RESEARCH ARTICLE

Decoupling Natural and Anthropogenic Fire Regimes: a Case Study in Everglades National Park, Florida

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ABSTRACT: Anthropogenic fire regimes obscure natural fire regimes, reducing the ability to manage fire-frequented habitats ecologically. To address this problem, we attempted to decouple natural and anthropogenic fire regimes by comparing them to seasonal climatic patterns and landscape characteristics in Everglades National Park (1948-1999). Of the total area burned by lightning fires, 57% resulted from ignitions seven days within onset of the wet season, 11% from ignitions starting 7-21 days before onset, and 36% from ignitions > 7 days after onset. In contrast, of the total area burned by incendiary fires, 89% resulted from ignitions > 7 days before onset, and 40% resulted from ignitions > 35 days before onset. Moreover, ~100% of the total area burned by prescribed fires resulted from ignitions > 7 days after onset. Lightning fires occurred most frequently in wet seasonal savanna that had limited accessibility to humans; incendiary fires were most frequent in wet seasonal savanna that had ready accessibility to humans. In addition, 35% of the total area burned by incendiary fires in areas of limited accessibility occurred when incendiary fires spread from readily accessible areas. We propose that, because incendiary fires occurred at the end of the dry season, they burned drier fuels and burned more intensely than lightning fires, which generally occurred following the first rains of the wet season. Incendiary fires thus should be more likely to burn lower elevation areas that normally hinder fire spread. Finally, by occurring later in the wet season, prescribed fires may have burned patchily and insufficiently intensely to achieve restoration goals. Decoupling anthropogenic and natural fire regimes using seasonal climate patterns and landscape characteristics leads us to propose strategies to guide fire management in the park.

Index terms: climate, incendiary fire, landscapes, lightning fire regimes, prescribed fire

INTRODUCTION

Humans reduce the integrity of fire-frequented ecosystems. One major effect is disruption of those fire regimes in which lightning is the primary natural source of ignition. For example, fragmentation of landscapes reduces fire frequency, causing fuel accumulation and high intensity fires in regions that naturally experience frequent, low-intensity, lightning-ignited fires (Platt 1999; Veblen et al. 2000). Anthropogenic effects, once present, hamper efforts to describe historical characteristics of natural fire regimes. As a result, land managers often have little scientific basis for implementing prescribed fire regimes that mimic natural fires and their effects.

Can characteristics of anthropogenic and natural fire regimes be decoupled sufficiently to develop a scientific basis for managing fires? Successful decoupling can be accomplished when a fire history is obtained from natural archives such as tree rings (Swetnam et al. 1999; Huffman et al. 2004). Many regions, however, do not provide these archives, including extensively logged forests, regions where trees have poorly-defined annual rings (e.g., the tropics and sub-tropics) (Taylor 1981), or where all aboveground biomass is consumed by fires (Keeley and Fotheringham 2001). These regions require alternative methods for decoupling anthropogenic and natural fire regimes.

One alternative approach is to describe how anthropogenic and natural fires regimes differ in their relationship to climate. Climate has strong influences on natural fires by controlling fuel status (e.g., moisture), fuel connectivity, and lightning ignition (Latham and Williams 2001; Beckage et al. 2003). Climate has less influence on anthropogenic fire regimes because it does not control when and where people ignite fires. Rather, anthropogenic ignitions tend to be governed by accessibility to fuels and by customs that lead to ignitions. For example, hunters use fires to clear fuels and maintain habitat, and prescribed fires are used for restoration efforts. If natural and anthropogenic fires start at different times and places, they are likely to burn under different fuel conditions, which should lead to predictable differences in fire characteristics, such as duration, size, intensity, and patchiness. Resultant discoveries should be capable of guiding fire management, even in regions where natural archival data are not available (Keeley and Fotheringham 2001).

The climate-based approach for decoupling natural and anthropogenic fire regimes has a number of advantages. It makes few assumptions other than those based on relationships between climate, ignition of fuels, and spread of fire. Moreover, high quality data describing climate are readily available, and therefore associations of climate with fire regimes are limited mostly by data describing fire. Where such data exist, predictions of fire regime characteristics based on climate should facilitate landscape-level fire management as well as experimental approaches aimed at further decoupling anthropogenic and natural fire regimes.

We attempt to decouple natural and anthropogenic fire regimes in one fire-frequented landscape, Everglades National Park (ENP) in southern Florida. ENP has recorded data on fires since 1948, a period well after fires had become influenced by fragmentation resulting from construction of canals and roads. Thus, natural and anthropogenic fire regimes in ENP are confounded. For each recorded fire, park personnel noted area burned, ignition date, and ignition source (lightning, incendiary [arson and accidental], and prescribed). For each ignition source, we describe fire frequency and area burned. We further characterize fire regimes of these ignition sources in different regions in the park (fire management units), which vary in physiognomy, accessibility for people, and connectivity of fuels. We then compare observed landscape-level patterns to data on climate, including annual onset of the wet season, rainfall, water levels, and lightning strikes. By combining these observations, we are able to describe seasonal differences in natural and anthropogenic fire regimes across the Everglades' landscape. These comparisons identify important anthropogenic alterations on the park's fire regimes, and suggest additional strategies for decoupling natural and anthropogenic fire regimes.

METHODS

Study site

Everglades National Park (25.25-25.75 °N, 80.5-81.1 °W) is located at the southern tip of the Florida peninsula (Figure 1). The low-relief terrain consists of a limestone substrate overlain with sand, marl, or peat (< 1 to 2 masl), as well as limestone outcroppings (1.5-4 masl) (Hoffmeister et al. 1967). During the wet season, this broad "river of grass" (Douglas 1947) can absorb large amounts of rainfall before the highest elevations become saturated. Moreover, the dry season is sufficiently long and intense (October to mid-May) that water levels typically fall below ground level at all but the lowest elevations (Chen and Gerber 1990; Beckage et al. 2003). These annual changes in hydroperiod across shallow elevation gradients result in distinct zones of vegetation, ranging from mangroves and coastal marshes (< 1 masl) to pine savanna (1.5-4 masl) (Craighead 1971). They also result in fuels throughout the park becoming moist and fragmented during the wettest periods, but becoming connected toward the end of the dry season, especially during droughts caused by the La Niña phase of the El Niño Southern Oscillation (Beckage et al. 2003).

Data collection

No accurate written records of natural fires in ENP exist prior to settlement and alteration of the greater Everglades landscape (Robertson 1953). In addition, reliable information on the region's fire regimes cannot be gathered from dendrochronology, as the region's trees produce either poorly-defined annual rings or rings that do not appear to be synchronized with environmental conditions governing growth (J.M. Huffman, manager, St. Joseph Bay Buffer Preserve, Florida Dept. of Environmental Protection, pers. comm.). Layers of charcoal do indicate a record of past fires, but it is unknown if these layers may be sufficiently defined to derive a fire frequency (Winkler et al. 2001).

When the park was created in 1948, ENP personnel initiated a record of all observed fires, noting each fire's size, ignition date, and ignition source (prescribed, incendiary, or lightning). They also assigned each fire a "fire management unit" – a region with overtly different fire regimes (Figure 1). For our study, we describe fire in the four units that were the most important because of their size or biodiversity, including: (1) pine savanna, dominated by *Pinus elliottii* Engelm. var. densa Little & Dorman (south Florida slash pine) in the overstory and a fire-adapted, species-rich community in the understory; (2) coastal area, dominated by mangroves mixed with salt/brackish marshes and salt flats; (3) wet seasonal savanna, seasonally inundated by fresh water and dominated by *Cladium jamaicense* Crantz (sawgrass) mixed with occasional tree islands; and (4) East Everglades, wet seasonal savanna that has a number of roads and had some human habitation. This last fire management unit has been outside of the park's jurisdiction until recently, but fire personnel were involved in fire suppression there because its fires posed a hazard to the park proper. The park started acquiring the East Everglades in 1991, and by 2004 owned > 99% of it.

We compared the fire records with data detailing onset of the wet season, rainfall, stage water levels, lightning strikes, and accessibility. Yearly onset of the wet season for 1965-2005 was derived by determining the day when average daily dew point temperature rose above and remained above 21 °C (Biedinger and Lushine 1998). A daily dew point temperature of 21 °C served as an indicator of the beginning of the wet season because it successfully predicted when daily summertime convections and increased rainfall began (Biedinger and Lushine 1998). Dew-point data were not available from 1956-1965, and therefore onset of the wet season was estimated using the daily minimum temperature as a proxy for the average daily dew-point temperature. Data for determining onset were collected at the Miami International Airport Weather Service Meteorological Observatory. For rainfall, we collected daily records (1948-1998) from a gauge (NOAA's station 088780-1) on the north border of the park (25°75' N, 80°83' W) (Figure 1). Daily stage water levels (1952-1999) were obtained from the park for a well (P33) located in the center of Shark Slough, the primary drainage system in ENP (Figure 1). Bimonthly cloud-to-ground lightning strikes (1991-2000) were obtained from Global Atmospherics, Inc. for a 300,000 ha rectangle that approximates the boundary of the park (Figure 1). We corrected these data for detection efficiencies using a 1999 standard developed by Global Atmospherics, Inc. To estimate accessibility, maps from the park were

