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Assessing drought-related ecological risk in the Florida Everglades

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Abstract

In the winter-spring of 2001, South Florida experienced one of the worst droughts in its recorded history. Out of a myriad of ecological concerns identified during this time, the potential for catastrophic peat fire and negative impacts to wading bird reproduction emerged as critical issues. Water managers attempted to strike a balance between the environment and protection of water supplies for agriculture and urban interests. It became evident, however, that a broad-scale, integrated way to portray and prioritise ecological stress was lacking in the Florida Everglades, despite this being considered a necessary tool for addressing issues of environmental protection. In order to provide a framework for evaluating various water management operations using real-time information, we developed GIS-based indices of peat-fire risk and wading bird habitat suitability. These indices, based on real physical, chemical, and biological data, describe two ecological conditions that help define the physical and biological integrity of the Everglades. In addition to providing continuous, updated assessments throughout the drought period, we incorporated predictive models of water levels to evaluate how various water management alternatives might exacerbate or alleviate ecological stress during this time.

Keywords: Everglades; Drought; Risk assessment; Fire; Wading birds

1. Introduction

Environmental management is an evolving discipline that seeks to reduce or eliminate anthropogenic impacts to natural systems. Documentation of the process by which impacts are evaluated and subsequent decisions are made can benefit the future evolution of this field. In general, effective management of large, complex ecosystems requires a holistic approach that integrates a suite of physical and biological features, each with their own local, regional, and system-wide importance. In the Florida Everglades (USA), hydrology is one of the most critical factors linking these features and influencing overall wetland structure and function. However, marsh hydrodynamics have been seriously compromised by a complex water management infrastructure (Light and Dineen, 1994). What was originally a contiguous array of wet prairies, open water, and tree-islands, now is divided into a series of impoundments defined by canals and dikes. Moreover, each impoundment can be managed separately in response to anthropogenic pressures such as flood control, water storage, and urban and agriculture water use. Unfortunately, these kinds of alterations to natural hydrology have become commonplace around the world and have impacted wetland habitats in many different ways (Carter, 1986; Bernáldez et al., 1993; Hollis and Thompson, 1993; Wilber et al., 1996; Lal, 1999). Reduced water levels and hydroperiod are often the outcome of human interference—conditions that in many regions may be further exacerbated by global climate change (Hogenbirk and Wein, 1991; Burkett, and Kusler, 2000).

Throughout its history, the Florida Everglades has had to contend with disturbances such as drought and fire. While fires were a natural component of the system, however, their frequency and severity began to increase when large portions of the marsh were completely or partially severed from overland water flows during the compartmentalization process (Alexander and Crook, 1973; Gunderson and Snyder, 1994; Robertson, 1953). Furthermore, nutrient enrichment from both soil oxidation and agricultural runoff

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has greatly increased macrophyte productivity, thereby generating more fuel to support larger and hotter fires.

From a wildlife perspective, the impacts of present-day drought vary with species, population size, and spatial distributions. While natural fluctuations in animal numbers are inherent to the normal functioning of ecosystems, populations of some species are so diminished that further reductions, however minimal, could be disastrous. This is particularly true for wading birds, which are highly dependent upon the timing and amplitude of water level changes for foraging and reproductive success (Bancroft et al., 1994, 2002).

In the winter-spring period of 2001, standing water was absent across most of the Everglades by March and, in some areas, more than 1 m below ground level by May. While the potential for catastrophic peat fire and wading bird reproductive failure were critical issues during this time, a broad-scale, integrated method to portray and prioritise ecological stress across the Everglades was non-existent. To provide a basic framework within which to make water management decisions using current hydrologic information, we developed GIS-based indices of peat-fire risk and wading bird habitat suitability as a template for managers to evaluate drought-related risk.

2. Methods

Data generated by the United States Environmental Protection Agency's Environmental Monitoring and Assessment Program (REMAP) and the South Florida Water Management District's STA Receiving Areas Monitoring & Research and Threshold programs provided data for a network of sites across the Everglades Protection Area (EPA) (Fig. 1) (Smith et al., 1999a,b; Environmental Protection Agency, 2000; McCormick et al., 2001). For each site there were available data on recent fire history, soil total phosphorus concentrations, soil bulk density, soil type, and vegetation type. Only REMAP sites had soil depth measurements, which were subsequently interpolated so that estimates could be generated for areas where data were not available (WCA-1, -2A, Holeyland, and Rotenberger). Real-time water elevation (stage) data from a network of gauges across the EPA was acquired by telemetry. Wading bird colony monitoring (locations and nest counts) were conducted by helicopter surveys. Peat fire risk (PFR) and wading bird habitat suitability (WBHS) indices were calculated from a number of variables defining physical and biological conditions across the Everglades.

For each location where data existed, values for each variable were categorized, ranked on a scale of 1 (lowest risk or suitability) to 5 (highest risk or suitability) over their range, weighted, and summed to produce a final value, which was then re-ranked over the range of final values to provide a relative degree of risk or suitability. Initially, weightings were determined by their proposed relative importance in creating conditions favourable for peat fire or good wading bird habitat as inferred from the relevant literature. Subsequently, as a way to ensure that the model produced reasonable results, the calculations were re-run using a multitude of different weighting values in different combinations that represented a wide range of possible scenarios. In the end, the system that best fit with existing conceptual models and produced the most reasonable approximation of reality was chosen.

