock (Fig. 1) using a Yellow Springs Instrument dissolved oxygen meter with thermistor (model 51B, YSI Incorporated, Yellow Springs, Ohio 45387). Measurements were recorded between 2 PM and 4 PM. We recorded tidal stage at the beginning of each aerial survey as high, medium (rising or falling) or low. Determinations were based on NOAA tide tables.

Air temperatures (°C), weather, air visibility, and wind speed (knots) and direction (compass bearing) were recorded at the beginning of the survey from National Weather Service information at Herlong Airport. In addition we recorded the survey date, Flight company, plane number, survey area, names of pilot and observer and survey start and end times.

We circled groups of manatees several times to increase the probability of spotting all individuals. Number and location of adults and calves and their behavior were recorded on U.S. Geological Survey 1:24,000 maps. Calves were defined as manatees less than or equal to half the size of the adult with which they were associated (Irvine, 1982). Surveys were not conducted when dense clouds, fog, smoke from fires, rain, or winds greater than 37 km/hr occurred.

Manatees swimming in a discernable direction were considered to be traveling. Resting animals appeared motionless on the bottom. In contrast, animals that were feeding stirred up mud and food debris around them. Cavorting manatees were observed swimming in close proximity to each other and caused considerable turbulence and turbidity in the water.

We recorded the number of manatees at warm-water effluents between December–March. These sites included the Jacksonville Electric Authority's Southside and Kennedy power plants (Fig. 1) which we surveyed at ground level from the bank of The St. Johns River on a daily basis around 11 AM. We also surveyed Jefferson Smurfit's paper mill in Jacksonville and The Containerboard Corporation of America's paper mill in Fernandina, Nassau County, by aerial survey twice per month.

We entered data into a Geographical Information System (GIS) data base as x-y coordinates in Geographic projection. Points were input by the observer working from the U.S. Geological Survey 1:24,000 maps. Each point represented a sighting of one or more manatees. Other Windows-based software used included ArcView 3.1, (Environmental Systems Research Institute, Inc., Redlands, CA). Statistical software used was Minitab 10.1 for Windows, (Minitab Incorporated, State College, PA). Manatees migrating into or out-of the study area tended to use the ICW in early spring or late summer, respectively. Manatees remaining in the study area tended to be concentrated in the St. Johns River during most of spring and summer. We created two data sets in order to analyze the LSJR and ICW data separately because manatees use these systems differently.

In the statistical analysis we used as the dependent variable the natural log (count+1) of the total number of manatees observed per flight. The reason for transforming the data was to correct for uneven variances in the data and avoid the log of zero. Zero counts frequently occurred in winter months so it was important to consider them. We counted the number of manatees occurring in seasons as follows: spring (March–May), summer (June–August), fall (September–November) and winter (December–February). We modified the year variable so that the month of December for a given year was included as part of the data for the following year (e.g., December 1996 was included with 1997, etc.). Step-wise regression analysis determined which variables explained the most variation in the data. Water temperature, tidal stage, season (forced into the analysis as dummy variables), month and year were the independent variables tested. Numeric values were assigned to the tide data as follows: Low (L) = 1, Medium (M) = 2 and High (H) = 3. Step-wise regression may have interpreted the numeric values as having some numeric significance so an ANOVA was conducted with The natural log (count +1) as dependent variable and tide as an independent variable to check this. We produced box plots of mean counts of manatees by season and year showing 5% and 95% confidence intervals. We also produced seasonal box plots of the percentage frequency of manatees engaged in traveling, resting, feeding or mating activity showing 5% and 95% confidence intervals. Numbers represent the percent frequency of behaviors encountered within seasons based on the total number of manatees observed within seasons.