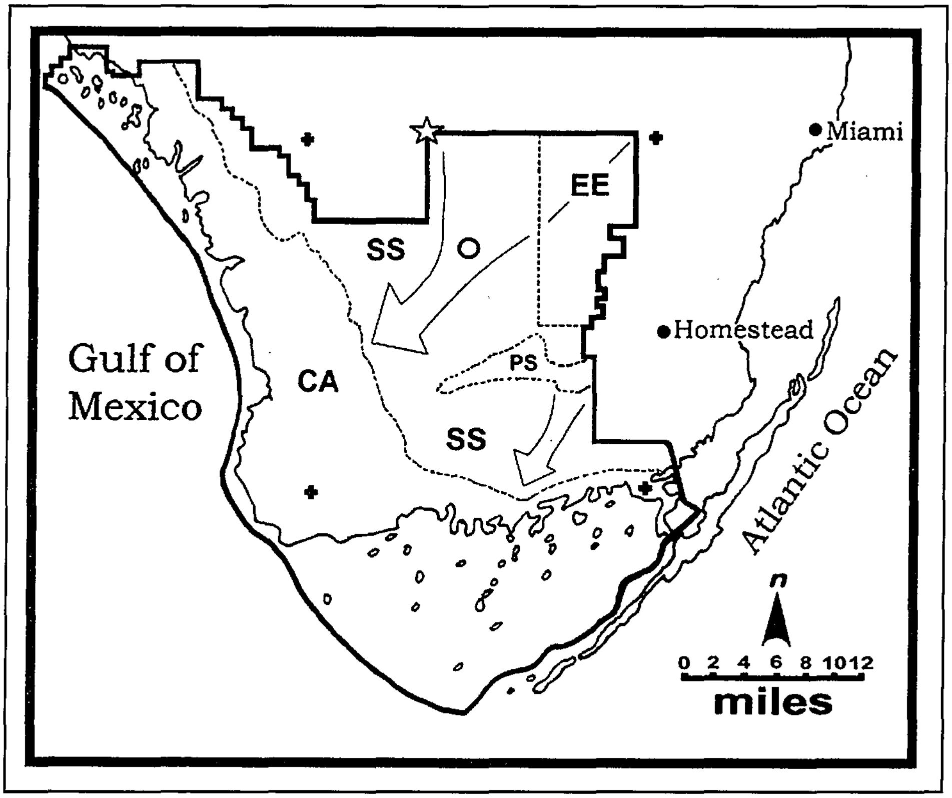

Figure 1. Four fire management units in Everglades National Park, south Florida, USA. The units include the coastal area (CA), wet seasonal savanna (SS), pine savanna (PS), and East Everglades (EE). The thick line indicates the boundary of the park, dashed lines indicate boundaries of the fire management units, and pluses (+) indicate corners of the area in which cloud to ground lightning strikes were recorded (25°25'-25°75' N, 80°5'-81°1' W). The circle with gray fill indicates the location of well P33 (25°36' N, 80°42' W). It is located in the center of Shark River Slough, the park's main drainage, whose flow is indicated with an arrow. The flow of Taylor Slough, to the southeast, is also indicated with an arrow. The star refers to rain station 088780-1 (25°45' N, 80°5' W).

examined to determine concentration of roads in each fire management unit.

RESULTS AND DISCUSSION

Park-wide fire regime characteristics

From 1948 to 1999, 1600 fires in the four fire management units burned 560,000 ha. This resulted in an overall return interval of 23 years (Table 1). Fires were highly variable in size, ranging from 0.1 to 59,000 ha and averaging 350 ± 2000 ha (± 1 SD). Small fires were more frequent than large fires; fires < 100 ha accounted for 70% of all fires (Figure 2). In contrast, large fires were far more important in accounting for total area burned over the half-century of records. The 44 fires > 1500 ha (Table 2) accounted for 69% of the total area burned, but only 3% of the ignitions (Figure 2). This tendency for large fires to account for most of the total area burned commonly occurs in other regions (e.g., boreal forest (Johnson 1992) and chaparral (Keeley and Fotheringham 2001)).

The park's lightning and incendiary (arson and accidental) fire regimes had some important similarities and one important difference. Both ignition sources produced large numbers of fires; of the total number of ignitions in the park, 42% were incendiary and 33% were lightning. Both sources also had a tendency to have many small fires and much fewer large fires that varied considerably in size (Figure 2). This resulted in each source having large coefficients of variation for area burned (549% for incendiary fires and 692% for lightning fires), as well as a strong positive skew in their frequency distribution of fire size (Figure 2). The major difference between the two regimes was that incendiary fires burned more than twice the area burned by lightning fires (Table 1).

The similarities of lightning and incendiary fire regimes in ENP probably occurred for two reasons. First, both sources had many "attempts" to start fires; there were many lightning strikes, and there were many accidents and attempts at arson. Second, because conditions for fire spread were usually poor, most ignitions resulted in small fires. On occasion, however, low rainfall, low humidity, and strong winds, when coupled with dry contiguous fuels, facilitated rapid fire spread. Under these conditions, there was good potential for large areas to be burned, whether from lightning or an incendiary source. Such weather conditions generally occurred during droughts at the end of the dry season in La Niña years (Beckage et al. 2003).

In contrast to lightning and incendiary fires, prescribed fires were highly controlled. Because each prescribed fire involved substantial financial, personnel, and time investments, they were less frequent (25% of the park's total ignitions) and burned less area (17% of the total area burned) (Table 1). Moreover, because they were ignited to burn designated areas, their size distribution was less skewed and had lower variability (COV = 168%; Figure 2). Prescribed fires rarely were small, but neither did they reach the size of the largest lightning or incendiary fires (Table 2).

Fire regimes across the Everglades landscape

Accessibility for people and connectivity of fuels influenced fire regimes in ENP. Fuel connectivity, which controls the spread of the fires, varies with elevation. Fire management units with higher elevations have shorter hydroperiods and are therefore drier, have more connected fuels, and have a greater proportion of flammable vegetation (Table 3A; Schmitz et al. 2002; Slocum et al. 2003). Based on this variation, we ranked within-unit connectivity as: pine savanna > East Everglades ≈ wet seasonal savanna > coastal area (Table 3A). Accessibility for people controls ignition frequency of anthropogenic fires. Within the park, roads govern access, as all of

Table 1. Statistics describing fire regimes in four fire management units in Everglades National Park, south Florida, USA (1948-1999). Return intervals were calculated by dividing total flammable area by average area burned per year.

	Fire Management Unit				
	Pine Savanna	Wet Seasonal Savanna	East Everglades	Coastal Area	Total
Flammable area (ha)	8,620	155,803	41,476	~ 40,000	248,409
(A) Incendiary					
Number of fires	99	178	333	64	674
Area burned (ha)	14,275	135,224	160,986	5,084	315,569
Area burned > 1500 ha*	8,747	122,728	117,484	2,939	168,762
Return interval	31	60	13	409	41
Mean size (ha) ± 1 SD	144 ± 440	879 ± 3,682	445 ± 2,441	79 ± 296	468 ± 2,572
(B) Prescribed					
Number of fires	209	127	23	34	393
Area burned (ha)	41,527	44,788	7,903	812	95,030
Area burned > 1500 ha*	4,044	15,835	2,868	0	22,747
Return interval	11	181	270	2,561	136
Mean size (ha) ± 1 SD	199 ± 271	352 ± 571	343 ± 431	23 ± 41	242 ± 405
(C) Lightning					
Number of fires	38	275	27	185	525
Area burned (ha)	9,139	117,172	8,462	17,356	152,129
Area burned > 1500 ha*	6,939	102,612	5,093	0	114,644
Return interval	48	69	252	120	85
Mean size (ha) ± 1 SD	240 ± 534	426 ± 2,746	313 ± 713	93 ± 190	290 ± 2,006
(D) All fires					
Number of fires	346	580	383	283	1,592
Area burned (ha)	64,941	297,184	177,351	23,252	562,729
Area burned > 1500 ha*	19,730	241,175	125,445	2,939	389,289
Return interval	7	27	12	89	23
Mean size (ha) ± 1 SD	188 ± 362	534 ± 2,799	429 ± 2,285	82 ± 209	353 ± 2,043

* Refers to area burned by fires that were 1500 ha or more in size. Many of these crossed into more than one fire management unit, in which case the area they burned in each unit was totalled and included in the representative cell.

the park's regions are difficult to traverse otherwise, having either rugged limestone or marshy terrain. We ranked access based on the concentrations of roads in the fire management units as: pine savanna > East Everglades >> wet seasonal savanna > coastal area (Table 3B).

Based on these rankings, we constructed a simple model to predict the proportion of area burned by natural fire in each fire management unit. We used proportion of area burned by natural fire as a measure of the "fire integrity" of each unit. In this model, we assumed connectivity and access contributed equally and negatively to natural fire, because access allows for more anthropogenic ignitions and connectivity allows these ignitions to spread. (Note that trails and roads could also be considered to reduce connectivity by fragmenting fuels, but this typically has not occurred because most roads and trails are narrow, unimproved, and occur at low densities.)