All calculations were automated within a multi-worksheet Excel® file. For each assessment, the computations were saved as a text file and imported into Arcview® 3.2 for

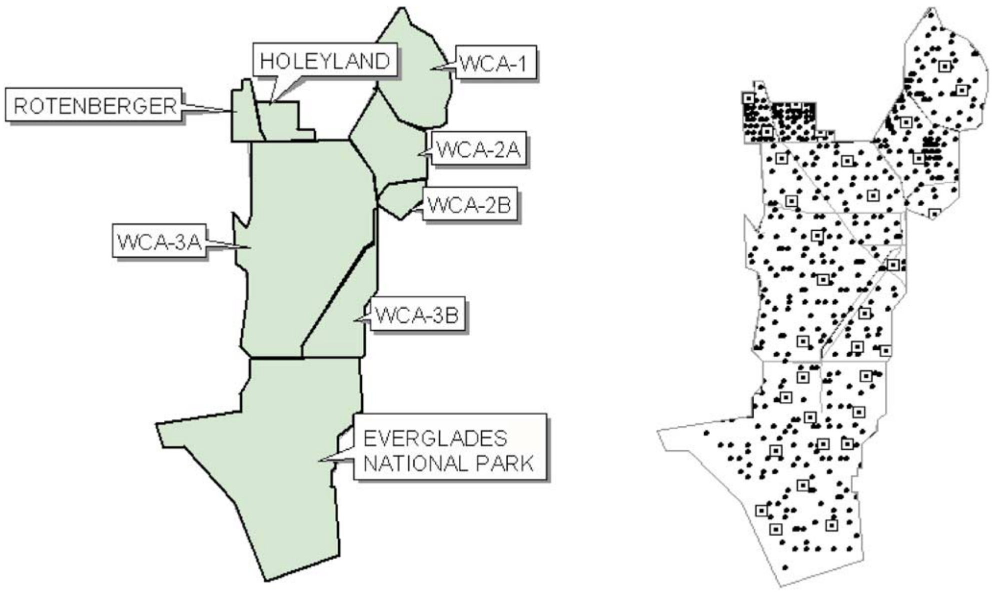

Fig. 1. Delineation of the Everglades Protection Area (left) and sites (right) for which data was available for PFR and WBHS computations (larger squares represent telemetric stage gauges).

map generation. The data were interpolated in Arcview 3.2 using the Inverse Distance Weighting (IDW) method (default method for this software), which assumes (1) that the variable being mapped decreases in influence with distance from the sampled location and (2) that the unknown point is likely to have a value more similar to points closer to it than those at greater distances. In general the IDW method is commonly used to interpolate data that do not have a lot of extreme high or low values (i.e. 'hot spots'), relative to those points surrounding them. As such, it is an appropriate method for describing topography, water-levels, and soil properties in places where transitions tend to be smooth and relatively subtle (Berlekamp, 1998; Mueller, 2001; Schloeder et al., 2001)

2.1. Assessment of peat fire risk

Each peat fire-related risk factor was categorized and ranked based on its proposed importance in the burning process as inferred from literature-derived conceptual models of fire dynamics and wading bird ecology (Bayley and Odum, 1976; Bancroft et al., 1994; Frederick and Spalding, 1994; Gunderson and Snyder, 1994; Curnutt et al., 2000). Complete lists of factors, classifications of factors, rankings, and weights can be found in Tables 1 and 2 for the PFR and WBHS assessments, respectively.

Stage—for obvious reasons, water levels are critical in determining the combustibility of marsh vegetation and underlying organic soils (Wade et al., 1980). Site-specific ground elevations were based on a 1994 topographic survey (Fennema et al., 1994). Site-specific stage levels were determined by extrapolation from the nearest stage recorder (which assumes a flat pool over that distance) within a network of 33 gauges throughout the EPA (Fig. 1). Water depths were then calculated as stage minus ground elevation and ranked as shown below. Although the potential for peat fire is high when water drops to ≥ 1 ft below ground (Stephens and Johnson, 1951), the ranges below take into consideration that (1) capillary action from a subsurface water table can keep upper level soils moist and (2) organic soils can retain moisture for considerable lengths of time following water level recession. In general, organic soils fail to ignite when moisture content is above 65 percent (Wade et al., 1980). In western WCA-2A, soil moisture levels dropped below this level only when water levels declined to < -60 cm (Smith, unpublished data).

Burn history—previous fires greatly influence susceptibility to subsequent burning through fuel reduction. Rates of recovery from fire can be quite variable, since numerous variables (e.g. soil nutrients, water levels) influence regrowth. Approximately 2 years after surface fire, however, the standing biomass of *Cladium jamaicense* (sawgrass) can reportedly reach pre-fire loads (Gunderson and Snyder, 1994 and references therein) while wet prairie vegetation may require 3 years or more for complete recovery (Hackney and de la Cruz, 1981; Herndon and Taylor, 1986). Notwithstanding, it may take several more years to accumulate similar amounts of above and below-ground fuel to support another fire (de la Cruz and Hackney, 1980; Gunderson and Snyder, 1994). In contrast to surface fires, peat fire consumes a portion of belowground organic matter and areas may initially be slower to recover, since re-vegetation will occur mostly through rhizomatous growth of peripheral (unburned or surface-burned) plants or by seed germination. However, this lag phase may be offset by increased vegetation growth in response to increased bioavailability of nutrients (Smith et al., 2001; Smith and Newman, 2001). Thus, no distinction between burn types

Table 1
PFR assessment factor classification, rankings and weights. Vegetation types are as follows: SAW = sawgrass, CAT = cattail, WP = wet prairie, SL = slough, TREE = shrubs, trees (for species associations see text)

