Research Article

WETLAND FIRE SCAR MONITORING AND ANALYSIS USING ARCHIVAL LANDSAT DATA FOR THE EVERGLADES

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ABSTRACT

The ability to document the frequency, extent, and severity of fires in wetlands, as well as the dynamics of post-fire wetland land cover, informs fire and wetland science, resource management, and ecosystem protection. Available information on Everglades burn history has been based on field data collection methods that evolved through time and differ by land management unit. Our objectives were to (1) design and test broadly applicable and repeatable metrics of not only fire scar delineation but also post-fire land cover dynamics through exhaustive use of the Landsat satellite data archives, and then (2) explore how those metrics relate to various hydrologic and anthropogenic factors that may influence post-fire land cover dynamics. Visual interpretation of every Landsat scene collected over the study region during the study time frame produced a new, detailed database of burn scars greater than 1.6 ha in size in the Water Conservation Areas and post-fire land cover dynamics for Everglades National Park fires greater than 1.6 ha in area. Median burn areas were compared across several landscape units of the Greater Everglades and found to differ as a function of administrative unit and fire history. Some burned areas transitioned to open water, exhibiting water depths and dynamics that support transition mechanisms proposed in the literature. Classification tree techniques showed that time to green-up and return to pre-burn character were largely explained by fire management practices and hydrology. Broadly applicable as they use data from the global, nearly 30-year-old Landsat archive, these methods for documenting wetland burn extent and post-fire land cover change enable cost-effective collection of new data on wetland fire ecology and independent assessment of fire management practice effectiveness.

Keywords: classification trees, Everglades, fire scars, Landsat, recovery, wetlands

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INTRODUCTION

The ability to document the frequency, extent and severity of fires in wetlands, as well as the dynamics of post-fire wetland land cover, informs fire and wetland science, resource management, and ecosystem protection. Aside from providing important ecosystem and other public services, the Everglades National Park and the wetland areas surrounding it (Figure 1) serve as a "living laboratory" for research that improves our understanding of wetland function and our ability to protect and enhance wetland habitats elsewhere. As with other wetlands, fire has played a major role in shaping the complex and dynamic nature of the Everglades (Jones 2011*a*). Information on Everglades National Park (ENP) fire history has been compiled from narrative reports, paper sketch maps, and more recently, field-based traces of fire scars using GPS. Less precise burn scar information is available for locations outside of the park, as fire locations have been noted using large administrative units such township and range (the US Public Land Survey system), often with an approximate size but no detailed scar boundary information (Gunderson and Snyder 1994). Systematic monitoring of post-fire landscape dynamics in sensitive wetland environments like the Everglades is difficult and costly. To date, monitoring has been based on detailed field surveys for limited, specific plot locations (e.g., data collected under the ENP fire effects monitoring plan; M. Vaidya, National Park Service, personal communication).

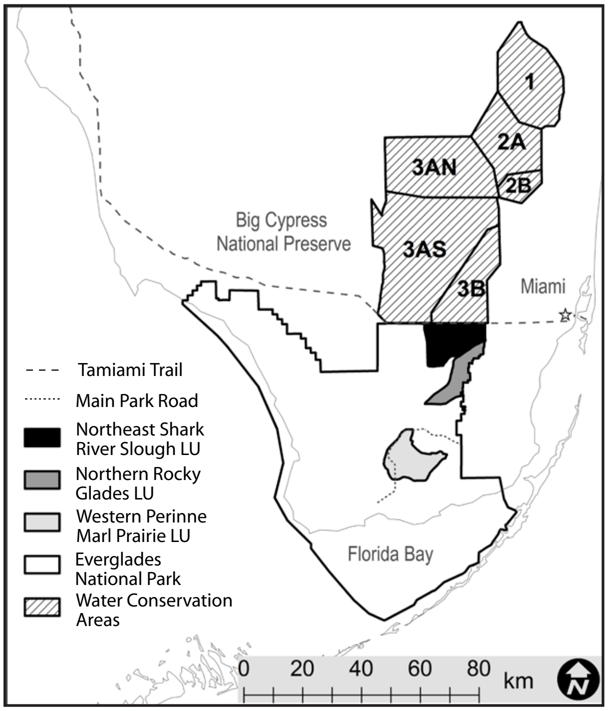

Figure 1. Study area for Greater Everglades pilot study areas of interest (AOI), including all of the South Florida Water Management District's Water Conservation Areas (WCAs) and three landscape units of the Everglades National Park selected from those delineated in the guidelines of the Comprehensive Everglades Restoration Project (CERP).

While remote sensing technology has been used to detect active fires and derive information on burn extent and severity throughout the world (Fuller 2000, Bowman *et al.* 2003), with very few exceptions (Cassidy 2007, Duncan *et al.* 2009, Salvia *et al.* 2012) the vast majority of fire remote sensing research has been performed within upland, not wetland, environments. We define the "Greater Everglades" as the combined areas of the ENP and the South Florida Water Management District (SFWMD) Water Conservation Areas (WCAs) as shown in Figure 1. The spatially heterogeneous, highly dynamic land cover and the subtropical climate of the Greater Everglades present particularly difficult challenges to the application of satellite remote sensing (Jones 2011*b*). On 21 April 2008, the US Geological Survey (USGS) announced that it would begin providing all archived Landsat scenes at no charge to users. This action created the opportunities to develop new approaches to landscape dynamics monitoring that may rely on partially cloudy imagery (i.e., processing at the individual pixel level if necessary), rather than restricting investigations to the rare dates when completely clear images are available. In this case, we capitalized on no-cost Landsat imagery (USGS 2012) through rapid, standardized ocular interpretation of all cloud-free portions of every Landsat scene available for the study period.

Because of the challenges associated with remote delineation of fire scars and post-fire land cover dynamics tracking in complex, dynamic, sub-tropical wetlands like those of the Everglades, our objectives in this study were to (1) design and test broadly applicable and repeatable metrics of not only fire scar delineation but also post-fire land cover dynamics through exhaustive use of the Landsat satellite data archive, and (2) explore how those metrics relate to various hydrologic and anthropogenic factors that may influence post-fire land cover dynamics.