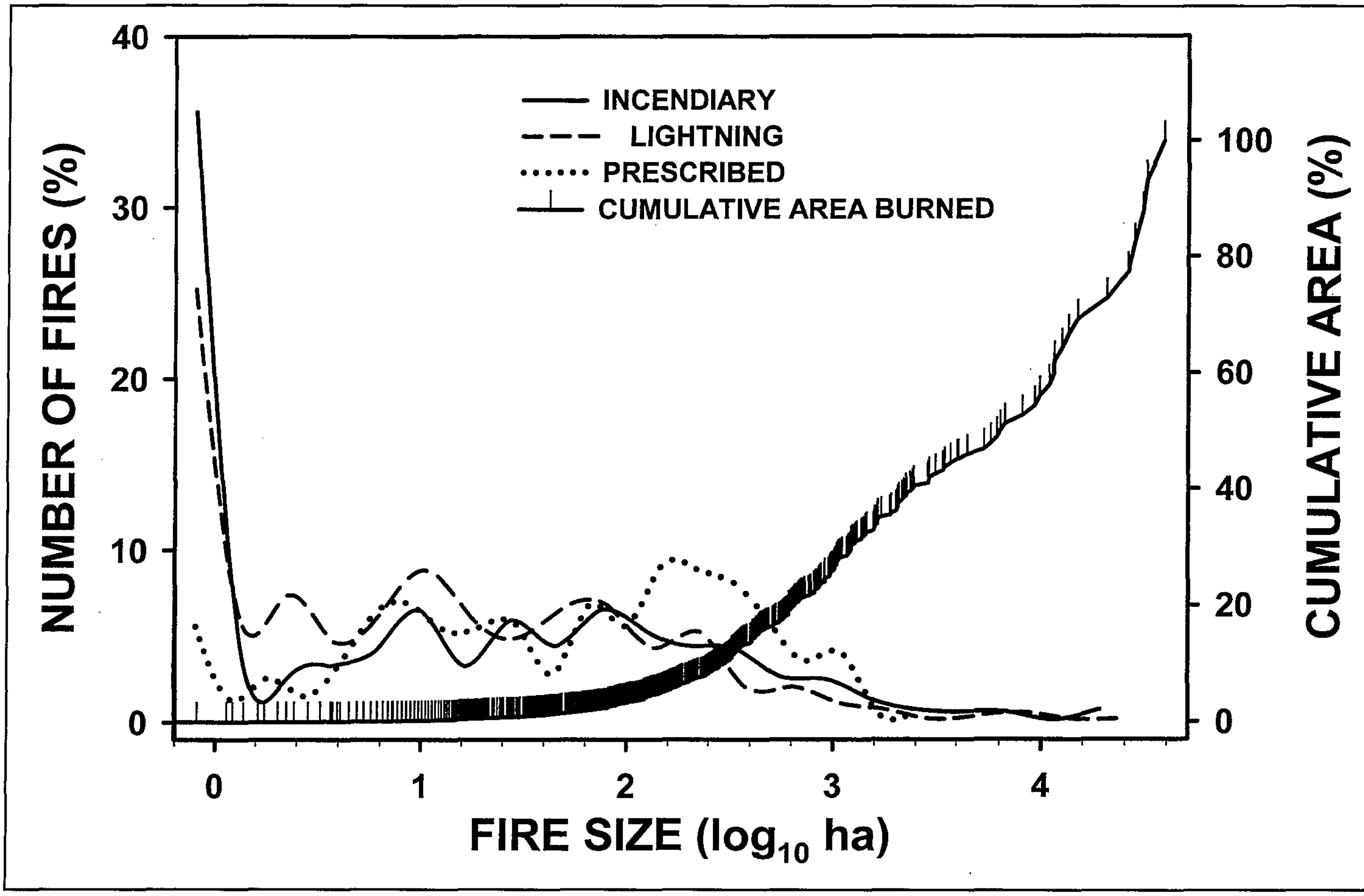

Figure 2. Relationship between size of fires (X-axis) with number of fires (left Y-axis) and cumulative area burned (right Y-axis). Data includes three ignition sources (incendiary, lightning, and prescribed fires), which burned in the four fire managements units (Figure 1) in 1948-1999 at Everglades National Park, Florida, USA. Cumulative area burned is shown with a black line on which each fire is shown with a vertical mark. Figure is a histogram with 22 bins, which are smoothed using the spline method.

We therefore predicted that the relative proportion of natural fire would be: coastal area > wet seasonal savanna > East Everglades > pine savanna (Table 3C). Although this model is crude, the percentage of area burned by lightning fires increased in the same order as our predicted order, except that pine savanna and East Everglades had similar percentages of natural fire (Table 3C). Thus, we propose that connectivity and access are important in governing fire regimes in ENP.

The importance of within-unit connectivity can be further illustrated by comparing the fire regimes of the wet seasonal savanna with the coastal area. Both of these regions had low access, but because they varied considerably in connectivity of fuels (Table 3), their fire regimes were substantially different. The naturally highly-fragmented coastal area was dominated by small lightning fires (Table 1). It had only one fire > 1500 ha (Table 2), and the estimated fire return interval was 89 years (Table 1). In contrast, the large and well-connected wet seasonal savanna was dominated by large fires (Table 2), and had a return interval a third that of the coastal area (Table 1). Because of connected fuels, the wet seasonal savanna was also more vulnerable to incendiary ignitions; incendiary ignitions accounted for 48% of the area burned in the unit, compared to just 22% in the coastal area. Many of the wet seasonal savanna's incendiary fires spread from outside the park; for this reason, fire personnel have used prescribed fires along park boundaries to reduce fuels and the entry of incendiary fire. These prescribed fires accounted for 14% of the area burned in the unit.

Anthropogenic fires dominated the pine savanna and East Everglades, both highly accessible units with well-connected fuels. In the East Everglades, incendiary fires accounted for 91% of the area burned, and the return interval was half that of the wet seasonal savanna (Table 1). The unit's most important fires were twelve incendiary fires > 1500 ha, which altogether accounted for 66% of the area burned in the unit (Table 2). In contrast, there were only two lightning fires > 1500 ha, accounting for 3% of the area burned. Prescribed fires accounted for only 4%. This small amount of prescribed fire was mostly conducted in the 1990s when the park began to buy parcels of the unit. Concurrently, incendiary fire activity decreased markedly; only 7% of the total area burned by incendiary fires in the unit occurred in the 1990s.

In contrast to the East Everglades, prescribed fire was the dominant anthropogenic fire type in the pine savanna,

Table 2. Characteristics of fires > 1500 ha in Everglades National Park, south Florida, USA (1948- 1999). Included for each fire are: rank size, area burned, % of total area burned in the park, date of fire, ignition source (I = incendiary, L = lightning, and P = prescribed), fire direction, days before/after onset of the rainy season, and fire management unit (with the first unit listed being where the fire ignited and with percentages being the proportion of area burned in each unit).

Rank size	Area burned (ha)	% Total	Date	Ign. source	Fire direction	Days before/ after onset	Fire Management Unit†
1	58,973	10.5%	5/15/1962	I	SW	-13	East Everglades (47%), wet seasonal savanna (53%)
2	39,838	7.1%	5/17/1989	L	NW	-6	Wet seasonal savanna (96%), pine savanna (4%)
3	30,168	5.4%	4/11/1971	I	SW	-53	East Everglades (100%)
4	26,003	4.6%	4/7/1974	I	W	-29	Wet seasonal savanna (99%), coastal area (1%)
5	22,267	4.0%	5/20/1950	I	SW	0 *	Wet seasonal savanna (91%), pine savanna (9%)
6	17,692	3.1%	6/13/1989	I	NW	21	East Everglades (64%), wet seasonal savanna (36%)
7	14,743	2.6%	5/22/1986	L	SW	1	Wet seasonal savanna (100%)
8	13,328	2.4%	3/27/1975	I	SW	-40	East Everglades (100%)
9	13,052	2.3%	5/8/1950	L	SW	-12 *	Pine savanna (17%), wet seasonal savanna (83%)
10	12,437	2.2%	6/22/1951	L	SW	33 *	Wet seasonal savanna (100%)
11	11,452	2.0%	4/24/1975	I	W	-12	Wet seasonal savanna (100%)
12	11,185	2.0%	5/15/1985	L	NE	-15	Wet seasonal savanna (82%), East Everglades (18%)
13	9,717	1.7%	5/6/1950	I	SW	-14 *	East Everglades (100%)
14	8,032	1.4%	4/11/1989	I	SW	-42	East Everglades (100%)
15	7,708	1.4%	7/5/1981	L	NW	40	Wet seasonal savanna (79%), pine savanna (21%)
16	7,640	1.4%	1/16/1957	I	SW	-90	Pine savanna (13%), wet seasonal savanna (87%)
17	7,287	1.3%	4/12/1981	I	SW	-44	East Everglades (61%), wet seasonal savanna (39%)
18	6,219	1.1%	2/20/1972	I	NW	-76	Wet seasonal savanna (54%), pine savanna (46%)
19	5,679	1.0%	4/27/1974	I	SW	-9	Wet seasonal savanna (100%)
20	5,482	1.0%	3/12/1976	I	NW	-57	Wet seasonal savanna (63%), pine savanna (37%)
21	5,265	0.9%	5/4/1974	L	SW	-2	Wet seasonal savanna (100%)
22	4,277	0.8%	4/30/1990	I	W	-23	East Everglades (52%), wet seasonal savanna (48%)
23	4,003	0.7%	5/4/1986	I	.	-17	East Everglades (100%)
24	3,730	0.7%	11/8/1985	P	NW	162	Wet seasonal savanna (99%), East Everglades (1%)
25	3,109	0.6%	6/12/1951	L	NE	23 *	East Everglades (100%)
26	2,785	7.1%	7/30/1999	P	NE	75	Pine savanna (56%), wet seasonal savanna (44%)
27	2,619	5.4%	3/18/1973	P	S	-65	Wet seasonal savanna (100%)
28	2,595	4.6%	6/7/1951	L	SW	18 *	Wet seasonal savanna (60%), pine savanna (40%)
29	2,591	4.0%	6/24/1951	L	NW	35 *	Pine savanna (16%), wet seasonal savanna (84%)
30	2,429	3.1%	4/29/1963	I	W	-19	East Everglades (100%)
30	2,429	2.6%	4/6/1981	I	SW	-50	East Everglades (99%), wet seasonal savanna (1%)
32	2,408	2.4%	4/4/1995	I	NW	-21	Wet seasonal savanna (83%), pine savanna (17%)
33	2,332	2.3%	5/3/1953	I	NW	-17 *	Coastal area (100%)
34	2,267	2.2%	2/12/1949	I	W	-97 *	East Everglades (82%), wet seasonal savanna (18%)

continued

Table 2. Continued.