TABLE 2. Mean total number of manatees observed in The Lower St. Johns River and The Intracoastal Waterway, March 1994–May 1998.*

Season	N flights	Mean total number	StDev
		LSJR	
Winter	24	0.39 a	0.611
Spring	28	14.46 b, d	1.566
Summer	23	67.92 c	0.494
Fall	20	26.39 c, d	1.279
		ICW	
Winter	25	1.21 a, c	0.921
Spring	27	4.33 b, c	0.903
Summer	18	1.88 a, b, c, d	0.723
Fall	16	0.62 a, c, d	0.630

* Means with the same letter are not significantly different. LSJR (F = 53.43, df = 3, 91, $P \leq 0.0005$); ICW (F = 8.35, df = 3, 85, $P \leq 0.0005$); StDev = Standard deviation; Pooled StDev = 0.830.

RESULTS—*Lower St. Johns River*—Step-wise regression indicated season (R^2 = 64.8%) and water temperature (R^2 = 78.4%) accounted for most of the variation in the data. Tidal stage was not a significant factor affecting manatee distribution (P = 0.2). ANOVA on total count [natural log (count + 1)] and season indicated season was significant (df = 3, 91, F = 53.4, P ≤ 0.0005). Fisher's LSD test of means (Minitab 10.1 for Windows, Minitab Incorporated, State College, PA) indicated a significant difference among seasons except for spring and fall (Table 2).

Box plots of the total count [natural log (count + 1)] by season within each year in the LSJR showed variances between mean summer and winter counts to be small in comparison to variances associated with mean spring and fall counts. Counts in summer were significantly higher than in winter (P = 0.05). Mean counts for spring and fall showed greater variances but were not significantly different from each other over the duration of the study (Fig. 2).

Box plots of the percentage of manatees observed in the LSJR engaged in traveling, resting, feeding and cavorting, by season indicated that between 17–21% of animals were engaged in traveling activity during all seasons. Between 50–79% of animals were engaged in resting behavior. Between 11–21% of animals engaged in feeding activity during spring, summer and fall with no animals observed feeding in winter. From 4 to 10% of animals were engaged in cavorting during spring, summer and fall over the course of the study. No manatees were observed mating in winter (Fig.3).

Atlantic Intracoastal Waterway—Step-wise regression indicated that winter, spring and summer accounted for most of the variation in the data (R^2 = 24.4%). Tide was not a significant factor affecting manatee numbers. Regression analysis indicated that there was no significant interaction between water temperature and season in the ICW. Also, the winter water temperature was significant (P = 0.03) and appeared different from the other

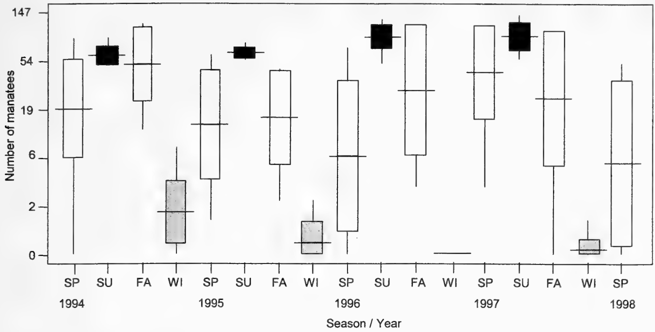

FIG. 2. Mean counts (horizontal lines) of manatees in Lower St. Johns River by season and year between spring 1994 and spring 1998. Vertical lines indicate minimum and maximum counts. Boxes indicate 5% and 95% confidence intervals for the mean. Summers are shaded black; winters gray; springs and falls are not shaded. The y-axis represents numbers converted from a log scale. On the x-axis SP = Spring; SU = Summer; FA = Fall; WI = Winter.

seasons. Fewer observations were made on fewer manatees during winter months.