METHODS

Study Area

To create a manageable scope for our pilot study, subunits of the Greater Everglades (Figure 1) and the Landsat archive were selected for data gathering and analysis. We looked at the region of the South Florida Water Management District's Water Conservation Areas (WCAs) in their entirety. The WCAs extend from just south of agricultural lands below Lake Okeechobee, to the southernmost portion of US Highway 41, known as Tamiami Trail. Agricultural and urban areas line their eastern borders; their northwestern borders abut sandy flatwoods and agricultural land; and their southwestern borders are adjacent to the Big Cypress National Preserve (BCNP). The WCAs are large water impoundments surrounded by levees—with the exception of WCA3AS, which receives inputs from BCNP's Mullet Slough. Canals, pumping stations, and other water control structures move water in and out of the WCAs to protect adjacent developed areas from flooding and to store and regulate the release of water in times of drought. Due to past water management practices and the disruption of sheet flow by the impoundment levees, the WCAs experience shallower water depths and shorter hydroperiods at their northern ends and deeper water at their southern ends than they did historically (Zahina 1998, Lodge 2005). The WCAs have peat soils ranging from 1 m to 3 m in depth (Scheidt and Kalla 2007) and are generally long-hydroperiod *Cladium jamaicense* Crantz flat marshes with ridge and slough microtopography that also include interspersed willow heads dominated by *Salix caroliniana* Michx.; bayheads dominated by *Magnolia virginiana* L., *Ilex cassine* L., and *Persea borbonia* (L.) Spreng.; and subtropical hardwood tree islands that support species needing drier conditions, such as *Lysiloma latisiliquum* (L.) Benth., *Quercus virginiana* Mill., and *Annona glabra* L., among others (Zahina 1998, US Fish and Wildlife Service 1999, Lodge 2005).

Everglades National Park (ENP) covers the remainder of South Florida's undeveloped mainland from Tamiami Trail to Florida Bay. This area was too large for this pilot study. Therefore, we evaluated fire scars in three landscape units (LUs) indicated in Figure 1, as defined by the Comprehensive Everglades Restoration Plan (CERP) (RECOVER 2004). A vegetation map produced by the University of Georgia (Welch and Madden 1999) provides vegetation composition information in the following descriptions of these LUs.

Northeast Shark River Slough (NESRS). The NESRS landscape unit is bordered by Tamiami Trail to the north; by agricultural areas, urban areas, and rocky flats to the east and southeast; and by the continuation of Shark River Slough to the west and southwest. NESRS is a flat marsh with ridge and slough microtopography that formed under the influence of seasonally driven sheet flows that historically inundated the area 9 to 12 months of the year (Olmstead *et al.* 1980, Noble *et al.* 2002). Water inputs are now governed exclusively by the WCA water control structures and rainfall in the immediate vicinity. Past management practices strongly impacted this LU by reducing overall water inputs, concentrating water delivery through limited numbers of control structures, and creating unnatural flooding and drying cycles (Olmsted *et al.* 1980, Olmsted and Armentano 1997, Lodge 2005). The peat soils in this LU are approximately 1 m deep (Noble *et al.* 2002), and short, sparse, *C. jamaicense* dominates the native vegetation. Tall, dense *C. jamaicense* dominates the marsh at higher elevations, and tree islands support species requiring drier conditions such as those listed for the WCAs (Welch and Madden 1999).

Western Perrine Marl Prairie (WPMP). The WPMP landscape unit is located south of the Miami Rock Ridge, a formation of oolitic limestone rock created by interlaid geologic marine and freshwater depositions (Noble *et al.* 2002). The WPMP is bordered on the west by a transitional zone to Shark River Slough, on the east by Taylor Slough, and on the south by oligohaline marshes. This LU is part of the deep soil (15 cm to 200 cm) (Noble *et al.* 2002) freshwater marl prairies of the Everglades that are typically submerged only two to four months of the year (Noble *et al.* 2002). The LU supports a broader array of vegetation than that found in long-hydroperiod peat marshes, including a patchwork of *C. jamaicense*, *Melaleuca quinquernervia* (Cav.) S.T. Blake, *Eleocharis cellulosa* Torr., and other graminoid marsh species in a mosaic with higher elevation areas containing willow head, bayhead, and subtropical forest vegetation. The southwest corner of this LU also includes a small area dominated by *Rhizophora mangle* L. (Welch and Madden 1999).

Northern Rocky Glades (NRG). The NRG is a flat prairie on the Miami Rock Ridge. Like WPMP, the NRG is typically inundated only two to four months of the year (Noble *et al.* 2002) and therefore does not accumulate peat. However, the marl soil layer in the glades is shallow (<15 cm) and interspersed with outcrops of the limestone ridge (US Fish and Wildlife Service 1999, Noble *et al.* 2002). Solution holes pit the surface of this rocky flatland (J.W. Jones and W.F. Loftus, US Geological Survey, Reston, Virginia, USA, unpublished report), and the deeper holes, which connect to the underlying aquifer, may accumulate organic litter, marl, and, in some cases, peat, which allows them to serve as refuges for water-dependent species during the dry season (Lodge 2005). The NRG encompasses the northern half of the Rocky Glades, and is bordered by the NESRS LU on the north, agricultural and urban areas on the east, and a transitional zone to Shark River Slough on the west. Short, sparse *C. jamaicense* predominates this LU, but other species dominate in some locations, including *Muhlenbergia filipes* M.A. Curtis, *E. cellulosa*, *Myrica cerifera* L., *S. caroliniana*, *M. virginiana*, *I. cassine*, *L. latisiliquum*, *Q. virginiana,* and *Typha* spp., among others. Non-graminoid emergent species such as *Pontederia lanceolata* Nutt., *Sagittaria* spp., *Nymphaea odorata* Aiton, and *Typha* spp., are associated with solution holes, as well as submergents such as *Ludwigia repens* J.R. Forst. and *Utricularia* spp. This LU, being adjacent to urban and agricultural lands, also includes many patches that are dominated by invasive species such as *M. quinquenervia*, *Casuarina* spp., and *Schinus terebinthifolius* Raddi, among others (Welch and Madden 1999).

We refer to the WCAs and LUs collectively as our areas of interest (AOI) to efficiently distinguish them from the potential study area of the entire Greater Everglades.

Image Collection

In the past, satellite remote sensing studies were severely constrained by the difficulty of obtaining cloud-free satellite imagery, as cloud-free days rarely occur in the sub-tropical Everglades. We visually interpreted all of the Level 1T Thematic Mapper and Enhanced Thematic Mapper imagery available for our areas of interest from 2000 to 2011. Level 1T products provide systematic radiometric and geometric corrections by incorporating ground control points in conjunction with a Digital Elevation Model (DEM) to achieve documented positional accuracy. We selected this time frame so that we could compare our interpreted fire scar boundaries with those contained in an ENP database for the years 2000 to 2004 while also tracking changes in the burned areas over at least a 7-year period (i.e., until 2011 for any fire that occurred in 2004). Both Landsat 5 and Landsat 7 instruments were operating through this time frame. Each satellite collects images at the same location on the earth every 16 days (termed its return period). In combination, the two satellites provide a potential image every 8 days assuming the specific ground location of interest is not obscured by clouds or cloud shadows.