Rank size	Area burned (ha)	% Total	Date	Ign. source	Fire direction	Days before/ after onset	Fire Management Unit†
35	2,119	0.4%	6/21/1974	L	NW	46	Wet seasonal savanna (100%)
36	1,987	0.4%	2/5/1983	P	SW	-114	East Everglades (59%), wet seasonal savanna (41%)
37	1,883	0.3%	2/4/1985	P	SW	-115	Wet seasonal savanna (100%)
38	1,814	0.3%	4/22/1949	I	NE	-28 *	Coastal area (22%), wet seasonal savanna (56%), pine savanna (22%)
39	1,688	0.3%	2/11/1982	P	SW	-99	East Everglades (100%)
40	1,657	0.3%	11/7/1981	P	W	165	Pine savanna (51%), wet seasonal savanna (49%)
41	1,628	0.3%	6/6/1999	P	SW	21	Wet seasonal savanna (100%)
42	1,626	0.3%	11/25/1981	P	SW	183	Wet seasonal savanna (100%)
43	1,577	0.3%	1/14/1975	P	N	-112	Pine savanna (100%)
44	1,570	0.3%	12/22/1977	P	N	211	Wet seasonal savanna (100%)
Total:	389,289	69.2%					

* When onset data was not available (1948-1955) we used the median onset date (May 20th) to calculate days before/after onset.

† Many large fires crossed the borders of the fire management units, but how much area they burned in each unit was not detaile in the fire record. To obtain an estimate of area burned in each unit, we superimposed maps of the fires onto maps of the fire management units.

accounting for 64% of the area burned versus 19% for incendiary fire. This prescribed fire resulted in the pine savanna having the shortest return interval of the fire management units (seven years) and fires that tended to be moderate in size (Figure 2; Table 2).

Similar to the pine savanna and the East Everglades, the importance of access has been noted in The Big Cypress National Preserve, northwest of ENP. Like ENP, this region has terrain that is difficult to traverse, and anthropogenic fires were found to be concentrated along roads (Duever et al. 1986).

Fires readily spread among fire management units that were well connected. The most important such connection was between the wet seasonal savanna and the East Everglades. Incendiary fires starting in the East Everglades spread into the wet seasonal savanna and were responsible for much of the area burned there (35% of the area burned by incendiary fires > 1500 ha; Table 2). Another important connection was between the pine savanna and the wet seasonal savanna. Historically, most fires in the pine savanna were probably large lightning fires that spread to or from the wet seasonal savanna. Some hint of this past connectivity can be seen in the fire record; in examining lightning fires that burned > 1500 ha, we found that all such fires that burned in the pine savanna also burned in the wet seasonal savanna (Table 2).

Before extensive anthropogenic changes, fires would have spread into the ENP region from surrounding areas that are now developed and no longer burn. The most important of these areas is probably the greater Miami region. This region, about one-third the size of ENP (Figure 1), used to be highly flammable because it was a mosaic of pine and wet seasonal savanna (Craighead 1971). It therefore represents a large area where lightning used to start fires. These fires would have frequently moved into the ENP region, as greater Miami lies to the east of ENP, and most of the recorded large fires in ENP moved from east to west (Table 2). Other areas that carried fire are north of ENP and are still relatively natural (e.g., The Big Cypress National Preserve and the Water Conservation Areas). They are separated from the park by highways and by prescribed fire along the park's periphery.

In summary, we found that as fuel connectivity and number of roads increased within ENP, fire regimes changed in dominance from lightning fires to anthropogenic fires. We also found that, historically, fire in the park appeared to be largely governed by fuel connectivity, which is now disrupted by anthropogenic alterations. These alterations include: (1) fragmentation of fuels, which reduces spread of fire; (2) habitat destruction, which reduces area where light-

Table 3. Ranking of two factors that govern fire integrity in the fire management units in Everglades National Park, Florida, USA. Included are: (A) connectivity of fuels and (B) access for people. Related factors are also shown under each ranking (e.g., elevation). By combining connectivity and access, we assigned a relative fire integrity to each fire management unit (C), and compared this to the proportion of the total area burned that was attributable to lightning fire.

(A) Connectivity of fuels							
Ranking:	Coastal area	<	Wet seasonal savanna	≈	East Everglades	<	Pine Savanna
Elevation (m):	< 1	≈	<1	≈	< 1	<	1.5 to 4
Hydroperiod (mos yr^{-1}):	> 6	>	< 3 to > 6	≈	< 3 to > 6	>	0 to 3
% area flammable*:	25%	<	96%	≈	98%	≈	99%
(B) Access for people							
Ranking:	Coastal area	≈	Wet seasonal savanna	<	East Everglades	≈	Pine Savanna
Roads (km 1000 ha^{-1}):	0.17		0.58		2.48		7.93
(C) Integrity of fire regime							
Ranking:	Coastal area	>	Wet seasonal savanna	>	East Everglades	≈	Pine Savanna
Contribution of lightning fires:	75%		49%		5%		14%

* Percentage of the fire management unit that contains flammable vegetation.

ning can start fires; and (3) anthropogenic fire, which uses fuels that could be burned by lightning fires. It therefore appears that these alterations have reduced the park's frequency of lightning fire compared to its historic levels. Anthropogenic changes also have made determining historic fire regimes extremely difficult.

Seasonal timing of fires

Ignition frequencies of incendiary and lightning fires varied in seasonal timing because these fires stem from very different ignition sources. Ignition frequency of lightning fires peaked in the middle of the wet season (Figure 3A) because this was the peak period for lightning strikes (Figure 4), and because lightning is extraordinarily powerful and can start fires even in very moist fuels (as indicated by rainfall and water levels as proxies of fuel moisture; Figures 5A, 5B). A typical cloud-to-ground strike reaches temperatures of 30,000°K and dissipates energy equal to one ton of TNT (Bazelyan and Raizer 2000; Rakov and Uman 2003). When a lightning flash of sufficient duration strikes a tree, nearby fine fuels are ignited even if they have a moisture content up to 30% (Latham and William 2001). In contrast, incendiary ignitions at the park are generally weak and have difficulty starting fires when fuels are moist. For this reason, incendiary ignition frequency was directly related to the dryness of fuels (Figures 5A, 5B). Incendiary ignitions may also have decreased in the wet season because the prevalence of biting insects at this time discourages hunting, camping, and other recreational activities in ENP.

Area burned by lightning and incendiary fires also varied in seasonal timing. For lightning fires, 53% of the total area burned over the past half-century was by fires starting seven days within onset, and 36% of the total area burned was by fires starting 7-21 afterwards (Table 2; Figure 3A). Only 11% of the area burned resulted from ignitions starting 7-21 days before onset. These trends in the lightning fire regime were explained mostly by large fires. For example, the park's second and seventh largest fires were lightning ignited, and were started six days after and one day before the onset of the wet season, respectively (Table 2; Figure 3A). In contrast, for incendiary fires, most area burned (89%) resulted from ignitions starting at least seven days before onset, and 40% resulted from ignitions starting 35 days or more before onset (Table 2; Figure 3B). As for lightning fires, these patterns were explained mostly by large fires. For example, the largest, third largest, and fourth largest fires were incendiary and were ignited 13, 53, and 29 days before onset, respectively (Table 2, Figure 3B).