ANOVA on total count [natural log (count +1)] and season indicated season was significant (df = 3, 82, F = 8.4, P ≤ 0.0005). Tukey's pairwise comparisons of means indicated that there was no difference between sea-

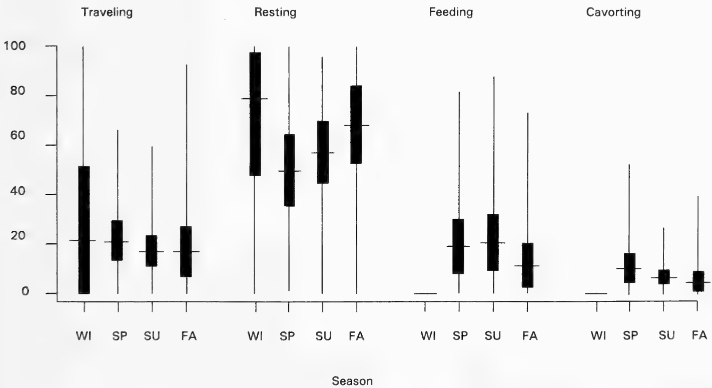

FIG. 3. Percent frequency of manatees engaged in traveling, resting, feeding and cavorting activity by season in LSJR, Duval Co., Florida between 1994–1998. Horizontal lines indicate the mean. Vertical lines indicate minimum and maximum. Boxes indicate 5% and 95% confidence intervals of the mean. On the x-axis SP = Spring; SU = Summer; FA = Fall; WI = Winter.

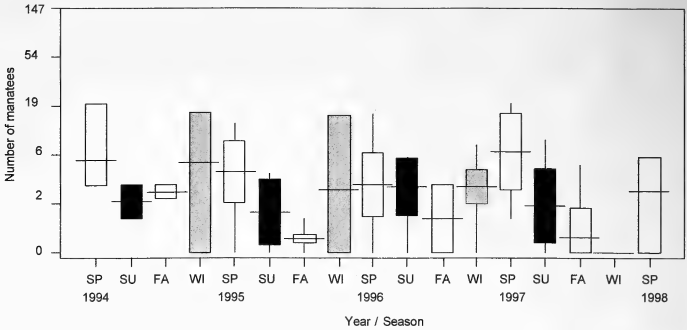

FIG. 4. Mean counts (horizontal lines) of manatees in the Intracoastal Waterway by season and year between spring 1994 and spring 1998. Vertical lines show minimum and maximum counts. Boxes show 5% and 95% confidence intervals of the mean. Summers are shaded black; Winters are shaded gray; Spring and Fall are not shaded. The y-axis represents numbers converted from a log scale. On the x-axis SP = Spring; SU = Summer; FA = Fall; WI = Winter.

sons except for spring (Table 2). Spring counts were significantly higher than those in fall and winter ($P = 0.05$). Confidence intervals showed overlap between spring and summer. An ANOVA was conducted to explore the interaction of season and year and was significant ($df = 16, 69$; $F = 3.4$ and $P \leq 0.0005$). Tukey's pairwise comparison of means indicated that the number of manatees observed was not significantly different among seasons. No difference was indicated between winter seasons by year except for the winter of 1997, which was significantly different from winter of 1996 ($P \leq 0.05$) and all springs except for an overlap with the spring of 1998. Fall counts were significantly lower in 1995 and 1997 than in the other years.

Box plots of the total count [natural log (count + 1)] by season within year indicated variances between seasons over the study period were relatively larger and uniform than fall 1994 and 1995. Mean number of animals seen in fall and winter seem to have declined over the study period. Summer variances were significantly smaller than winter variances ($P = 0.05$). Springs were not significantly different from other seasons except fall 1995 and fall and winter 1997. Summers were not significantly different from other seasons except for winter 1997 (Fig. 4). Falls were not significantly different from other seasons except winter 1997. Fall variances were smaller in 1994 and 1995 and larger in 1996 and 1997. Winters were not significantly different from other seasons except winter 1997. Winter variances were larger in 1994 and 1995 and smaller in 1996 and 1997.