Fire Scar Boundary Mapping

Fire scar boundaries in the ENP LUs were taken from the park's GIS database. Fire scar boundaries in the WCAs were collected through visual assessment. Using ENVI (Exelis Visual Information Solutions, Boulder, Colorado, USA) image processing and analysis software[1], we displayed each Landsat image on a computer screen using bands 5 (middle infrared, MIR), 4 (near-infrared, NIR), and 3 (red, R) in red, green, and blue colors, respectively. We refer to this display method as a "543 composite." We chose these bands because they provide good contrast between burned and unburned areas and yield images whose colors are intuitive to those unfamiliar with multispectral imagery (Jones *et al.* 2001). We located fires scars originating within our areas of interest in the years 2000 to 2004 and hand-digitized their boundaries. In many cases, scar boundaries were only completed after numerous later satellite images were used to infill portions obscured by cloud or shadow in earlier images. During this process, no independent data on fires were available for the WCAs. Therefore, we relied solely on our visual assessments to discover and document visible fire scars. In ENP, we searched for all fires recorded in the park's fire management GIS database.

Burned Area Comparisons

We tested for statistical differences in fire scar area as a function of AOI over the 5-year span (2000 to 2004) using the Kruskal-Wallis statistic. Pairwise comparisons for differences among AOI median area were conducted using Mann-Whitney U test. The null hypothesis in all cases was that of no difference among AOIs. Areas for fire scars in ENP were obtained from the fire management database, whereas fire scar areas for the WCAs were computed from their hand-digitized polygons. The database contains fire scars that are too small to locate in 30 m resolution imagery. To eliminate this bias in our area comparisons, ENP fires smaller than the smallest fire detected by visual examination in the WCAs (1.6 ha) were removed prior to analysis.

Dependent Variables: Post-Fire Landscape Dynamics

The ENP database provided detailed information not available for the WCAs at the time of the analysis. Therefore, we only evaluated ENP LUs for post-fire land cover changes, tracking them through the temporal series of Landsat scenes. For each fire, we determined an "end date," a "green-up date," and a "return to pre-burn condition (PBC) date." We further estimated the number of days from the fire end date to green-up (DTG) and number of days from the fire to PBC (DTP). All of these terms were defined and estimated as follows:

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[1] Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US government.

End date. The ENP fire database includes both discovery dates and dates on which the fires were declared out by ENP fire management. In most cases, the declared date was accepted as the fire end date for use in calculations. However, in cases where discovery and declared out dates coincided and the burn scar visible in imagery captured before the discovery date completely filled the area demarked by the corresponding database fire extent polygon, we assigned an end date. This assigned end date was calculated as midway between the dates of the last image in which the scar had not completely burned to the edges of the final scar footprint and the date of the first image in which it had reached maximum extent. In those cases, we estimated a potential error of half the number of days between the two images. Again, in cases where no discrepancies between discovery and declared dates and the imagery where apparent, we used the database information, and no error was reported.

*Greening, or green-up***.** When live vegetation returns to a fire scar in the Everglades, the scar will frequently appear much greener in a 543 composite than adjacent areas will, due to the presence of lower dry and dead fuel loads within the scar. Green-up was declared when newly greened vegetation visibly returned to any portion of the scar.

Green-up date. Because we could not pinpoint the exact time of green-up, given both the return period of the Landsat satellites and frequent south Florida cloud cover, we designated the green-up date as midway between the last image in which we could see that the scar had not yet greened and the first image in which the scar had greened. Similar to the end date variable, we report the error associated with these dates as a function of the time between these two images. In a handful of cases, the first greened image was also the first image in which the fire scar could be identified. For those fires, we estimated the green-up date using the midpoint between the end date and the first greened image, also assigning a temporal error.

Return to pre-burn character (PBC). Due to variability of recovery rates within scars and among the different landscape units, we sought to maintain consistency in our visual assessments by looking for the disappearance of scar edges rather than a more subjective assessment of overall scar recovery. Therefore we designated a particular scar as "returned to pre-burn character" (i.e., PBC) once all of a scar's edges could no longer be clearly pinpointed. In a handful of cases, a return to PBC did not take place, and this was documented as well.

PBC date. Similar to image-derived end and green-up dates, the PBC date was calculated as the midpoint between the first image in which a scar's edges could no longer be reliably located and the last image in which any of its edges could still be discerned. The temporal error created by the window between images was again reported.

DTG. Days to green-up was determined by subtracting the end date from the green-up date.

DTP. Days to PBC was determined by subtracting the end date from the PBC date.

Independent Variables

Wetland water levels prior to, during, and following a fire are likely to influence burn severity and post-fire vegetation dynamics. Appropriate hydrologic variables are needed to explore relationships among water levels, hydroperiods, and Everglades fire ecology. The Everglades Depth Estimation Network (EDEN) is composed of approximately 250 surface water gages (Telis 2006) from which water surfaces have been modeled and made available online (http://sofia.usgs.gov/eden). We differenced those daily water surfaces with a unique wetland digital elevation model created for EDEN applications (Jones *et al.* 2012) to produce water depth information. Water depths become negative when the water is below the ground surface—a common occurrence in the Everglades. Derived daily water depths for the centroid of each burn scar were processed to generate 12 hydrologic variables (Table 1) for every fire in our database. Some were direct measurements of water depth while others estimated the timing of a fire with respect to that of minimum or maximum water depth for the year (e.g., DAYSf2min and DAYSf2max, respectively). We also needed a way to characterize wetness of the year in which each fire

Table 1. Variables evaluated in conditional inference forests for their ability to predict the timing of fire scar green-up in Everglades National Park.

Variable	Description
Hydrology Based on EDEN Depths[a]	
MINyr	Minimum daily water depth during the year of the fire
MAXyr	Maximum daily water depth during the year of the fire
MEANyr	Mean daily water depth during the year of the fire
MEAN6yr	Mean daily water depth during the year of the fire and five years following
MINburn	Minimum daily water depth during the fire[b]
MAXburn	Maximum daily water depth during the fire[b]
MINf2g	Minimum daily water depth between the fire date and green-up date
MAXf2g	Maximum daily water depth between the fire date and green-up date
AveZ	Quantifies relative dryness the year of the fire, with respect to a 6-year window starting the year of the fire
Timing	
DAYSburn	Fire duration, calculated by subtracting the discovery date from the fire date
DAYSf2min	Days between the fire date and the date of minimum water for the year
DAYSf2max	Days between the fire date and the date of maximum water for the year
Additional	
AOI	Area of interest
TYPE	Fire type, designated by management
Hectares	Number of hectares burned, declared by management
CauseG	General cause of fire
CauseS	Specific cause of fire
Vdom	Dominant vegetation species[c]
V2nd	Second most prevalent vegetation species[c]
V3rd	Third most prevalent vegetation species[c]

[a] Water depths were calculated by subtracting estimated elevations from estimated surfaces, using values produced by the Everglades Depth Estimation Network (EDEN).