Our finding that lightning and incendiary fires differed in seasonal timing of peak area burned differed from previous studies (Taylor 1981; Doren and Rochefort 1984; Snyder 1991; Gunderson and Snyder 1994). These studies all noted considerable overlap in peak area burned by lightning (May-June) and incendiary fires (April-May). Our standardization of ignition dates to onset of the wet season allowed a more

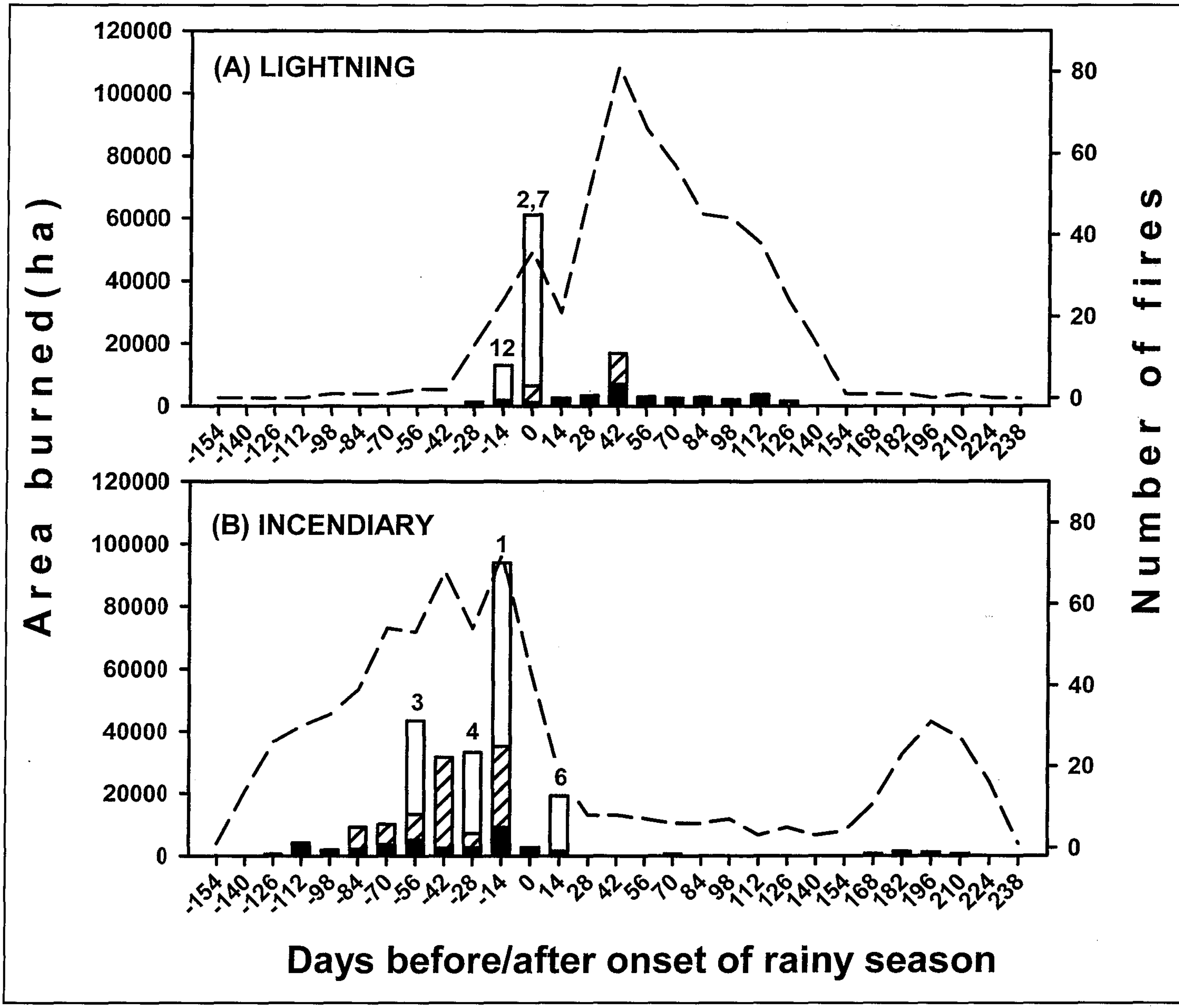

Figure 3. Relationship between onset of the wet season and fire regime characteristics (area burned and number of fires) for (A) lightning fires and (B) incendiary fires in Everglades National Park, Florida, USA (1956-1999). Onset of the wet season is set as zero; intervals on the x-axis are two weeks (e.g., –14 refers to 7 days before onset to 21 days before onset). Area burned is represented by bars, with area in white referring to area burned by the five largest fires of each ignition source; the rank size of these fires are labeled (see Table 2). Area with hatched lines refers to area burned by fires > 1500 ha, but do not include the top five fires. Black area refers to area burned by fires < 1500 ha. Number of fires is shown with dashed lines. Fires from 1948-1955 are not included in the figure because data describing the onset of the wet season does not start until 1956 (see Table 2). The timing of the fires relative to wet season onset is based on recorded dates of ignition; the largest fires may burn more than a month after their ignition dates.

finely-tuned analysis, which revealed this important difference between the lightning and incendiary fire regimes at ENP.

Seasonal differences in incendiary and lightning fire regimes probably generate differences in fire characteristics. Lightning fires igniting close to the onset of the wet season should initially burn fuels that are dry and well connected, resulting in non-patchy, intense fires. These fires should, however, become progressively less intense and patchier as the rains during the dry/wet season transition start to moisten fuels (Figure 5A). These rains will also flood lower lying areas, which will then be protected against burning and will act as firebreaks (Figure 5B). In addition, many lightning fires occur later in the wet season, and should burn patchily and non-intensely.

In contrast, incendiary fires, because they ignite well before onset, will burn when water levels are low and still falling and while rainfall is decreasing (Figures 5A, 5B). We therefore postulate that incendiary fires will generally burn more evenly, intensely, and for longer periods than lightning fires. We further suggest that the

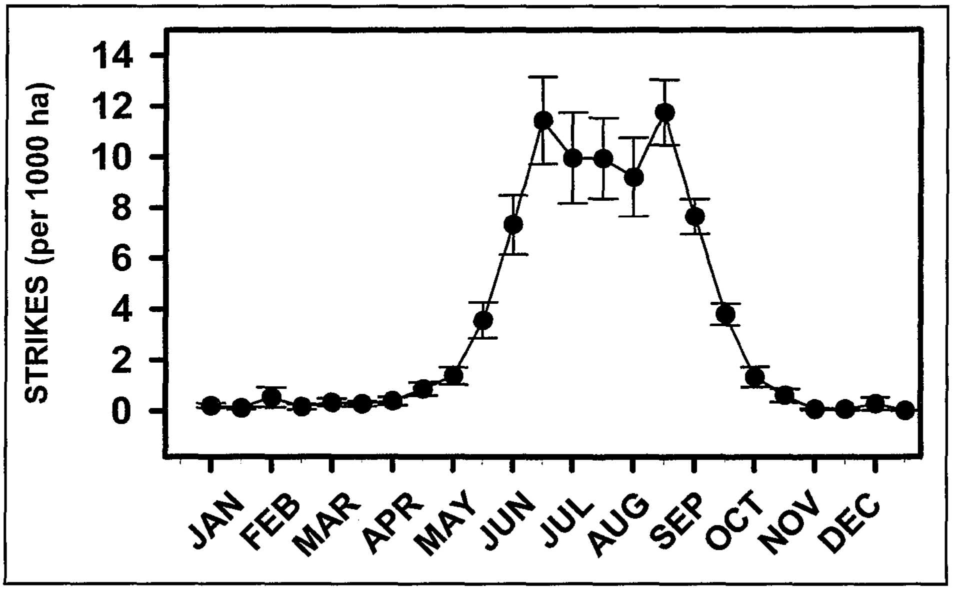

Figure 4. Bimonthly frequencies (mean ± 1 SE) of cloud-to-ground lightning strikes during 1991-2000 within a 300,000 ha box located over Everglades National Park, Florida, USA (25°25'-25°75'N, 81°1'-80°5'W) (Figure 1).

shift from lightning to incendiary ignitions as the most common source of large fires in ENP has resulted in the accumulation of the seasonal effects of these incendiary fires. This shift has driven decade-by-decade changes in fire management policy in ENP (Doren et al. 1993).

Empirical evidence for differences in fire effects between lightning and incendiary fires in ENP is scant. However, a study of prescribed fires in pine and wet seasonal savanna found that seasonal timing has important effects on fire patchiness and intensity (Slocum et al. 2003). Fires conducted late in the wet season were patchier and less intense than fires conducted earlier in the wet season. These characteristics were moderated by elevation, and lower elevation areas operated as fire breaks once inundated. The study did not, however, address the characteristics of fires ignited very close to or earlier than the onset of the wet season. Evidence that these fires are more intense and less patchy is mostly anecdotal, dating back to Robertson (1953).

Incendiary fires that occur before the onset of the wet season may negatively affect the biota of ENP. Compared to natural fires, these fires are more likely to occur when water levels are low and unable to protect vegetation and soils. They may thereby consume peat in wet seasonal savanna, lowering elevations and generating open water (Craighead 1971). This, in turn, leads to shifts in species composition (e.g., lowered water levels reduce the ability of sawgrass to compete against the invasive plant cattail (*Typha domingensis* Pers. southern) (Herndon et al. 1991; White 1994; Newman et al. 1998). Similarly, fires that occur when water levels are low are more likely to burn tree islands in wet seasonal savanna and hardwood hammocks in pine savanna. This may be one reason why these islands and hammocks are being lost in the region (Alexander and Crook 1974; Craighead 1974; Platt 1999; Wetzel 2002; Wetzel et al. 2005). These negative effects of incendiary fires may be especially harmful if they are exacerbated by artificially lowered water levels (Craighead 1971; Newman et al. 1998). Incendiary fires ignited before the onset of the wet season are also more likely to be less patchy than natural fires. Less patchy fires leave fewer refugia for wildfire during fires, as well as fewer patches of suitable habitat afterwards (Gabrey and Afton 2000). Together these effects may have negative impacts on vulnerable wildlife populations (e.g., *Ammodramus maritimus mirabilis* [Cape Sable seaside sparrow]; Taylor 1983; Curnutt et al. 1998; Lockwood et al. 2003). Similarly, less-patchy fires leave behind reduced spatial heterogeneity and microclimate conditions, and a corresponding decrease in biodiversity (Turner et al. 1997).