Box plots of the percentage of manatees engaged in traveling, resting, feeding and cavorting indicated 8% of animals were traveling during winter which was significantly different from spring and summer but not fall. Spring (53%), summer (76%) and fall (41%) percentages were not signifi-

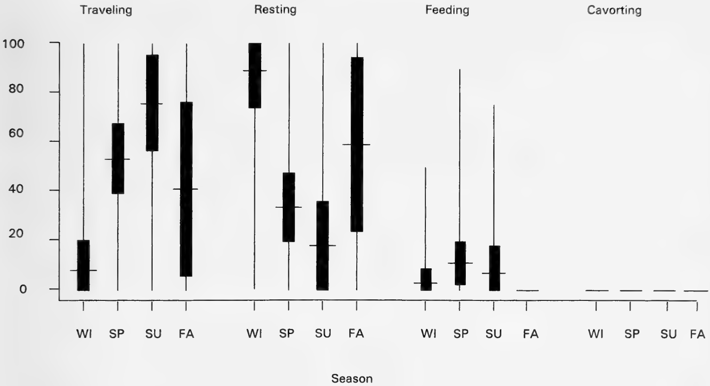

FIG. 5. Percent frequency of manatees engaged in traveling, resting and feeding activity by season in ICW, Duval Co., Florida between 1994–1998. Horizontal lines indicate the mean. Vertical lines indicate minimum and maximum. Boxes indicate 5% and 95% confidence intervals of the mean. On the x-axis SP = Spring; SU = Summer; FA = Fall; WI = Winter.

cantly different. In winter, 89% of animals were observed resting which was a significantly higher percentage than in spring and summer but not fall. Spring (34%), summer (18%) and fall (59%) were not significantly different from each other. Fall had the greatest variances for traveling and resting animals compared to the other seasons. Low numbers of animals were observed feeding in the ICW during winter (3%), spring (11%) and summer (7%) which were not significantly different from each other. No animals were observed feeding during the fall (Fig. 5).

Warm-water refuges—Daily ground surveys in winter showed manatees remaining in the study area assembled in groups at 3 warm-water outfalls. Jacksonville Electric Authority's Southside (JEAS) and Kennedy Generating Stations (JEAK) and Jefferson Smurfit's paper mill are located within an 11 km radius of downtown Jacksonville (Fig. 1). Power plants operated intermittently during cold weather each year and manatees moved between them (Fig. 6). In 1994, the total daily count of manatees varied from 0–21 animals at JEAS between 11/29 to 12/14. These animals then moved 9 Km from JEAS to JEAK over 4 days, when JEAK began to produce electricity and the JEAS plant went off-line. Total daily count of manatees varied from 0–21 animals between 12/15 to 12/24 (1994). On 12/29, a total of 15 animals were recorded by aerial survey at JEAS, none were observed at JEAK. In 1995, total daily count varied from 0–9 animals between 11/11 to 11/19 at JEAS. A total of 2 animals were observed at JEAK on 12/24, none at JEAS. In 1996, total daily counts varied from 0–19 animals between 11/11 to 11/22 at JEAS. A total of 3 animals were seen at JEAK from 11/29 to 11/30,