Factor	Classes	Ranking	Weight
Burn history	Burn > 3 yrs	5	= Stage rank*4
	Burn 2.5–3 yrs	4	
	Burn 2–2.5 yrs	3	
	Burn 1.5–2 yrs	2	
	Burn < 1.5 yrs	1	
Stage	< −2 ft	5	20
	−2 to −1.5	4	
	−1.5 to −1.0	2	
	−0.5 or above	1	
Dry out	N/A	N/A	= Stage rank*3.5
Water level-soil depth	< −0.5 ft below rock	5	= Stage rank*3
	−0.5 to −0.25	4	
	−0.25 to 0	3	
	0–0.25	2	
	> 0.25	1	
Vegetation type	SAW	5	= Stage rank*2.5
	SAW–CAT	4	
	CAT–SAW	3	
	SAW–WP	3	
	CAT	2	
	CAT–WP	2	
	WP–SAW	2.5	
	WP	2	
	CAT–SL	1.5	
	TREE	2	
	SL	1	
Soil TP	> 700 mg/kg	5	= Stage rank*2
	600–700	4	
	500–600	3	
	400–500	2	
	< 400	1	
Soil bulk density	> 0.4	5	= Stage rank*1.5
	0.3–0.4	4	
	0.2–0.3	3	
	0.1–0.2	2	
	< 0.1	1	
Soil type	Peat	5	= Stage rank*1
	Peat/Marl	4	
	Marl	3	
	Marl/Sand	2	
	Sand	1	

Table 2
WBHS assessment factor classification, rankings and weights

Factor	Classes	Ranking	Weight
Stage (foraging)	<-0.3 ft	1–4 according to magnitude	2
	-0.3 to 1	5	
	>1	1–4 according to magnitude	
Recession rate	0.1 ft/wk or above	5	
	0.08–0.1	4	
	0.06–0.08	3	
	0.04–0.06	2	
	<0.04	1	
Recession rate	Stage rank*	1–5 according to magnitude	1
Adjustment	Recession rank		
Distance-size (Wood Stork)	$\Sigma(1-(x/34)$*no.nests) $x=$ distance in km	1–5 according to magnitude	2
Distance–size (White Ibis)	$\Sigma(1-(x/18)$*no.nests) $x=$ distance in km	1–5 according to magnitude	
Stage at colony adjustment	<-0.3 ft	1	2
	-0.3 to -0.2	2	
	-0.2 to -0.1	3	
	-0.1 to -0.1	4	
	0 or above	5	

was made for the PFR calculation. In general, however, the more recent an area was burned the lower the risk for subsequent peat fire.

The burn history component of the PFR assessment reflects known fires that have occurred within the last 3 years. For March, this includes northern Rotenberger (June, 1999), western Holeyland (September 2000), northwest WCA-2A (June, 1999) and northwest WCA-3A (February 2001).

Duration of dry out—because the duration of drought conditions greatly influences fire risk (Keetch and Byram, 1986), values for each site were calculated that attempted to roughly define the process of dry out (i.e. how long and to what extent a site had been dry). If the water level at a site was equal to or above ground elevation (i.e. wet conditions), it was assigned a numerical value equal to the month of the assessment date (e.g. March = 3, May = 5). If the water level was below ground level (dry), it was given a value of 1. To calculate a cumulative dry out value for a specific date, the maximum of all monthly values prior to the assessment date (using stages for the 1st of each month) was subtracted from the number of the current month for which the model was being run. Thus, sites that were dry throughout several preceding months had higher values. Conversely, sites that were wet during previous months had lower values, and the more recent the site was wet the lower the value. These results were then ranked 1–5 over their range for the overall risk calculation. Since there are so many different ways that this factor can be classified (according to temporal variability in stages), a summary table is not presented.

Water level-soil depth—soil depth is an important consideration in assessing peat fire potential since the capillary action of water is lost when stages fall below the rock surface. In fact, artificial capillary barriers are commonly used to prevent upward fluxes of groundwater contaminants and limestone, which comprises the underlying rock floor of the Everglades system (McFarland et al., 1994; Walter et al., 2000). When a barrier to capillary action exists, there is no upward movement of water to keep soils moist and the rate of dry out is accelerated. Thus, categorizations of water depth in relation to soil depth were developed, which attempt to account for a certain level of microtopographic variation in the rock layer. Thus, sites with water levels below the underlying limestone fell into the highest risk category. Specific criteria for categorizing all water depth-soil depth scenarios are listed in Table 1.

Vegetation type—the combustibility of vegetation varies with tissue moisture content, structure, and chemical composition. *C. jamaisense* is highly flammable compared to other Everglades plant species (Kushlan, 1990). Dead leaves of *C. jamaicense* remain standing for long periods of time and the live material has low water content (S. Miao, personal communication). In addition, the rhizomes are short and new ramets tend to be very densely packed (Miao and Sklar, 1998). Accordingly, areas dominated by *C. jamaicense* vegetation ranked highest in their potential contribution to peat fire. *Typha domingensis* (southern narrow-leaved cattail) has a much higher water content and there is more distance between ramets but can produce high amounts of biomass (Miao and Sklar, 1998). Wet prairie vegetation (e.g. *Panicum hemitomon*, *Sagittaria lancifolia*, *Eleocharis*spp.,*Rhynchospora* spp.) is much shorter, thinner in stature, and tends to be comprised mainly of live tissues with little standing dead biomass. As a result, this community cannot carry fire well (Gunderson and Snyder, 1994).

Tree islands in the Everglades are commonly fringed by willow and wax myrtle trees that bear live, green leaf tissue throughout the year. This zone can act as a protective barrier during fires (i.e. the material has low combustibility) that frequently prevents interior burning (personal observation). Thus, shrub/tree island communities were given low risk values (see Table 1). Mixed upland vegetation (primarily *Eupatorium capillifolium*) in the Rotenberger Wildlife Management Area was given a high rank based on field observations of dead biomass quantities and tissue moisture levels. Slough communities have the longest hydroperiods and are dominated by water lily (*Nymphaea odorata*, *Nymphoides aquatica*) and spikerush (*Eleocharis* spp.), both of which accumulate virtually no standing dead biomass. These characteristics make sloughs a very low risk for peat fire.