[b] Where fire dates were derived from imagery rather than the fire record, the minima and maxima in the error window associated with Landsat periodicity were used.

[c] Vegetation classes were taken from Welch and Madden (1999).

occurred relative to the wetness in years following the burn. For this purpose, we created a standardized value (*AveZ*) for daily water level:

$$AveZ = \frac{\sum_{x=1}^{n} Zx}{n} \,, \tag{1}$$

and,

$$Zx = \frac{Dx - MD}{\sigma} \,, \tag{2}$$

where: Zx = standardized depth for day x of the year of the fire; n = number of days in the year of the fire; Dx = depth of water for each day x in the year of the fire; MD = mean of daily depths for every day over the fire year and the five years following; and σ = standard deviation of daily depths over the fire year and the five years following.

GIS was used to attribute each fire in our study database with a large number of potentially pertinent variables, including both our EDEN hydrologic metrics as well as other ancillary data derived from the ENP fire database and other sources (Table 1). All of these variables were used as input for decision tree analysis.

Decision Tree Analysis

We used recursive partitioning to evaluate our many discrete and continuous variables (Table 1) for their ability to explain variation in DTG and DTP. Even with complex interactions, forests of decision trees are able to effectively select best predictors from large combinations of nominal, ordinal, and continuous variables (Strobl *et al.* 2009). Because of the high degree of correlation known to be present in the mixture of nominal and continuous variables that we evaluated, we elected to use an implementation of conditional inference forests and trees. This algorithm was designed to eliminate a bias present in classical decision tree approaches that favors continuous variables and variables with many categories over discrete variables with fewer categories (Strobl *et al.* 2007). It additionally eliminates bias introduced by the resampling scheme of classical random forests and affords an option that corrects importance score bias associated with correlated predictors in decision tree forests (Strobl *et al.* 2009).

We used conditional inference forests to survey for best predictors among our variables, running nine different seeds of unbiased forests of 2000 trees, testing five variables at each split, with a univariate testing alpha level of 0.05. From these runs, we selected the six strongest predictors and ran similar forests for five seeds. Finally, we used individual trees to gain insight into how specific variables predicted DTG and DTP, in this case testing the total number of variables available at each split (<5), and again using univariate testing with a 0.05 alpha level.

RESULTS

Fire Scar Boundary Mapping

We delineated 107 fire scars in the WCAs for the 2000 through 2004 study period. While the ENP database included 72 fire scar perimeters for this time period, only 47 of them were large enough (>1.6 ha) to be visible at the Landsat 30 m pixel scale and therefore included in the study.

Burned Area Comparisons

A Kruskal-Wallis test of individual fire scar areas over the 5-year study window rejected the hypothesis of no difference among ranked means ($\chi^2 = 39.996$, df = 8, $P < 0.001$). Even with the smallest fires removed to avoid bias, Mann-Whitney U tests (Table 2) showed that median area of fires in the ENP LUs were smaller than those found in the WCAs, with the exception of those in WCA2A, which

Table 2. Median and total area burned for each area of interest (AOI). Medians for areas, in hectares, that have no superscripts a to d in common represent significantly different groups (Mann-Whitney U test, $P < 0.05$). WCA: Water Conservation Area. NESRS: Northeast Shark River Slough. NRG: Northern Rocky Glades. WPMP: Western Perrine Marl Prairie.

AOI	Number of fires over 1.6 ha	Area burned in 5 years (ha) Median	Area burned in 5 years (ha) Total
WCA1	12	$190.5^{a,b,c}$	7 919
WCA2A	17	$62.7^{b,e}$	21 145
WCA2B	5	$533.3^{a,b,c}$	11 160
WCA3AN	27	460.6^{c}	43 773
WCA3AS	27	$207.4^{a,b,c}$	10 551
WCA3B	19	$486.7^{a,b,c}$	28 915
NESRS	12	56.9^{d}	2 234
NRG	22	29.7^{e}	1 973
WPMP	13	80.9^{d}	3 817

could not be said to differ from fires in either NESRS or WPMP. Fire sizes for LUs within the ENP could not be declared different from one another, and the WCAs only confirmed a difference in one case, in which fire scars in WCA3AN were larger than scars in WCA2A ($U = 154$, $P = 0.02$). Total burned area by AOI was typically low following years with high burn area (Table 3).

Post-Fire Landscape Dynamics

Post-fire dynamics of 79 % (37 of 47) of the total visible ENP fires during the study time period were traced to a return to PBC (Table 4). Two burn scars became re-vegetated but exhibited very different texture and tone than their antecedent conditions or surroundings. Of the three fires tracked with boundaries that persisted through 2011, no visible macrophytic vegetation returned after two fires in the NESRS LU (noted by end dates of 29 Jul 04 [SE = 12 days] and 2 Aug 04 [SE = 8 days] in Table 5). Instead, those two became open

Table 3. Yearly total area burned for the years 2000 through 2004 in the Greater Everglades areas of interest (AOI). Low annual total burned area values typically follow high ones. WCA: Water Conservation Area. NESRS: Northeast Shark River Slough. NRG: Northern Rocky Glades. WPMP: Western Perrine Marl Prairie.

AOI	No. of fires over 1.6 ha	Year	Total area burned (ha)
WCA1A (total area 56 554.2 ha)			
	2	2000	1 038
	4	2001	4 017
	0	2002	0
	3	2003	968
	3	2004	1 897
Total	12		7 919
WCA2A (total area 42 556.3 ha)			
	3	2000	632
	3	2001	16 680
	1	2002	144
	8	2003	1 537
	2	2004	2 151
Total	17		21 145
WCA2B (total area 11 447.6 ha)			
	3	2000	1 615
	1	2001	9 276
	0	2002	0
	0	2003	0
	1	2004	269
Total	5		11 160
WCA3AN (total area 71 190.8 ha)			
	1	2000	164
	6	2001	15 051
	5	2002	2 503
	5	2003	2 700
	10	2004	23 355
Total	27		43 773
WCA3AS (total area 128 462.0 ha)			
	11	2000	1 094
	4	2001	2 253
	6	2002	4 383
	5	2003	2 807
	1	2004	15
Total	27		10 551
WCA3B (total area 39 934.0 ha)			
	3	2000	1 614

Table 4. Number of fires in three areas of interest in the Everglades National Park that were identified and tracked to green-up, return to pre-burn character (PBC), or return to another state via visual assessment of Landsat archival imagery.