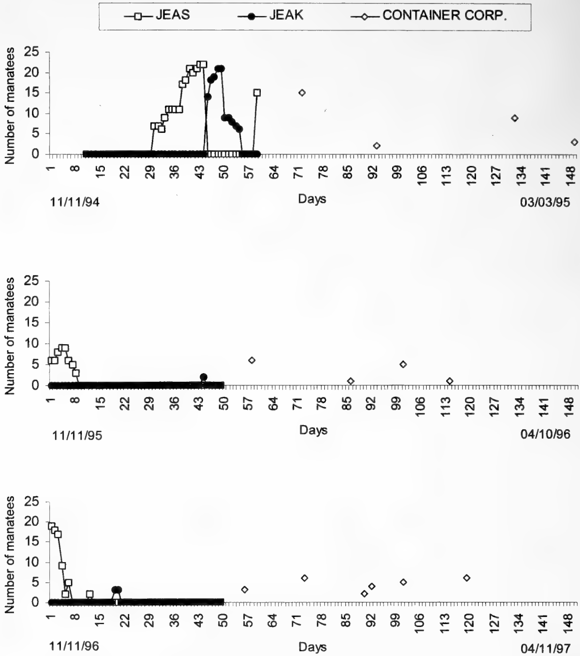

FIG. 6. Manatees recorded using daily ground surveys for 150 day period each winter, beginning 11 November to April 11, 1994–1996, at Jacksonville Electric Authority's Southside (JEAS) and Kennedy (JEAK) Generating Stations in downtown Jacksonville, Duval County, Florida. Manatees sighted at Containerboard Corporation of America, Nassau County, Florida were recorded by aerial survey.

none at JEAS. In 1997 no manatees were observed at JEAS or JEAK. Although manatees have been seen at Jefferson Smurfit's paper mill, none were observed on bi-weekly aerial surveys in winter. Manatees were observed at Containerboard Corporation of America (CCA), Fernandina, Nassau County between January to April (1995–98) using aerial surveys twice per month. In 1998, no manatees were observed at this site.

The spatial distribution of manatee groups appeared to be the same from year to year. Observations about the seasonal distribution of animals were demonstrated more effectively when displayed on GIS maps (Fig. 7–10). Each dot on these maps indicates one or more manatees and the maps are a representative sample of one year of five (1997) depicting that distribution.

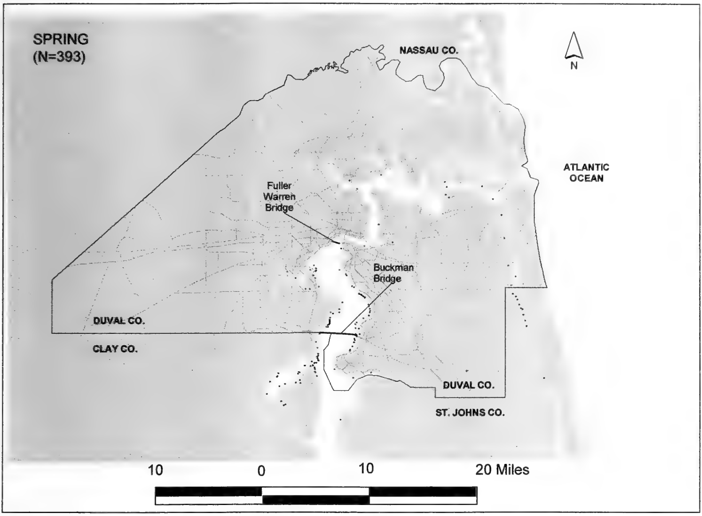

FIG. 7. Aerial sightings of manatees in Spring of 1997, Duval Co., FL.

DISCUSSION—Data were analyzed separately for two reasons: (1) Manatees used the LSJR and ICW differently; (2) The LSJR data set was larger and more robust because of more sightings in comparison to the ICW data set. Manatees used the ICW primarily as a travel corridor during their north/south migration. Increased use was seen in spring as manatees moved north into the study area and in winter when the animals moved south out of the study area—except for the winter of 1998 when manatees migrated earlier because of an earlier onset of cold weather that year (Fig.4). These observations are supported by Valade (1991) who reported that the ICW was used as a migratory route for manatees along the east coast of Florida and south Georgia and that increased numbers of sightings in the ICW were staggered one month ahead of increased sightings in the LSJR. Valade (1991) also reported that manatee distribution in LSJR was correlated with food resources. We found that most manatees were observed in shallow, near-shore habitat with abundant tape grass. This has been reported by others (Irvine, 1982; Kinnaird, 1983; Ackerman, 1995).