Soil Total Phosphorus (TP) Concentration—phosphorus (P) is the primary limiting nutrient for Everglades vegetation and elevated levels of soil TP correspond with enhanced plant productivity and biomass (Davis, 1994; Craft et al., 1995; Miao and Sklar, 1998). Oligotrophic regions of the Everglades typically have soil with 400 mg/kg TP or less, while moderately enriched regions show variation from 400–700 mg/kg. Concentrations of 700 mg/kg and above are correlated with very high levels of plant biomass and productivity (Craft and Richardson, 1997; Wu et al., 1997).

Bulk density—when organic soils dry out oxidation, consolidation, and compaction results, to some extent, in the irreversible loss of water-holding capacity (Kushlan, 1990). Soils of higher bulk densities also generally have higher nutrient concentrations by unit volume, which can translate into higher fuel loadings through enhanced plant productivity (Newman et al., 1998, DeBusk et al., 2001; Smith and Newman, 2001).

Soil type—peat soils contain a higher percentage of undecomposed organic matter than marl (also known as calcitic mud), which is comprised of hardened layers of periphyton-derived calcium carbonate (Gleason and Stone, 1994). Dried peat soils also are much more loosely packed (leaving more airspace and therefore allowing less capillary action) and thus more flammable than marl. Sandy soils tend to have the lowest organic matter content and are therefore much less combustible. Combinations of these soil types were given intermediate ranks. This factor was included as an unweighted component of the overall risk calculation.

The final, integrated PFR calculation is as follows:

$$\text{RISK} = \sum(\text{factor rank}^{*}\ \text{factor weight})$$

In developing this calculation, the weighting system was manipulated to ensure that the model was sensitive to fluctuations in water level (see Table 1). The weights of other (secondary) factors differed in magnitude according to their importance in contributing to risk and were made to vary as a function of water level in that the weights increased as water level decreased. Thus, when water levels fell into the lowest risk category they contributed very little to the final value. Conversely, as water level risk increased, the secondary factors had increasingly more influence, particularly in combination. The rationale for this variable weighting system is that conditions of soil phosphorus concentrations or vegetation composition are insignificant to peat fire risk when water levels are high or the area has just burned. However, when water level conditions result in a moderate risk of peat fire, conditions of these secondary factors can alleviate or exacerbate the situation. As such, their ranks increasingly had the ability to modify final values as the level of risk dictated by water level increased.

2.2. Development of a wading bird habitat value assessment model

The use of foraging sites by wading birds decreases rapidly after surface water disappears when birds are forced to fly increasing distances from the nesting colony to find aquatic prey (Bancroft et al., 1994). At some distance from the nest, however, it becomes energetically unprofitable (or birds are limited by the time required) to transport food to the young. Thus, one measure of suitability of a foraging site is distance from a colony, with closer sites having a higher suitability. Distance thresholds that cause abandonment vary among species, stage of the nesting cycle, and prey availability at foraging sites. Droughts also can affect wading bird nesting behaviour. Nesting sites are adversely impacted when surface water directly under the colony disappears and provides access to mammalian predators (Rodgers 1987; Frederick and Collopy, 1989a). When sites go dry adults may abandon the colony (Bancroft et al., 1994).

Wading bird habitat values were developed using Wood Stork (*Mycteria americana*) and White Ibis (*Eudocimus albus*) colony locations, the number of nests in each colony, and species-specific foraging distances. Wood Stork and White Ibis were given priority over other wading bird species in these assessments because the Wood Stork is a federally Endangered Species and the White Ibis is a Florida Species of Special Concern. These two species have shown dramatic population declines over the past 70 years (Ogden, 1994; Crozier et al., 2000). Historic nesting data have shown that during drought years, few herons and egrets attempt to nest whereas large numbers of Wood Storks and White Ibises may (Crozier et al., 2000). Thus, focusing attention on the species that have the best chance of nesting success during drought years appears the most sensible management strategy.

Water depth suitability for foraging—a range of 0–0.5 ft has been postulated as an optimal water depth range for wading bird foraging (Gawlik, 2002). In this model, however, the optimal range was expanded to −0.3 to −1 ft. Although negative water depths intuitively suggest unsuitable habitat, this range presumes some level of micro-topographic variation in the immediate surrounding area that would allow surface water to occur in depressions. Similarly, a 1 ft depth would result in shallower depths over higher landscape features such as ridges. Water depths that were higher or lower than these end points received successively lower suitability values. These categorizations essentially follow a modified bell curve, whereby foraging suitability is constant over an ‘optimal’ range of water depths but declines rapidly in linear fashion beyond minimum and maximum thresholds.

Rate of recession—receding water decreases the amount of available living space for aquatic macrofauna and effectively concentrates prey items in shallow water for wading birds. In general, and depending on water levels, a rapid rate of recession seems to produce good nesting effort (Kahl, 1964; Frederick and Spalding, 1994). When recession rate drops below 0.5 cm per day (0.1 ft/week) or when it reverses, nest abandonment can occur (Kushlan, 1976; Frederick and Collopy, 1989a,b). Recession rates up to the date of assessment were calculated from preceding stages (1st of the month values) and scaled according on the above criteria. In addition, a water depth adjustment was incorporated into this component based on the assumption that recession rate is considerably less important when water depths are sub-optimal (e.g. recession rate is essentially irrelevant when water depths at sites too low (<-0.3 ft) or too high (>1 ft)).

Colony location and relative colony size—distances from each Wood Stork colony were calculated so that for each site there were *N* distances from *N* colonies. Each of these distances was then scaled based on a foraging range of 0 − 34 km (Kahl, 1964; Bryan and Coulter, 1987; Bryan et al., 1995). Thirty-four km is the maximum distance that Wood Storks flew using flapping-based flight (Bryan et al., 1995). Storks foraged at greater distances only when weather conditions allowed them to use soaring-based flight. Distances exceeding this threshold of 34 km received a value of 0, whereas distances within this range were transformed by the linear function $y = 1-$(distance from colony in km/34 km). In this way, closer sites received higher values. Each distance-related rank value for a particular site was then multiplied by the number of estimated nests in the colony from which the distance was calculated. Nest numbers used in these calculations are presented in Table 3 and were updated through field observations on a monthly basis when possible. Finally, these nest-weighted values were summed and ranked to obtain a number that identified a site's value as wading bird habitat based on (1) proximity to multiple colonies and (2) the relative importance (size) of the colonies.