	Landscape unit		
Number of fire scars…	**NESRS**	**NRG**	**WPMP**
… listed in the database	18	31	23
… visible in Landsat imagery	12	22	13
… traced and returned to state similar to PBC	7	11	14
… traced and returned to vegetated state other than PBC	2	0	0
… traced and boundaries persisted	2	0	1

water ponds with seasonal periphyton coverage. One fire in the WPMP LU returned to PBC throughout most of the scar's area, but retained open water ponds along its northern edge.

Decision Tree Analysis

DTG. The two scars that converted to ponds could not be evaluated for a return to green-up and were removed prior to decision tree analysis. By far, the best predictor of the DTG was AveZ, with conditional inference forest importance scores above 1000 for all seeds. Other predictors had importance scores below 50 in all seeds. Scores for the type of fire (TYPE) ranged from 11 to 43. Timing variables, such as MINf2g and MAXf2g—indicating the time span between the end of the fire and minimum and maximum water, respectively—ranged from −1 to 13. The other variables had importance scores at or below 10 in all seeds.

From the many significant trees available, we reported two that illuminate the influence of management actions and hydrology. Both show AveZ splitting the data into discrete groups at a value of −0.194. The mean DTG for fires in the drier node was (120 ± 90) days. TYPE (Figure 2A) further divides the data according to whether or not a fire was unplanned and suppressed (Figure 2A, node 4). Types in the opposing node (node 5) included one unplanned fire that was discovered after it had gone out, and several fires that were either ignited by management or natural ignitions that were allowed to burn in service to management goals (Table 5). The mean DTG for node 4 was (66 ± 26) days, and the mean DTG for node 5 was (21 ± 15) days.

Another way of effectively dividing the data that did not pass the yearly dryness threshold was based on the annual minimum water depth at the fire centroid as modeled by EDEN. Fires with end dates on or before four days after that minimum (Figure 2B, node 4) had a mean DTG of (63 ± 30) days. Later fires, that is fires that ended more than four days after the annual minimum (Figure 2B, node 5), had lower mean DTG values of (22 ± 15) days.

DTP decision trees: All three of the scars retaining any discernible edges at the close of the study window were removed prior to DTP analysis. In the remaining fires, MAXyr , MAXf2g, and σ were among the top predictors of DTP, with importance scores of up to 15 509, 4 698, and 1 310, respectively. Fires occurring in locations with maximum water depths at or below 17.45 cm in the year of the fire tended to recover more quickly and were less variable than areas experiencing higher maximum depths (Figure 3A). Mean DTP for fires in node 2 was (2.9 ± 0.04) years, while mean DTP for fires in node 3 was (4.2 ± 1.60) years.

Table 5. Terminal node allocations for conditional inference trees derived from Landsat-based tracking of three landscape units in the Everglades National Park fires. Days to green (DTG) trees detail correlations among the time to green-up (DTG) and a measure of relative dryness for the year of the fire (AveZ), timing of fire with respect minimum water depth the year of the fire (d2Min), and the type of fire (Type). Types included fires that were set as part of the management plan (pm) and unplanned fires that were suppressed by management (us), discovered out (ud), or let burn in service to management goals (um). Days to PBC (DTP) trees detail correlations among the timing of the return of a scar to its pre-burn character (DTP), maximum water the year of the fire (MAXyear) and during green-up (MAXf2g), and 6-year water depth variability (σ).

				Days to green (DTG) trees					**Days to PBC (DTP) trees**						
				Node							**Node**		**MAXyear**		
End date	**±**	**DTG**	**±**	**A**	**B**	**AveZ**	**Type**	**d2Min**	**DTP**	**±**	**A**	**B**	**year**	**f2g**	**σ**
Northeast Shark River Slough															
1 Feb 01	--	170	4	2	2	–0.6377	us	–83	850	12	3	3	35.65	–2.4	26.31
11 Jun 01	--	32	12	2	2	–0.5629	us	50	1435	12	3	3	42.24	–8.5	23.79
16 Jul 01	--	81	32	2	2	–0.4738	us	55	2809	48	3	5	57.59	57.6	19.69
14 Aug 01	--	52	32	2	2	–0.5086	um	84	1300	40	3	5	53.14	51.7	22.61
26 Sep 01	--	309	60	2	2	–0.5038	um	127	1449	56	3	5	70.75	70.8	29.89
20 Aug 02	--	45	20	4	5	0.1554	us	98	1505	8	3	5	44.96	45	14.37
20 Aug 02	--	41	32	5	5	0.2014	ud	98	1097	48	3	3	42.77	–42.8	15.36
26 May 03	--	34	16	5	5	0.5429	um	64	2358	20	3	5	94.62	59.2	29.12
12 Aug 03	12	56	44	4	5	0.5004	us	110	1049	4	3	5	67.05	67	15.53
Northern Rocky Glades															
20 May 00	--	43	12	4	4	0.1857	us	–22	1215	64	3	3	42.14	–29.1	12.72
29 May 00	--	62	8	4	4	–0.1926	us	4	1114	28	2	4	9.00	–50.7	28.80
23 Mar 01	12	120	4	2	2	–0.3239	us	–60	2008	4	3	4	18.9	5.9	41.36
16 Jul 01	--	69	44	2	2	–0.3790	us	55	1181	44	2	3	17.45	–18	19.87
26 Feb 02	--	84	12	4	4	0.0689	us	–77	1072	8	2	3	–13.98	–37.2	18.45
30 Mar 02	--	52	12	4	4	0.0616	us	–45	984	48	2	3	–8.86	–36.7	20.30
21 Apr 02	--	26	16	5	4	0.1064	pm	–23	398	20	2	3	–8.6	–50.9	18.02
9 May 02	24	27	16	5	5	0.0842	pm	7	1336	16	2	3	–6.25	–28.1	24.66
10 May 03	--	22	12	5	5	0.6775	pm	57	1069	20	2	3	12.42	–0.2	22.15
10 May 03	--	22	12	5	5	0.6841	pm	57	1171	8	3	4	20.11	12.2	31.65
9 Mar 04	--	134	12	2	2	–0.2617	pm	–87	1522	8	3	4	22.95	–45.5	37.72
Western Perrine Marl Prairie															
3 May 00	8	60	4	5	4	0.218	pm	–23	1236	28	3	3	38.47	1.1	26.03
19 Jun 01	4	24	12	5	5	–0.136	pm	54	2104	212	3	4	25.53	10.9	31.56
26 Jun 01	--	17	12	5	5	–0.1616	um	61	1881	20	3	4	19.59	–6.9	27.81
16 May 02	--	117	4	4	4	0.1775	us	1	1385	112	3	3	20.81	20.8	23.30
26 May 02	--	11	4	5	5	0.1571	pm	11	2219	52	3	4	24.91	8.5	28.36
10 Jun 02	--	36	12	5	5	0.0332	pm	26	2272	16	3	5	29.35	29.4	23.37
2 Sep 02	--	8	4	5	5	0.1305	um	110	1176	12	2	3	8.86	–0.7	21.73
2 Sep 02	--	8	4	5	5	0.1797	um	110	1148	16	2	3	10.47	6.7	22.77
15 May 03	--	17	12	5	5	0.4489	pm	60	1201	28	2	3	–3.46	–24.6	26.42
28 May 03	--	8	8	5	5	0.3924	pm	75	1144	40	3	3	32.6	12.5	18.02
28 May 03	--	8	8	5	5	0.4324	um	73	832	32	3	3	37.13	9.4	23.40
28 May 03	--	8	8	5	5	0.4118	pm	75	--	--	--	--	--	--	--
27 Jul 03	--	2	2	5	5	0.4725	um	135	2064	108	3	3	31.7	9.3	20.97
25 Jul 04	16	24	8	2	2	–0.2827	pm	50	812	4	2	3	10.89	9.5	27.75
24 Oct 04	--	213	40	2	2	–0.1943	us	140	389	8	3	3	30.72	26.5	21.68