Increased spring and summer sightings are not attributed to an influx of animals from Blue Springs (170 Km further south within the St. Johns River system). Satellite telemetry indicates that animals moving into the LSJR were Florida's east coast animals migrating north/south each year (Deutsch et al., 2000). Scar pattern identification suggests significant numbers of manatees are part of the Atlantic sub-population and that in the last decade, only

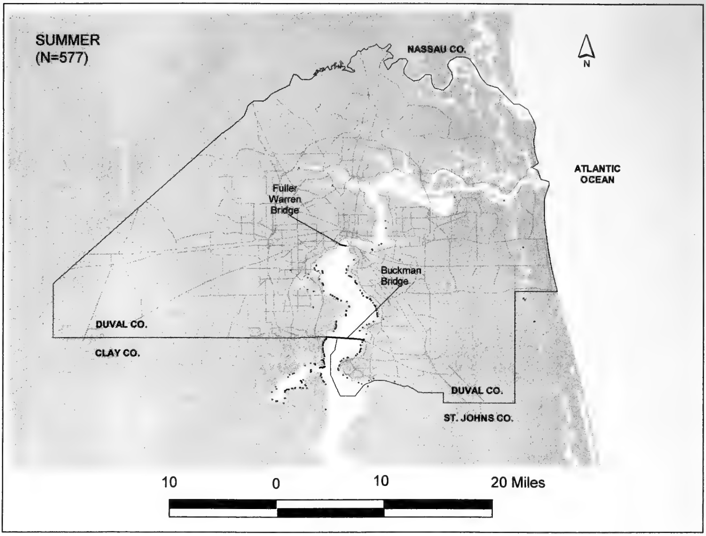

FIG. 8. Aerial sightings of manatees in Summer of 1997, Duval Co., FL.

one manatee has been identified as coming from the Blue Springs population that has been recovered dead in Duval County (Beck, 2000).

Manatees were distributed throughout the LSJR and ICW in spring (Fig. 7). Highest concentrations of manatees occurred south of the Fuller Warren Bridge (east and west banks) and Doctor's Lake in summer where significant quantities of submerged aquatic vegetation exist (Fig. 8). During spring and summer, manatees with new calves were consistently seen in the back waters of tributaries. These areas may provide more shelter than the open river. In late summer and fall, manatees tended to be seen in the main stem of LSJR (Fig. 8–9). This may be caused by tributary waters becoming too warm and possibly uncomfortable for manatees. In winter, few manatee sightings occurred because most animals moved south of Duval County (Fig. 10).

Manatees engaged in traveling, resting, feeding and cavorting during all seasons in LSJR. Manatees spent most of the time resting, followed by traveling and feeding and the least time was spent cavorting. In winter it was difficult to find manatees feeding because manatee abundance was low and distribution was not at the grass beds. No manatees were observed cavorting in winter (Fig.3). In the ICW, manatees spent most of the time traveling, followed by resting and then feeding (Fig. 5). Number of manatees traveling in winter was low because of low abundance and the fact that they tended to congregate at warm-water sources. We observed little or no sub-

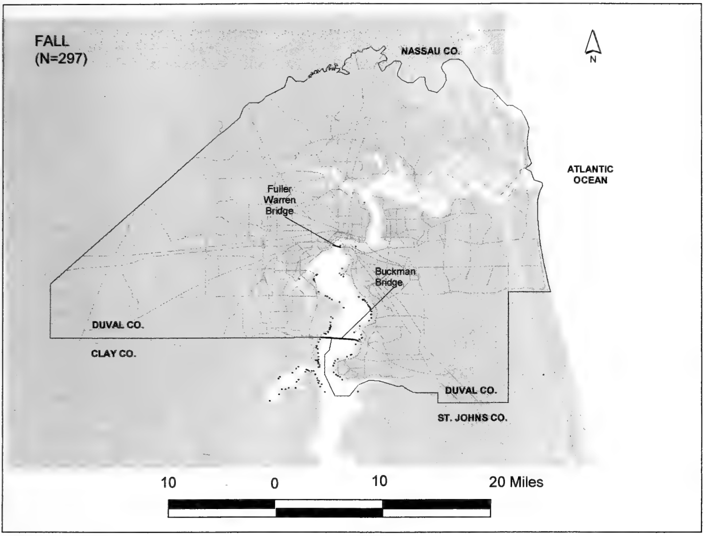

FIG. 9. Aerial sightings of manatees in Fall of 1997, Duval Co., FL.

merged aquatic vegetation in the ICW, which may be the reason for finding low numbers of manatees feeding there.