The same procedure was repeated with White Ibis colony data using a foraging range of 0 − 18 km (Bancroft et al., 1990) so that two separate species values were generated for every map site. Eighteen km was used as the upper threshold for White Ibis foraging distance because a foraging distance of 20 km has been reported to result in total nest abandonment (Bancroft et al., 1990). Because Wood Storks are listed as a federally endangered species, however, they are considered a higher priority from the standpoint of environmental management. Accordingly, habitat suitability values were weighted 1.5:1 in favour of Wood Storks. The two values for each site were then summed to obtain a combined species habitat value, which were ranked 1–5 based on equal intervals over the range.

A time switch that turns the nesting component 'on' during the breeding season and 'off' during the rest of the year was incorporated in the model. During the non-breeding season, the term for site proximity to colonies and their nest numbers is excluded from the risk equation. During the breeding season, all distance-related ranks of 5 (i.e. closest sites to nests) were substituted with water depth ranks to account for the potential for predatory access to nests. This assures that any dry sites in close proximity to large colonies have a low habitat suitability rank.

Integration of all factors—water depth, recession, and distance (weighted by nest numbers and species)-related ranks for each map site were weighted and summed to produce the final WBHS values, which were ranked 1–5 for mapping.

The final (integrated) WBHS calculation is as follows:

$\text{Risk} = \sum(\text{factor rank}^* \text{ factor weight})$

From February to June of 2001 we ran the assessment models monthly and then weekly. Analyses were done for both current conditions (using real-time water level recorder data) and scenarios predicted by water level position analyses similar to the methods others have used in conducting environmental risk assessments (Hirsch, 1978; Smith et al., 1992). Here we present assessments for PFR and WBHS based on actual conditions for March 1 and May 1, 2001.

Table 3
Location and size of wading bird colonies

Species	Area	Colony name	Estimated nest numbers		
			March 16	April 19	May 11
Wood stork	WCA-1	111	0	5	11
	WCA-2B	2B Melaleuca	(50)	50	8
	ENP	Tamiami west	900	1100	920 λ
		Cuthbert lake*	(20)	20	(20)
		Paurotis*	(125)	125	(125)
		Rodgers river*	(40)	40	(40)
White ibis	WCA-1	70	950	1700	600
	111	5400	4000	0 (all fledged)	
	WCA-2B	2BMelaleuca	(150)	150	200

Numbers in parentheses are assumed values (not surveyed on that date); asterisks denote National Park Service estimates of nest numbers; λ denotes bird rather than nest count (no. nests may be much lower).

3. Results

3.1. Peat fire risk

Although peat fire risk was closely correlated with water levels, a scatterplot of water level vs. risk value (unranked)

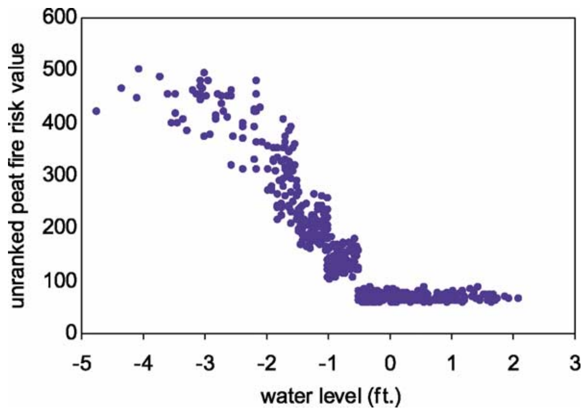

Fig. 2. Plot of peat fire risk values vs. water levels to show the effect of secondary factors on the relationship.

shows the effect of the secondary variables on the relationship. In this regard, the status of these other factors substantially lowered or enhanced risk at many locations, particularly where water levels were between −2 and −3 ft (Fig. 2).

In terms of overall peat fire risk, values were low throughout most of the EPA in March (Fig. 3). In ENP, however, a substantial area in the east was identified as either extreme or high risk. Smaller areas of moderate and high risk appeared in the northwestern portion of ENP as well as in southern Holeyland and northwestern WCA-3A. Low to moderate risk areas were present across Rotenberger and the northern half of WCA-2A. By May, most of the ENP (except for the western reaches of this tract) emerged as having a high to extreme risk of peat fire. With the exception of northwest WCA-3A, where a surface burn occurred in