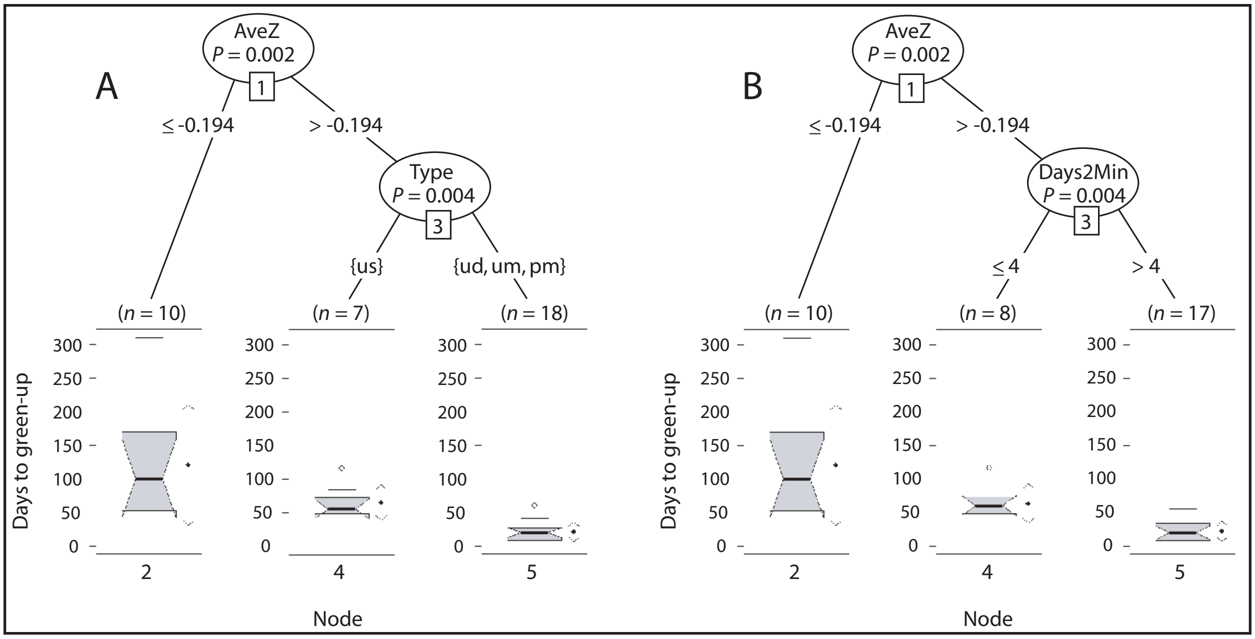

Figure 2. Sample conditional inference decision trees show how variables related to hydrology and management practice predicted time to visible re-sprouting as seen in Landsat imagery. *Z* scores represent relative dryness, negative values indicate drier years, and positive values indicate wetter years. A) The TYPE variables indicate whether fires were planned and implemented by management (pm) or naturally ignited and either suppressed (us), discovered out (ud), or allowed to burn (um). B) Days2Min measures time from the end of the fire to yearly water minimum, estimated using EDEN.

The maximum EDEN depth during the green-up window (MAXf2g) divided the data so that the variability in water depths over six years starting in the year of the fire (σ) became another decision point for further partitioning (Figure 3B). Mean DTP for fires with higher water depths during the green-up window (>26.5 cm) was (5.0 ± 1.8) years. Mean DTP for fires with lower water depths and higher water variability (>27.8 cm) was (4.7 ± 1.2) years, whereas fires with lower water variability had a mean DTP of (3.0 ± 1.0) years.

DISCUSSION

Highly dynamic vegetation common to many wetlands (Cassidy 2007, Duncan *et al.* 2009), as well as clouds, frequent changes in water level, and periphyton variability in the Everglades all significantly challenge attempts to remotely sense fire scars, as well as vegetation recovery, in the study region. However, we used rigorous visual interpretation of any cloud-free portion of every image in the dense time series of the Landsat archive to create a unique database of fire scars and post-fire landscape dynamics for our AOIs. We created metrics of time to green-up and assessments of whether vegetation of burned areas returned to those of pre-burn character (PBC) or some other state over the course of up to a 12-year period. We also developed methods to derive pertinent hydrologic information through geospatial processing of available stage data and applied the combination of these and our dynamics information along with published vegetation and fire management data to explore relationships among hydrology, management, and landscape dynamics. Plausible explanations for relationships among landscape dynamics, hydrology, and management practices were uncovered through our various analyses.