Warm-water refuges—Data provided some information about the number of manatees using power plant effluent each year. No more than 25 animals per survey were observed at power plants. Kinnaird (1983) reported seeing up to 13 animals in the warm water out-falls of two generating stations and one industrial plant in Jacksonville. Moreover, Kinnaird and Valade (1983) maintain that these aggregations are unstable and are made up of transient animals. The reason for manatees congregating at these plants was in part due to Jacksonville Electric Authority (JEA) conducting on site testing of power plant facilities in November. In 1997, JEA refrained from testing their plants in November. As a result, manatees were not drawn to the thermal effluent and proceeded to move out of the area. Manatees sighted at Containerboard Corp. of America, Nassau County, did not exceed 15 animals in 1994 or 6 in 1995–96. In 1997 Containerboard Corp. installed diffusers on their thermal effluent pipe and no manatees were sighted.

There is a strong seasonal distribution of manatees in Duval County, Florida. Analysis of aerial survey data supports the conclusion that manatees migrate into northeast Florida during the spring, remaining throughout the summer and migrate south in the fall. The ICW is a travel corridor for

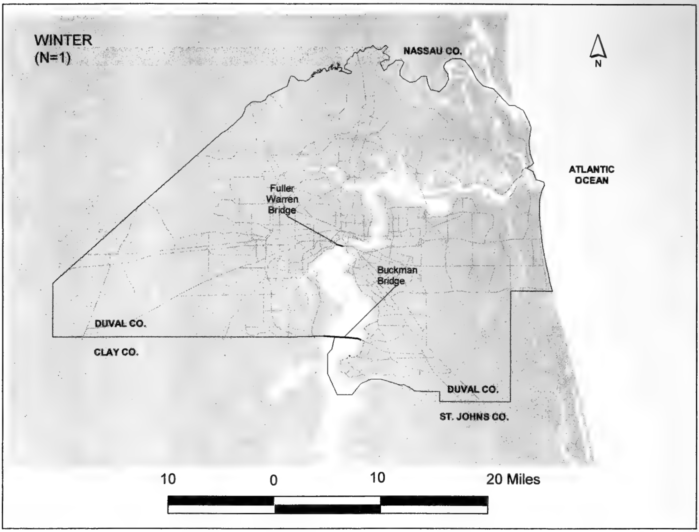

FIG. 10. Aerial sightings of manatees in Winter of 1997–1998, Duval Co., FL.

Atlantic Coast animals moving north/south. Manatees also use the industrial warm water discharges during the winter months. Manatees were generally distributed close to shore with distribution correlated with food resources containing relatively high concentrations of tape grass (*Vallisneria americana*). Developing this comprehensive data base has allowed the City of Jacksonville to create a Manatee Protection Plan.

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REVIEW

Paul Martin Brown with drawings by Stan Folsom, *Wild Orchids of Florida: with References to the Atlantic and Gulf Coastal Plains.* University Press of Florida, Gainesville FL. Pp. 409. Price $24.95.