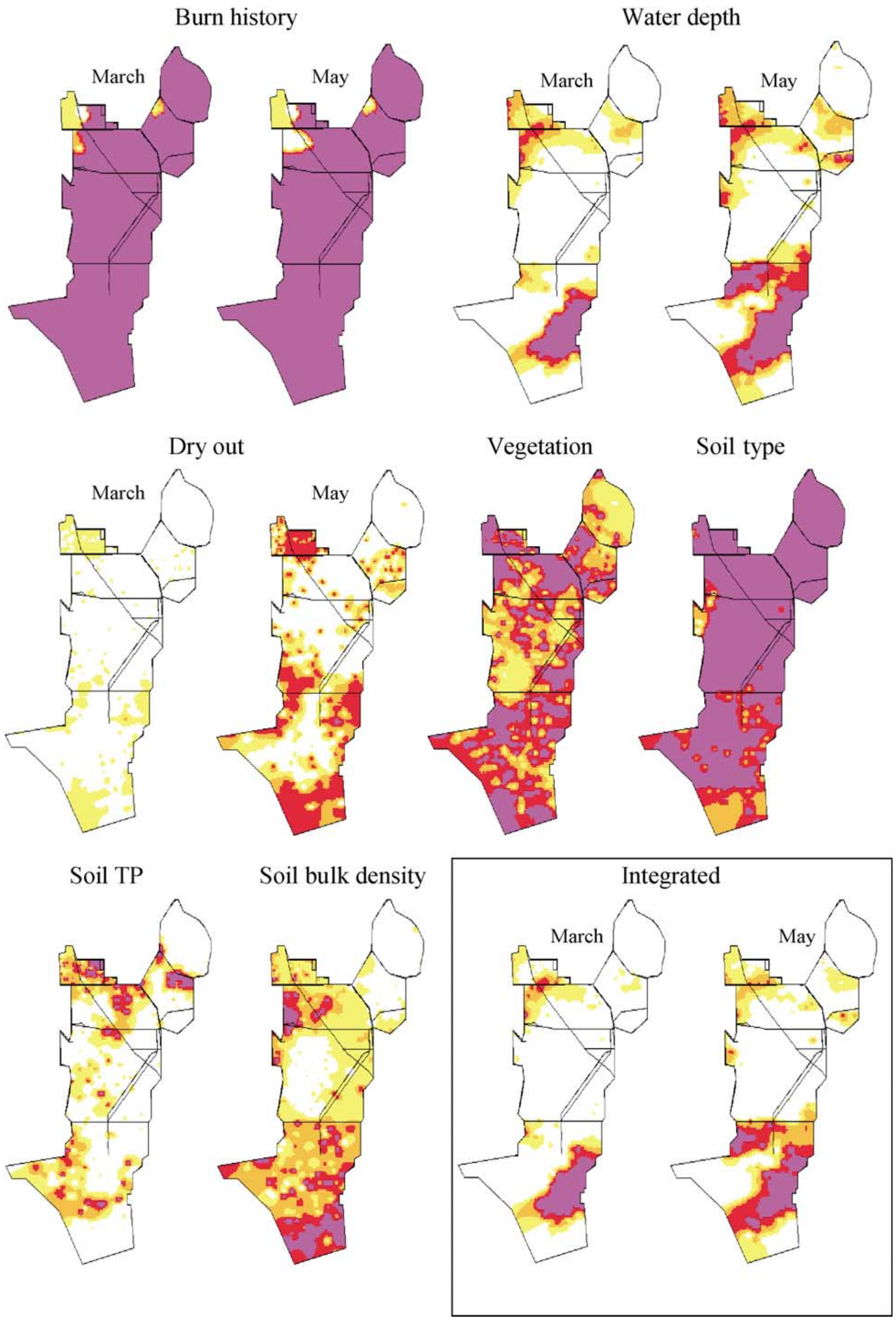

Fig. 3. Assessment of peat fire risk for individual and integrated (boxed) components for March 1 and May 1, 2001 (darker colors indicate increasing risk with white and purple representing the lowest and highest risk, respectively).

April, Rotenberger, WCA-2A, western WCA-3A and WCA-3B all showed elevated risk. WCA-2B exhibited the greatest temporal change, moving from the no risk category in March to variably low-high risk in May.

From the standpoint of peat fire prevention, the assessments highlighted areas where temporary pumps might be needed and where future prescribed burning could be used to eliminate fuel and reduce risk. However, while eight separate surface fires burned throughout the EPA (most of them during the month of June) during 2001 (Fig. 4), no peat fires occurred. This was presumably due to the absence of an ignition source (e.g. lightening and/or accidental or deliberate human sources) in the right place (i.e. high-risk areas) at the right time. The fire that occurred in northwest WCA-3A in February was confined to the surface vegetation since water had not receded early enough or to levels low enough for peat combustion to occur. In April, a fire in the same region overlapped to a limited extent with areas of marginal risk for the March 1 assessment. Presumably, peat burning did not occur here because stages increased by ~0.5 ft from March 1–April 1 as a result of a major precipitation event. This would have reduced risk in an April assessment (data not shown). A number of other fires occurred during the month of June. However, these fires burned only the surface vegetation as copious amounts of rainfall in late May and early June virtually eliminated any chance of peat combustion.

3.2. Wading bird habitat suitability

Colony names and locations are presented in Fig. 5. The highest WBHS values in March were limited to the central and southern portions of WCA-3B and northeastern ENP (Fig. 6). However, moderately to highly suitable habitat appeared across most of WCA-1 and as a band that stretched from the southern fringe of WCA-2A southwest into southern WCA-3A. This was the result of suitable water levels in close proximity to key colony locations. However, other areas with highly suitable water levels and recession rates were ranked lower based on their remoteness from colonies. Rotenberger, Holeyland, the northern reaches of all the WCAs, and southeastern ENP appeared as highly unsuitable habitat, primarily due to low values for all factors.

By May, the highest suitability zones appeared along the southeast portions of WCA-1 and -3A and in central WCA-3B. In general, the prominent band of marginal to highly suitable habitat moved in southeasterly direction while smaller, disconnected patches disappeared from other regions. One colony (Roger's River) benefited from reductions in what were otherwise high water levels near its location. However, several colonies (i.e. 70, 111, Crossover, Tamiami West) experienced a substantial decrease in the area of highly suitable habitat nearby. These conditions were confirmed by field observations and an effort to protect the Tamiami West colony was begun in