Lightning fires may also be intense, especially during La Niña-induced droughts (Beckage et al. 2003). This is one way that natural fires maintain environmental heterogeneity. For example, lightning-ignited peat fires produce ponds and sloughs, and generate sites for peat accumulation (Winkler et al. 2001). Similarly, the lightning-ignited Ingraham Fire of 1989 (40,000 ha; Table 2) occurred during a strong La Niña year. This fire, based on field observations made by W.J. Platt and W.B. Robertson (Everglades National Park & U.S. National Park Service Research Biologist, deceased), produced patches in pine savanna, subtropical hammocks, and in wet seasonal savanna that differed in both the occurrence of fire and in the intensity with which they burned. Besides these intense fires, however, lightning fires often start later in the wet season and will have milder characteristics (Figure 3A). We suggest that incendiary fires tend to produce effects that resemble the most intense natural fires, but at a higher frequency, while a more natural (or restored) fire regime would produce greater temporal heterogeneity in fire effects.

The earlier seasonal occurrence of incendiary fires may partly explain why incendiary fires burned more area (Table 1). Early incendiary fires probably have a greater chance to spread because they occur when fuels are drier and less fragmented. In addition, early incendiary fires may preempt fuels that might later be burned by lightning fires. Lastly, conditions a month or two before the wet season are ideal for determined hunters and others to start fires, as during this time fuels are dry and there are very few mosquitoes. The park's largest fire, for example, was actually a conglomeration of fires ignited by hunters seeking to reduce heavy fuel loads that interfered with airboat travel and hunting.

Given that incendiary fires differed from lightning fires in seasonal timing, how did the seasonal timing of prescribed fires differ from that of lightning fires? Here we only describe prescribed fires

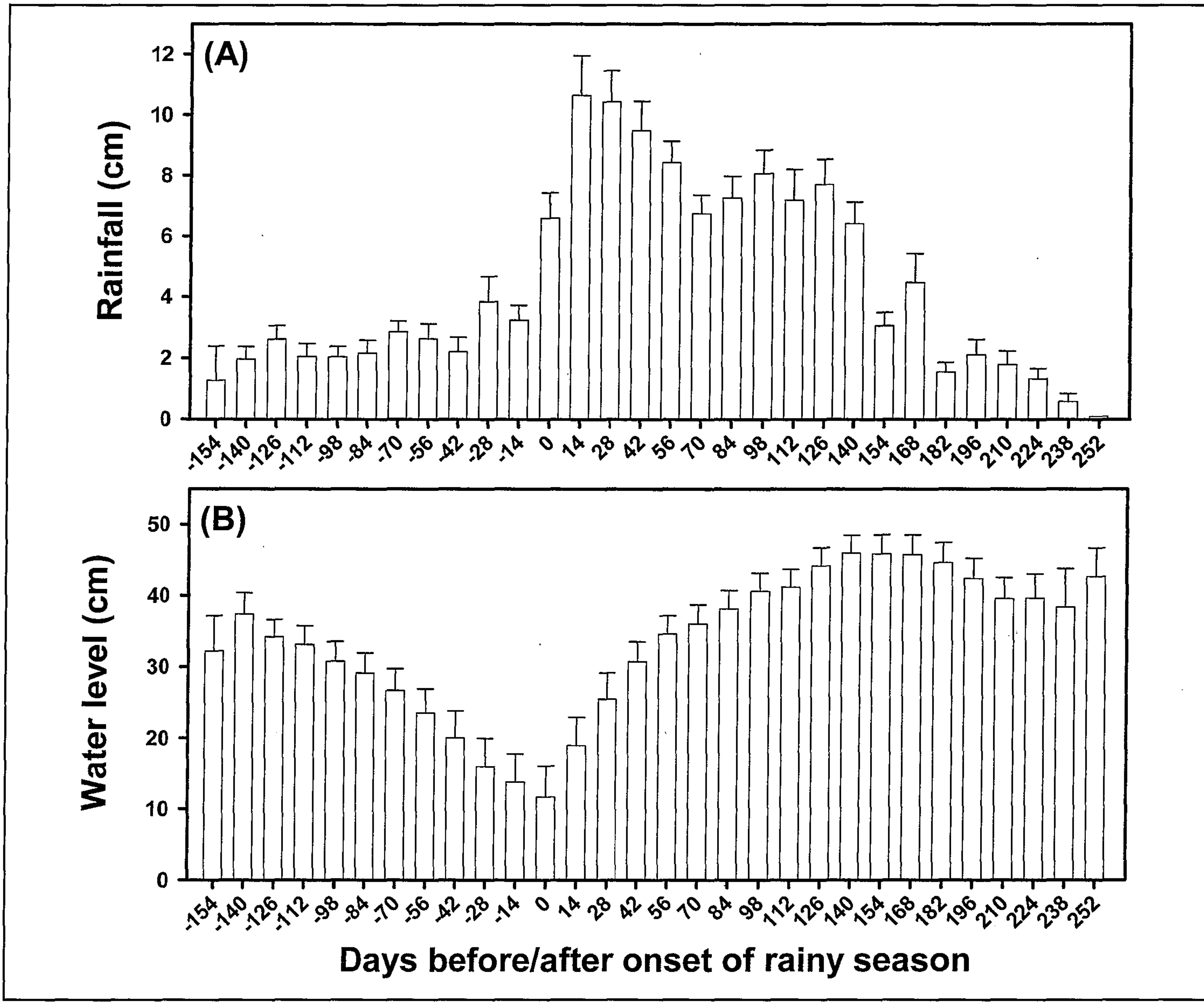

Figure 5. Relationship of onset of the wet season with (A) rainfall and (B) stage water levels. Onset of the wet season is set as zero, and intervals on the x-axis are two weeks (e.g., –14 refers to 7 days before onset to 21 days before onset). Rainfall levels are sums within interval, averaged over years (± 1 SE; 1956-1998). The gauge for rainfall was located on the north border of the park (Figure 1). Stage water levels are mean daily levels (± 1 SE) within each time interval (1956-1999) at a well in the center of Shark Slough (Figure 1).

in the pine savanna, because these were specifically ignited for restoration (i.e., to reduce cover of invasive hardwoods and to restore the unit's species rich, fire-adapted understory). Logically, the seasonal timing of these prescribed fires should match that of lightning fires (Beckage et al. 2005b). Before 1989, however, the importance of mimicking the timing and effects of lightning fires was not fully understood, and as a result, there were a number of ineffective strategies prior to this date (Doren et al. 1993). This included a period of fire suppression from 1948-1957, and a period from 1958-1979 of infrequent fires ignited in the dry season (126 days after onset to –14 days before; Figure 6). Because of low fire frequency, these efforts encouraged the invasion of non-fire-adapted hardwoods (Taylor and Herndon 1984; DeCoster et al. 1999). In addition, the occasional prescribed fire during the late dry season damaged the groundcover by consuming the humus substrate (Doren et al. 1993; Schmitz et al. 2002). From 1980-1988, area burned was substantially increased, and timing was moved to the middle and late wet season (35 to 105 days after onset; Figure 6). Again, these efforts to curtail invasion of hardwoods were ineffective (Slocum et al. 2003). Once an attempt to mimic lightning-ignited fires was initiated in 1989, the seasonal timing of prescribed fires was shifted to earlier in the wet season (seven to 77 days after onset; Figure 6). This last shift in policy resulted in more intense and less patchy fires that reduced cover of hardwoods (DeCoster et al. 1999; Slocum et al. 2003). This prescribed fire regime, however, still failed to mimic the peak of lightning fire activity that occurred closer to the onset of the wet season (com-