FLORIDA has 118 species and varieties of orchids growing wild, of which 106 are native. This is about half of all known species of orchids found in the United States and Canada. The classical work on Florida orchids for over 30 years is *The Native Orchids of Florida* by Carlyle A. Luer. With color photographs, technical line drawings, species distribution maps, technical descriptions, and detailed nomenclature, Luer's book was a necessity for anyone with a serious interest in orchids. It is now not only expensive and difficult to obtain, but a significant number of changes in nomenclature have taken place and several new species discovered in Florida in the past 30 years. Paul Martin Brown's *Wild Orchids of Florida* brings us up-to-date on the native orchid flora of the state. He appropriately dedicates his book to Carlyle Luer. While Luer's book is a hardbound coffee table classic, Brown's book is a flexible cover field guide that can be easily carried with you on your orchid forays. *Wild Orchids of Florida* is well illustrated with over 400 photographs primarily by the author, line drawings of each species by Stan Folsom, and Florida distribution maps for each species. The design of the book is very effective with text for each species on the left page and with two to seven photographs on the right. Each species account includes a description of the plant, habitat, flowering period, and often interesting notes. As Luer says in the forward to Brown's book, it is more than a field guide for identification, and this is certainly true. Paul Martin Brown, founder of the North American Native Orchid Alliance and the *North American Native Orchid Journal*, has extensive knowledge of Florida orchids and brings his familiarity with the plants in the field into his book. In the last ten years, due mostly to advances in DNA analysis, our increased knowledge has resulted in a significantly revised taxonomy to help us better understand the family. Some names now used for Florida orchids may be unfamiliar to the reader. Some of these names result from the splitting up of large genera such as *Spiranthes, Oncidium, and Epidendrum.* Others are the result of circumscribing Florida plants in a narrow sense, sometimes as endemic species, rather than as wide-ranging polymorphic species. Still others are recently described species (e.g., *Spiranthes sylvatica*) or recently discovered non-native, naturalized species (e.g., *Phaius tancarvilleae* and *Spathoglottis plicata*). Paul Martin Brown brings us painlessly up-to-speed on these changes. Part three of the book helps the user with the unfamiliar names by providing a list of recent literature references for new taxa, combinations, and additions to the flora, lists of synonyms and misapplied names, and a cross reference to the names in Luer's book (Luer, 1972). Also included in the back of the book are some interesting orchid statistics and suggestions for orchid hunting in Florida. The keys are simple and are written to assist in the identification of orchids in the field. They work very well for that purpose. I encountered only a couple of minor glitches in the keys. *Wild Orchids of Florida* is a "must have" book for everyone interested in these fascinating plants, whether you are a beginner or a professional. Brown is to be congratulated for this excellent book.—Richard P. Wunderlin, University of South Florida, Tampa.

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REVIEW

C. J. S. Thompson, *Alchemy and Alchemists,* Dover Publications, Inc., Mineola, NY, 2002. iv + 249 pp, 77 illustr., 13.5 × 21.5 cm, paper, $13.95.

THIS is an unabridged republication of a classic work, *The Lure and Romance of Alchemy,* originally published in 1932. It is a well-written account of a field that is now called a pseudo-science. The author, properly, I believe, is concerned with illustrating the role of alchemy in the development of chemistry. The transition between pseudo-science and chemistry is most significant in the life of Robert Boyle (1627–1691), commonly known as "the father of chemistry", who was an alchemist earlier in his life and a chemist towards the end. Thompson's account is thorough, useful, and replete with helpful insights. The illustrations are particularly helpful in appreciating development of distillation in general and stillheads in particular. His is a balanced account that reveals the greed as well as the glory of particular alchemists, the useful discoveries and the dead ends, the mystical and the systematic (for elements for example as well as for operations such as precipitation, distillation, filtration, sublimation, etc.). Brief, but useful, biographies are available for significant participants and prominent contributors (Albertus Magnus, Raymond Lully, Basil Valentine, Cornelius Agrippa). A useful comparison of alchemy in different locales (Egypt, Arabia, China, India, Europe) is available, reminding us of the universality, and perhaps intertwining, of greed and love of knowledge. Alchemy, if a pseudoscience, was also a significant endeavor that occupied worthy (and some unworthy) persons for about 2000 years and produced useful results. This book provides an economical, authoritative, very readable source of information on this important topic in the development of chemistry.—Dean F. Martin, University of South Florida, Tampa.

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