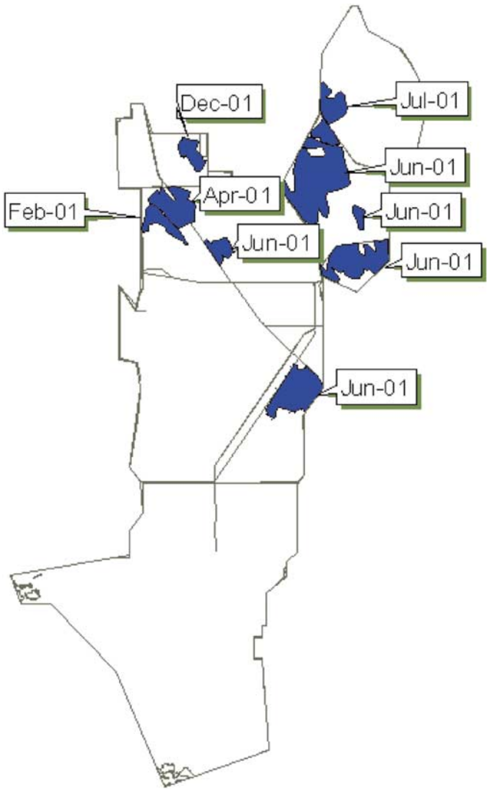

Fig. 4. Surface fires occurring within the Everglades Protection Area during 2001.

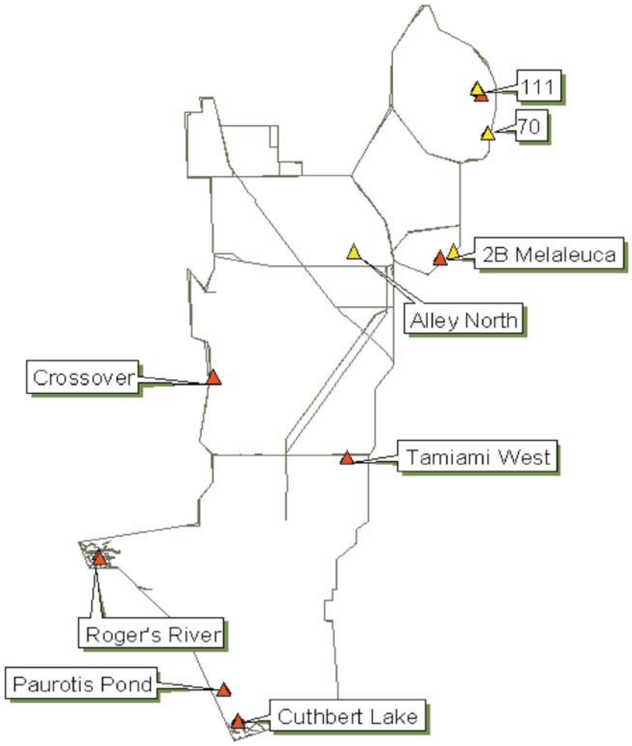

Fig. 5. Major wading bird nesting sites within the EPA during 2001 (yellow triangles represent White Ibis colonies; red triangles represent Wood Stork colonies).

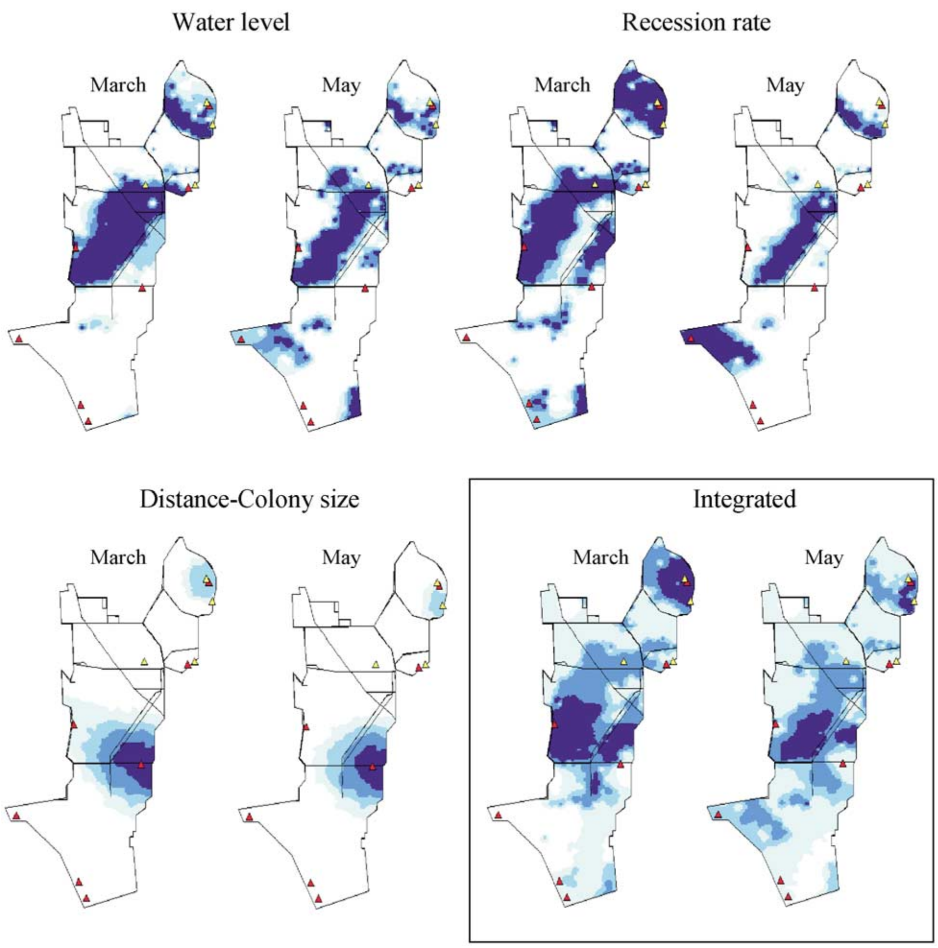

Fig. 6. Assessment of wading bird habitat suitability for individual and integrated (boxed) components for March 1 and May 1, 2001 (darker shades of blue correspond indicate increasing suitability with white and dark blue representing the lowest and highest suitability, respectively; yellow triangles represent White Ibis colonies while red triangles represent Wood Stork colonies).