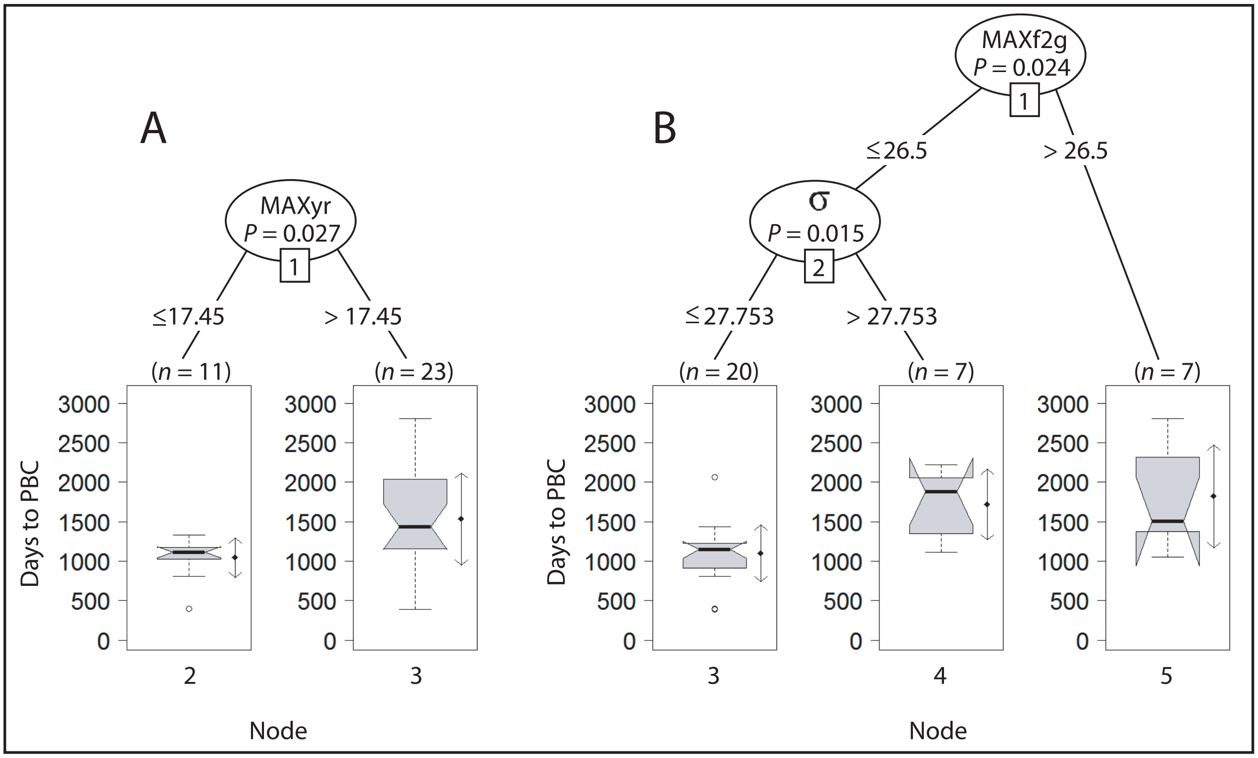

Figure 3. Sample conditional inference decision trees show how variables related to hydrology predicted time to return to pre-burn character as seen in Landsat imagery. MAXyr represents maximum water depth during the year of the fire and MAXf2g represents maximum daily water depth between the fire date and green-up. The variable σ represents variability of water depths during the year of the fire. Dry years and hydrologic variability predict widely varying time frames for vegetation recovery.

Area Comparisons

While fire management information was only available for ENP fires, observed trends and differences in burn area size by LU or WCA (Tables 2 and 3) may reflect the influence of fire management activities on fire history. ENP fuel loads were reduced by controlled burns on a rotating schedule while undesirable fires were actively suppressed (National Park Service, Everglades National Park, Homestead, Florida, USA, unpublished report 2010). The individual ENP LU burn areas were significantly smaller than burn areas for all but one WCA (Table 2). WCA2A contained the largest fire for the entire study area and study period (15 882 ha, or 37 % of the WCA), and reduction of fire loads by this event at the start of the study period could explain the small fire sizes in subsequent years (Table 3). While WCA2A contained the largest fire for our period of record, the later fire sizes made its ranks within Kruskal-Wallis and Mann-Whitney tests similar to fires in NESRS and WPMP LUs, which we know were managed and had reduced fuel loads. And while WCA3AN experienced larger median fire sizes and total burned area than WCA2A, it had a median value smaller than WCA2B, which could not be said to differ from WCA2A (Table 2). WCA2B provides another example of reduced fires following extensive burning. In 2001, 9276 ha or 81 % of WCA2B burned, leaving little fuel for fires in subsequent years. In fact, our visual assessments found no fires at all in WCA2B in 2002 or 2003 (Table 3).

Post-Fire Landscape Dynamics

Predictors of green-up. Our exploratory approach used decision forests to identify which variables had the most predictive power for each post-fire land cover response. We focus our discussion on trees that contain the most powerful explanatory variables and on trees that expose variables that, while less powerful than their correlated competitors, nonetheless provide valuable interpretive information. Figure 2 shows two representative trees for the response variable of days to green-up. In both, all fires in node 2 (AveZ at or below –0.194 m) occurred in 2001 or 2004 (Table 5). This finding indicates that they occurred in locations where conditions were drier than in the years following (Table 1). Four of these fires are noted in the ENP database as "managed." That is, they were either prescribed burns or discovered active fires that were allowed to burn. The remaining fires were actively suppressed (Table 5). In the other node, representing wetter conditions, the algorithm in one case (Figure 2A) classified the fires into disparate groups based on fire management actions. Actively suppressed fires occupied one of these daughter groups, and the remaining fires consisted of one lightning strike fire that was already out when discovered and 17 fires that were either set or naturally ignited and allowed to burn (i.e., not suppressed), presumably in accordance with management goals (Figure 2A, Table 5). The node dominated by managed fires has the smallest variability in days to green-up of any group, ranging from 2 to 60 days, and its median is significantly lower than the medians of either of the other terminal node groups (Figure 2A and Table 5). If a management objective is to reduce fire loads and return locations to green vegetation as quickly as possible, it would seem that those objectives were met for these fires. Thus, the combined results of nodes 2 and 5 (Figure 2A) suggest that current management actions are usually able to produce scars that green in the same year. However, in extremely dry years, such as 2001 and 2004, outcomes are less certain. Days to green-up values for the four managed fires allocated to the driest node (Figure 2A, node 2) were highly variable, ranging from 24 to 309 days.

Timing of the fire with respect to the yearly water minimum for the year (Days2Min, Figure 2B) is also able to effectively split the data not allocated to the driest node. It also produces one node with a lower median value than the other two terminal nodes in the tree (range 2 to 41 days, Table 5). This finding indicates that fires in normal to wet years that occur after minimum water for the year are likely to green-up sooner than earlier fires (range 26 to 117 days, Table 5). This may simply be a function of the natural phenologic pattern of green-up for all marsh vegetation. In our analysis, no fire scar greened before surrounding vegetation also began to green-up in response to the arrival of the wet season. However, in years that reach beyond a drier than normal threshold for the year, as represented by node 2 (Figure 2B), the timing of the fire with respect to low water is not predictive of time to green-up. Only three of those fires occurred before lowest water, yet green-up for the later fires was highly variable, ranging from 24 to 309 days (Table 5).