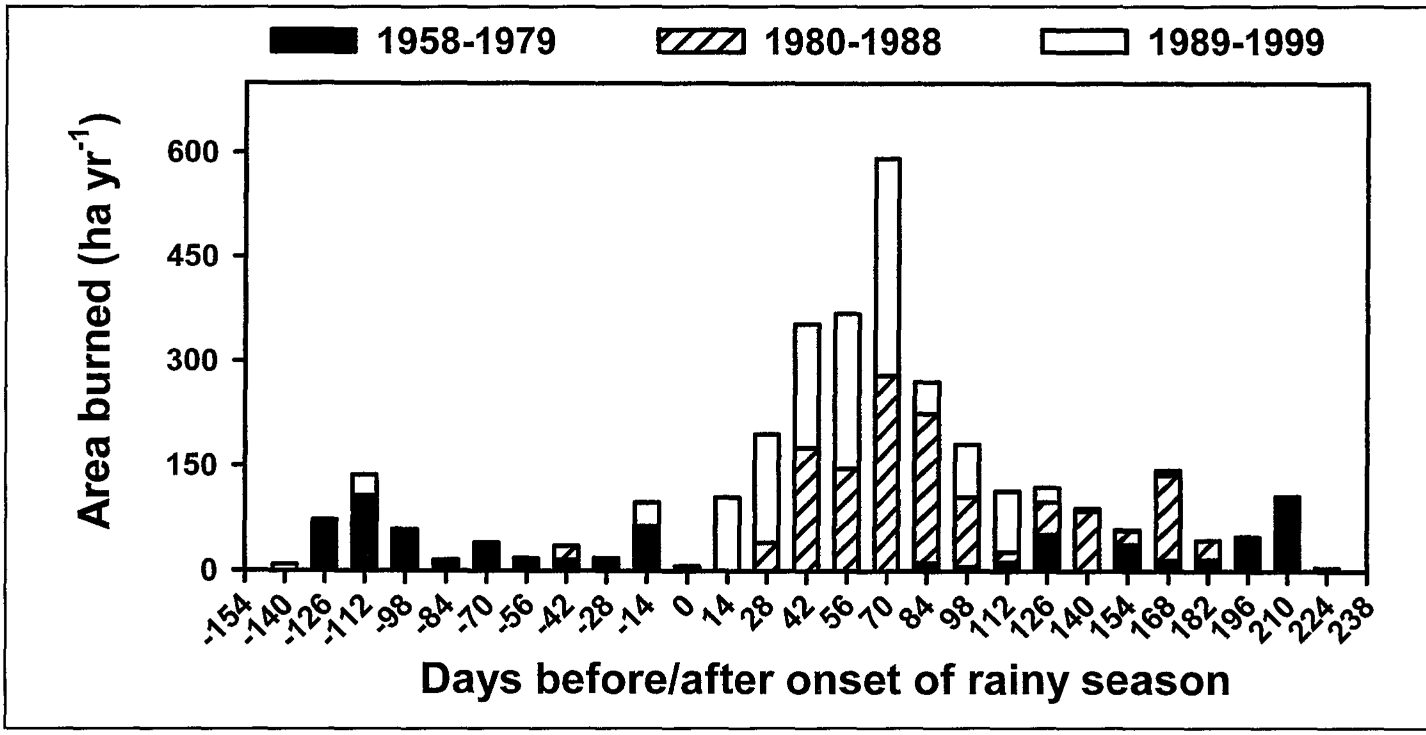

Figure 6. Relationship between onset of the wet season and annual area burned for three periods of fire management in the pine savanna in Everglades National Park, Florida, USA. These management periods included a period of infrequent winter prescribed burning (1958-1979), a period when prescribed burning was shifted to the late wet season (1980-1988), and a period when prescribed fires were ignited closer to the onset of the wet season (1989-1999). Onset of the wet season is set as zero, and intervals on the x-axis are two weeks (e.g., –14 refers to 7 days before onset to 21 days before onset).

pare Figures 3A and 6). Therefore, the effects of an "on-time" prescribed fire regime remain to be seen. It is possible that such a regime would be even more effective in reducing cover of invasive hardwoods and promoting the herbaceous species that were once more prevalent in the pine savanna groundcover (Robertson 1953; Synder et al. 1990; Platt 1999).

CONCLUSIONS

We have attempted to decouple anthropogenic and lightning fire regimes in ENP by analyzing how climate affects landscape-level patterns of fires over the past 50 years. Our data indicate that anthropogenic actions have generated fire regimes that differ in four main ways from those expected based on the influence of climate. First, humans have reduced the size of the greater Everglades region, eliminating large areas where lightning can start fires that spread into ENP. Second, fuel connectivity both within and surrounding ENP has been reduced by roads, canals, and other anthropogenic barriers. Third, access for people, resulting primarily from trails and roads, has resulted in many large incendiary fires that have occurred earlier in the year than lightning fires. Fourth, seasonal timing of prescribed fires has differed from that of lightning fires for much of the last 50 years. Altogether, these four changes have resulted in some yet unknown reduction in fire frequency and replacement of "on-time" lightning-ignited fires with "off-time" incendiary and prescribed fires. These changes in fire regimes have likely had important influences on the biota and habitats of ENP.

In 1980, ENP began an adaptive management approach to address issues related to changes in fire regimes (Doren et al. 1993). They have addressed "off-timed" fires by shifting the seasonal timing of prescribed fire closer to that of lightning fires, by using prescribed fires along the park's borders to block entry of incendiary fires, and by purchasing the East Everglades, thereby reducing access to hunters and others who start fires. The park has also addressed problems with fuel connectivity. Park personnel have started to meet with agencies that control surrounding flammable areas to create new fire management units that cross jurisdictional boundaries and that can be managed along ecological lines. In addition, they are reducing internal barriers to fire (e.g., they are restoring wet seasonal savanna in a 4000 ha region now dominated by the non-flammable exotic *Schinus terebinthifolius* Raddi (Brazilian Pepper)) (Doren and Whiteaker 1990; Dalrymple et al. 2003).

Further modification of ENP's fire regimes using adaptive management depends on advancements in fire ecology. In this current study, we sought to increase our understanding of fire ecology at ENP by attempting to decouple anthropogenic and natural fire regimes using climate and landscape-level data. This approach leads us to suggest the following steps for improving fire management strategies. First, more data are needed on fire characteristics, especially data not detailed in the current study (e.g., fire duration, patchiness of burn, and intensity). These data then need to be paired with climate data to see how fire characteristics and effects change under shifting climatic conditions. Such studies should be useful for further development of models that decouple natural and anthropogenic fire regimes.

Second, methods are needed to address the loss of fires that historically would have spread into ENP from surrounding areas. We propose that fires in surrounding areas be simulated using spatially explicit computer models that use climate and fuels data and consider natural and anthropogenic fragmentation. These models could be used to project when and where prescribed fires might be ignited to simulate fires that would historically have entered into the park (see Beckage and Platt 2003). Several crude attempts have been made towards this goal (Maehr and Larkin 2004; Beckage et al. 2005a). One way to immediately implement changes would be to assist natural fires in crossing roads and canals so that they could continue to burn under the appropriate climatic and fuel conditions. Some attempts to do this were used in the Ingraham Fire of 1989.

Third, to further understand and decouple natural and anthropogenic fire regimes, long-term, landscape-level experiments are needed (e.g., Glitzenstein et al. 1995; Beckage et al. 2005a,b). Such experiments should involve scientists from multiple disciplines and examination of different indicators of ecological integrity (e.g., Andersen et al. 1998; Costanza et al. 1998; Williams et al. 1998). These experiments are expensive, but are the only way to determine conclusively how differences in fire regimes affect biota. For example, these studies can address how different fire regimes affect refugia and populations of endangered species, as well as the condition of their habitat. Currently, there are no such experimental studies in ENP, despite the fact that a study of this type in the pine savanna (DeCoster et al. 1999; Slocum et al. 2003) guided adaptive management of the seasonal timing of prescribed fires and reintroduction of an extirpated species, *Meleagris gallopavo* (wild turkey).

Fourth, and perhaps most importantly, we propose scientific study of the interaction between fire and hydrology. Hydrologic regimes in the park have strong influences on the integrity of the park's fire regime, including vegetation structure, fuel loadings, and fuel moisture (Herndon et al. 1991; White 1994). In turn, fires affect hydrology by lowering elevations and increasing hydroperiods, and by removing fuel accumulations, which impede flow (White 1994). Despite the clear importance of this interaction, it remains poorly understood (Lockwood et al. 2003; Beckage et al. 2005b). This lack of understanding is of concern because fires in recent decades generally have not burned under natural hydrologic conditions (Craighead 1971; Newman et al. 1998), and even lightning fires will produce unnatural effects during periods of over- or underdrainage (Lockwood et al. 2003). Part of the reason for the lack of study is that there has been no long-term funding dedicated to the study of the interaction. For example, the current effort to restore the Everglades, the Comprehensive Everglades Restoration Program (CERP), with a projected budget of $7.8 billion over the next 30 years, only examines hydrology and has no provisions to study fire (Chimney and Goforth 2001; Lockwood et al. 2003; see also www.evergladesplan.org). We and other scientists (e.g., Lockwood et al. 2003) propose that, although it is admirable that CERP seeks to restore historical hydrological regimes, not knowing the effects of proposed changes in hydrological regimes on fire regimes is likely to add new anthropogenic effects with important, unforeseen consequences.

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LITERATURE CITED

Alexander, T.R., and A.G. Crook. 1974. Recent vegetational changes in southern Florida. Pp. 61-72 *in* P.J. Gleason, ed., Environments of South Florida: Present and Past. Memoir 2, Miami Geological Society, Miami, Fla.

Andersen, A.N., R.W. Braithwaite, G.D. Cook, L.K. Corbett, R.J. Williams, M.M. Douglas, A.M. Gill, S.A. Setterfield, and W.J. Muller. 1998. Fire research for conservation management in tropical savannas: introducing the Kapalga fire experiment. Australian Journal of Ecology 23:95-110.

Bazelyan, E.M., and Y.P. Raizer. 2000. Lightning Physics and Lightning Protection. Institute of Physics Publishing, Bristol, U.K.

Beckage, B., J. Comiskey, and S. Duke-Sylvester. 2005a. Natural fire regimes in southern Florida. Natural Areas Journal 25:6-8.

Beckage, B., and W.J. Platt. 2003. Predicting severe wildfire years in the Florida Everglades. Frontiers in Ecology and the Environment 1:235-239.

Beckage, B., W.J. Platt, and B. Panko. 2005b. A climate-based approach to the restoration of fire dependent ecosystems. Restoration Ecology 13:429-431.

Beckage, B., W.J. Platt, M.G. Slocum, and B. Panko. 2003. Influence of the El Niño Southern Oscillation on the fire regimes in the Florida Everglades. Ecology 84:3124-3130.

Biedinger, R.E., and J.B. Lushine. 1998. Duration of the summer season in southeast Florida. Available online <www.srh.noaa.gov/mfl/newpage/summer_season.html>.

Chen, E., and J.F. Gerber. 1990. Climate. Pp. 11-34 *in* R.L. Myers and J.J. Ewel, eds., Ecosystems of Florida. University of Central Florida Press, Orlando.