May. Using a temporary pump, water from the Tamiami canal was discharged into the area to prevent predatory access to the nests.

With a couple of exceptions, the wading bird habitat assessments were reasonably good predictors of colony success. For example, the Tamiami West colony had some nest abandonment by Wood Storks by the May 11th survey, which coincides with a major reduction in habitat suitability in the near vicinity. Similarly, abandonment was observed in the 2B Melaleuca colony (White Ibis and Wood Stork) during April and May. During this time, habitat suitability within WCA-2B also diminished rapidly. However, Alley North (a White Ibis colony) and Crossover (a Wood Stork colony) were both completely abandoned by the April 19 survey, despite an apparent abundance of suitable foraging habitat. In WCA-1, some nests in the 70 and 111 White Ibis colonies were abandoned by the April 19 and May 11 and surveys under similar circumstances. There are some plausible explanations for this. First, a major precipitation event in April that caused a reversal in recession may have triggered this response by some birds. Also, the 111 colony was at the surface water edge on May 1 (date of assessment) so further water level recession in early May probably exposed the site. Finally, the Alley North and Crossover sites were located on a prominent tree island perceived to be well above the elevation of surrounding marsh. Thus, the ground immediately underneath these colonies may have gone dry long before the surface water of surrounding foraging areas, thereby eliciting an abandonment response.

4. Discussion

Similar habitat models have been developed for fire and wading birds in the Everglades. Bayley and Odum (1976) modeled interrelations of *C. jamaicense*, peat, fire, water, and surface water phosphorus. However, our model concentrates on ecologically damaging peat fire rather than surface fire, which is generally beneficial or of no consequence (Gunderson and Snyder, 1994). It also includes information on vegetation composition, burn history, soil depths, soil properties, and duration of dry out. Furthermore, we used soil P rather than water column P—an important distinction given that soil concentrations reflect a long history of nutrient loading rather than a variable condition, the latter of which may be irrelevant to plant biomass (fuel loading) at the time of measurement. For wading birds, Curnutt et al. (2000) has developed system-wide spatial indices for the Cape Sable Seaside Sparrow, Snail Kite, Wood Stork, and 'long-legged wading birds'. Hoffman et al. (1994) and Bancroft et al. (2002) used statistical models to evaluate wading bird habitat in the Water Conservation Areas using vegetation categories and water depths. Our assessments differ primarily in the inclusion of recession rates, colony locations, nest numbers, species-specific foraging distances, and real-time stage readings. In addition, monitoring nest numbers by helicopter surveys allowed us to examine temporal shifts in the 'importance' of various regions to the nesting effort throughout the season.

One of the limitations of our assessment methodology is that only two aspects of ecosystem health (peat fire and wading bird habitat risk) are included and drought has major impacts on organisms ranging across all trophic levels and on other aspects of the physical environment such as soil oxidation, vegetation changes, etc. In addition, peat fire can significantly transform the vegetation, topography and character of the landscape, thereby creating a need for updated elevation, soil properties, and vegetation data that is critical to the model output. For example, *T. domingensis* may begin proliferate in areas that were formerly *C. jamaicense* following peat burning (Smith et al., 2001; Smith and Newman, 2001). In lieu of costly elevation surveys, fire boundaries can be delineated by GPS points and soil loss estimated by measuring water depths at various locations within and outside the burned area.

The PFR assessments could not be compared with actual peat fire-related data from 2001 because no such disturbances occurred during this time. However, when the model was run using data from May 1999 when peat burning occurred in northern Rotenberger and northwestern WCA-3A, these areas fell into the highest risk categories, indicating that the model appears to provide a reasonable basis for risk evaluation. Hindcasting for older peat fire events could not be done with much reliability since accurate vegetation, soil nutrients, and precise fire boundary data are not available. For the WBHS assessments, the model may overestimate water depths immediately underneath colonies because virtually all sites were located within tree-island habitat. Moreover, wading bird behaviour during nesting also may be highly influenced by extremely localized conditions and events, such as a short-term reversal in water level recession.

Despite these shortcomings, and the need for further refinement through calibration and continued evolution of conceptual models, the assessments described the system in a way that provided a meaningful perspective on drought-related ecological risk. For example, in addition to providing continuous assessments throughout the drought period, we were able to evaluate how various water management alternatives might further affect conditions across the system. Based on predicted stages from the South Florida Water Management Model developed by Fennema et al. (1994), we ran assessments for several different operational schemes that sought to lower the minimum allowable stages for the WCAs for the benefit of water supply. They showed that the deviations would result in little to no increase in ecological risk in WCAs 1 and 2A, but would significantly increase peat fire potential and reduce suitable wading bird habitat in WCA-3A. Consequently, operational procedures were implemented to utilize the former for water supply needs while protecting the latter for environmental purposes. Increasingly, such methods of translating scientific information into practical tools for managers and decision makers are becoming an integral component of environmental management.

5. Summary

In the winter-spring of 2001, South Florida experienced a severe period of drought. Many ecological concerns arose during this time, including the potential for catastrophic peat fire and impacts on wading bird reproduction. Water managers attempted to balance environment and water supply needs, but it became evident that a way to portray and prioritise ecological stress was lacking. Consequently, we developed a method to generate a set of GIS-based indices of peat-fire risk and wading bird habitat suitability. The indices describe two ecological conditions that are considered extremely important to the physical and biological integrity of the Everglades. In addition to providing continuous, updated assessments throughout the drought period, we were able to evaluate how various water management alternatives might exacerbate or alleviate ecological stress during this time. The manuscript describes and justifies the methodology for this assessment procedure and details how it was used to make water management decisions.

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