Chimney, M.J., and G. Goforth. 2001. Environmental impacts to the Everglades ecosystem: a historical perspective and restoration strategies. Water Science and Technology 44:93-100.

Costanza, R., M. Mageau, B. Norton, and B.C. Patten. 1998. Predictors of ecosystem health. Pp. 240-250 *in* D. Rapport, R. Costanza, P.R. Epstein, C. Gaudet, and R. Levins, eds., Ecosystem Health. Blackwell Science, Malden, Mass.

Craighead Sr., F.C. 1971. The Trees of South Florida, Vol. 1 *in* The Natural Environments and Their Succession. University Miami Press, Coral Gables, Fla.

Craighead Sr., F.C. 1974. Hammocks of south Florida. Pp. 53-60 *in* P.J. Gleason, ed., Environments of South Florida: Present and Past. Memoir 2, Miami Geological Society, Miami, Fla.

Curnutt, J.L., A.L. Mayer, T.M. Brooks, L. Manne, O.L. Bass Jr., D.M. Fleming, M.P. Nott, and S.L. Pimm. 1998. Population dynamics of the endangered Cape Sable seaside-sparrow. Animal Conservation 1:11-21.

Dalrymple, G.H., R.F. Doren, N.K. O'Hare, M.R. Norland, and T.V. Armentano. 2003. Plant colonization after complete and partial removal of disturbed soils for wetland restoration of former agricultural fields in Everglades National Park. Wetlands 23:1015-1029.

DeCoster, J., W.J. Platt, and S.A. Riley. 1999. Pine savannas of Everglades National Park: an endangered ecosystem. Pp. 81-88 *in* D.T. Jones and B.W. Gamble, eds., Florida's Garden of Good and Evil: Proceedings of the Joint Symposium of the Florida's Exotic Pest Plant Council and the Florida Native Plant Society, 1998 June. South Florida Water Management District, West Palm Beach.

Doren, R.F., W.J. Platt, and L.D. Whiteaker. 1993. Density and size structure of slash pine stands in the Everglades region of south Florida. Forest Ecology and Management 59:295-311.

Doren, R.F., and R.M. Rochefort. 1984. Summary of fires in Everglades National Park and Big Cypress National Preserve, 1981. South Florida Research Center Report 84/01, National Park Service, Everglades National Park, Homestead, Fla.

Doren, R.F., and L.D. Whiteaker. 1990. Effects of fire on different size individuals of *Schinus terebinthifolius*. Natural Areas Journal 10:106-113.

Douglas, M.S. 1947. The Everglades: River of Grass. Rinehart, New York. Also printed as 50th anniversary edition. 1997. Pineapple Press, Sarasota, Fla.

Duever, J.M., J.E. Carlson, J.F. Meeder, L.C. Duever, L.H. Gunderson, L.A. Riopelle, T.R. Alexander, R.L. Myers, and D.P. Spangler. 1986. The Big Cypress National Preserve. Research Report No. 8, National Audubon Society, New York.

Gabrey, S.W., and A.D. Afton. 2000. Effects of winter marsh burning on abundance and nesting activity of Louisiana Seaside Sparrows in the Gulf Coast Chenier Plain. The Wilson Bulletin 112:365-372.

Glitzenstein, J.S., W.J. Platt, and D.R. Streng. 1995. Effects of fire regime and habitat on tree dynamics in north Florida longleaf pine savannas. Ecological Monographs 65:441-476.

Gunderson, L.H., and J.R. Snyder. 1994. Fire patterns in the southern Everglades. Pp. 291-306 *in* S.M. Davis and J.C. Ogden, eds., Everglades: the Ecosystem and Its Restoration. St. Lucie Press, Delray Beach, Fla.

Herndon, A., L. Gunderson, and J. Stenberg. 1991. Sawgrass (*Cladium jamaicense*) survival in a regime of fire and flooding. Wetlands 11:17-27.

Hoffmeister, J.E., K.W. Stockman, and H.G. Multer. 1967. Miami limestone of Florida and its recent Bahamian counterpart. Bulletin of the Geological Society of America 78:175-190.

Huffman, J.M., W.J. Platt, H. Grissino-Mayer, and C.J. Boyce. 2004. Fire history of a barrier island slash pine (*Pinus elliottii*) savanna. Natural Areas Journal 24:258-268.

Johnson, E.A. 1992. Fire and Vegetation Dynamics. Cambridge University Press, Cambridge, U.K.

Keeley, J.E., and C.J. Fotheringham. 2001. Historic fire regime in southern California shrublands. Conservation Biology 15:1536-1548.

Latham, D., and E. Williams. 2001. Lightning and forest fires. Pp. 376-418 *in* E.A. Johnson and K. Miyanishi, eds., Forest Fires: Behavior and Ecological Effects. Academic Press, New York.

Lockwood, J.L., M.S. Ross, and J.P. Sah. 2003. Smoke on the water: the interplay of fire and water flow on Everglades restoration. Frontiers in Ecology and the Environment 1:462-468.

Maehr, D.S., and J.L. Larkin. 2005. Response to Beckage et al.: fire regimes and large terrestrial carnivores in south Florida. Natural Areas Journal 25:8-9.

Newman, S., J. Schuette, J.B. Grace, K. Rutchey, T. Fontaine, K.R. Reddy, and M. Pietrucha. 1998. Factors influencing cattail abundance in the northern Everglades. Aquatic Botany 60:265-280.

Platt, W.J. 1999. Southeastern pine savannas. Pp. 23-51 *in* R.C. Anderson, J.S. Fralish, and J. Baskin, eds., The Savanna, Barren, and Rock Outcrop Communities of North America. Cambridge University Press, Cambridge, U.K.

Rakov, V.A., and M.A. Uman. 2003. Lightning: Physics and Effects. Cambridge University Press, Cambridge, U.K.

Robertson, W.B. 1953. A survey of the effects of fire in Everglades National Park. U.S. Department of the Interior, National Park Service, Everglades National Park, Homestead, Fla.

Schmitz, M., W.J. Platt, and J. DeCoster. 2002. Substrate heterogeneity and numbers of plant species in Everglades savannas (Florida, USA). Plant Ecology 160:137-148.

Slocum, M.G., W.J. Platt, and H.C. Cooley. 2003. Effects of differences in prescribed fire regimes on patchiness and intensity of fires in subtropical savannas of Everglades National Park, Florida. Restoration Ecology 11:91-102.

Snyder, J.R., A. Herndon, and W.B. Robertson Jr. 1990. South Florida Rockland. Pp. 150-193 *in* R.L. Myers and J.J. Ewel, eds., Ecosystems of Florida. University of Central Florida Press, Orlando.

Snyder, J.R. 1991. Fire regimes in subtropical south Florida. Proceedings Tall Timbers Fire Ecology Conference 17:303-319.

Swetnam, T.W., C.D. Allen, and J.L. Betancourt. 1999. Applied historical ecology: using the past to manage for the future. Ecological Applications 9:1189-1206.

Taylor, D.L. 1981. Fire history and fire records for Everglades National Park 1948-1979. Report T-619, National Park Service, South Florida Research Center, Everglades National Park, Homestead, Fla.

Taylor, D.L. 1983. Fire management and the Cape Sable Sparrow. Pp. 147-152 *in* T. Quay, J. Funderburg Jr., D. Lee, E.Potter, and C. Robbins, eds., The Seaside Sparrow, Its Biology and Management. North Carolina Biological Survey, Raleigh.

Taylor, D.L., and A. Herndon. 1984. Impact of 22 years of fire on understory hardwood shrubs in slash pine communities within Everglades National Park. Report T-640, National Park Service, South Florida Research Center, Everglades National Park, Homestead, Fla.

Turner, M.G., W.H. Romme, R.H. Gardner, and W.W. Hargrove. 1997. Effects of fire size and pattern on early succession in Yellowstone National Park. Ecological Monographs 67:411-433.

Veblen, T.T., T. Kitzberger, and J. Donnegan. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado front range. Ecological Applications 10:1178-1195.

Wetzel, P.R. 2002. Analysis of tree island vegetation communities. Pp. 357-390 *in* F.H. Sklar and A.G. van der Valk, eds., Tree Islands of the Everglades. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Wetzel, P.R., A.G. van der Valk, S. Newman, D.E. Gawlik, T.T. Gann, C.A. Coronado-Molina, D.L. Childers, and F.H. Sklar. 2005. Maintaining tree islands in the Florida Everglades: nutrient redistribution is the key. Frontiers in Ecology and the Environment 3:370-376.

White, P.S. 1994. Synthesis: vegetation pattern and process in the Everglades ecosystem. Pp. 445-460 *in* S. Davis and J. Ogden, eds., Everglades: the Ecosystem and Its Restoration. St. Lucia Press, Del Ray Beach, Fla.

Williams, R.J., A.M. Gill, and P.H.R. Moore. 1998. Seasonal changes in fire behavior in a tropical savanna in northern Australia. International Journal of Wildland Fire 8:227-239.

Winkler, M.G., P.R. Sanford, and S.W. Kaplan. 2001. Hydrology, vegetation, and climate change in the southern Everglades during the Holocene. Pp. 57-99 *in* B. R. Wardlaw, ed., Paleoecological Studies of South Florida. Bulletins of American Paleontology, Paleontological Research Institution, Ithaca, New York..