Return to Pre-Burn Character (PBC). Post-fire dynamics for some scars could not be traced because their edges coincided with natural boundaries in the landscape that existed prior to burning and persisted afterwards. In other cases, the fire's boundaries were entirely obscured by subsequent fires. While the smallest visible scar from the ENP fire database was a 1.2 ha thinly shaped fire scar in WPMP LU, background variability prohibited definitive judgments about its subsequent recovery.

Our interpretations of post-fire burn scar dynamics in traceable scars were made in the context of their surroundings. For example, the 543 composite for a moderately sized lightning-ignited fire in NESRS (end date 26 May 2003, Table 5) indicated that earlier vegetation associations at some locations within the scar were replaced with a different association, possibly recruited from areas nearby. However, visual interpretation of Landsat data alone is inadequate to estimate with confidence exactly what changes occurred. Additional ancillary data are necessary. In the case of another, larger, lightning-ignited NESR fire (end date 6 June 2001, Table 5), the vegetation character within the scar remained patchy and mottled, unlike its prior appearance, long after its borders disappeared. Without context, this might suggest that the burn patch itself was wetter than it had been prior to the fire and that fire had affected patch soils and elevation. However, the change was not unique to the burned area. Other patches in the vicinity also changed in the same way. In this case, it is unclear whether the action of the fire lowered elevation in the scar or the fire happened to occur in a broader, slightly lower area that would have changed in this manner with or without fire.

Our derived hydrologic variables provided important insights. For example, the two NESRS scars that converted to open water ponds with seasonal periphyton coverage in 2004 burned during what is typically the wet season in the Everglades. However, EDEN-based depths indicated that the dry season that year was extended by several weeks and conditions prior to the fire were unusually dry. While the exact timing of these fires cannot be pinpointed due to the temporal window dictated by the Landsat imagery, we know that they occurred somewhere during the time when water levels in NESRS were rising from well below the surface to well above. As a specific example, one of these fires occurred between 25 July and 10 August, when depths rose from 29.0 cm below to 34.1 cm above the surface (Figure 4). Both of these fires were caused by lightning strikes and were discovered after they had already expired (Table 5), presumably due to the rising water levels. Because *C. jamaicense* (the dominant vegetation in this scar) will not survive if its sprouts are unable to emerge above the water within about six weeks

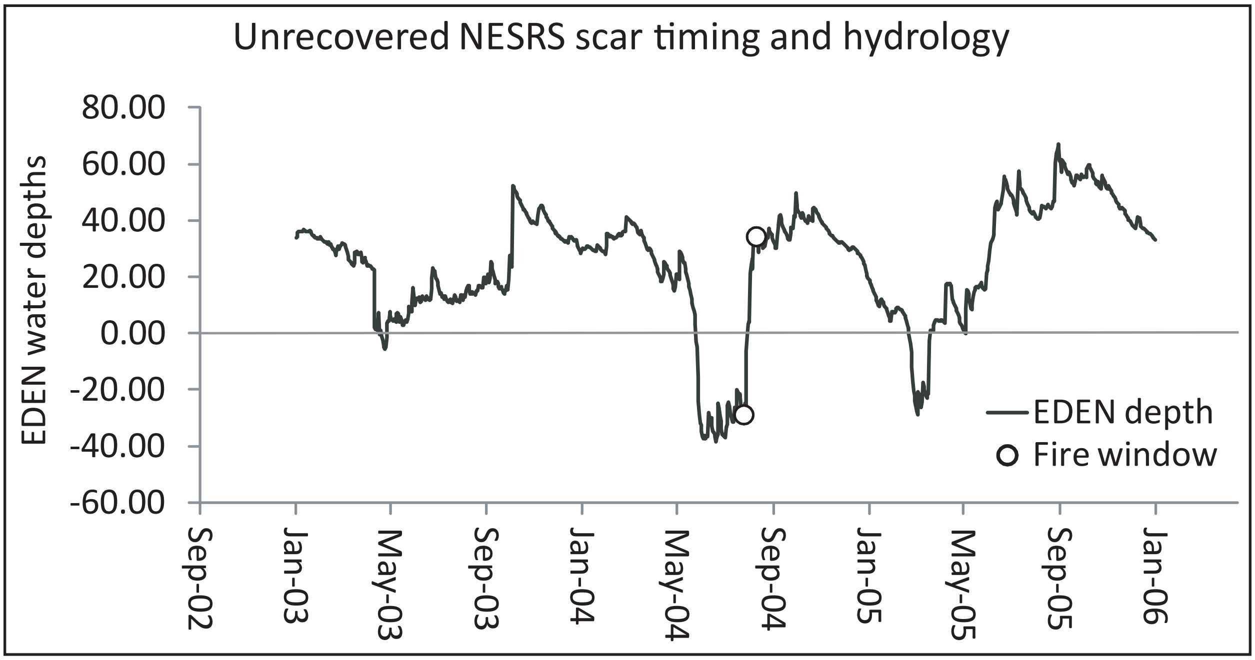

Figure 4. Three-year hydrograph of EDEN water depths at the centroid of a fire that occurred sometime between 25 July and 10 August, 2004.

of a burn (Wade *et al.* 1980, Lodge 2005), the vegetation in these scars apparently died in the wake of these fires.

Additionally, given the sharp scar boundaries and lack of edge recruitment many years later, it seems quite possible that the two 2004 NESRS fires that converted to open water occurred when the water levels were still below the surface and that peat substrate burned along with the vegetation, sufficiently altering the hydrology so as to discourage later re-colonization of the scar by adjacent emergent vegetation. Similarly, a WPMP LU managed fire occurring 5 May 2003 (Table 4) has northern scar borders that persisted as late as the wet season in 2011. This fire happened in the western portion of the LU, close to the transitional zone between prairie and slough. The fire burned at a time when our hydrologic variables again estimated that water levels at the centroid of the scar were below the surface (−12.9 cm to −4.0 cm) and yet rose soon thereafter (maximum 22 cm). The persistence of wet season ponds along select portions of the northwestern and northeastern borders suggests that elevations there were low enough to drown re-sprouting emergent vegetation and may have also been reduced through the burning of soil.

The factors of water depth and variability were important in explaining length of return time to PBC (i.e., DTP) as well. Fires in ENP locations where the maximum water depth during the year of the fire (MAXyr) was less than or equal to 17.45 cm (Figure 3A) occurred at higher elevations and had shorter hydroperiods than their counterparts. Table 5 shows which fires fell in this category (node A2). They represent 70 % of NRG fires and 30 % of WPMP burns. Under these conditions, fire scars return to PBC occurs most rapidly (2.9 years on average), suggesting that these conditions foster more rapid regrowth and return of fuel loads, and therefore support more frequent burning. This time frame is similar to the two to three year time frame for return to "steady state fuel load" reported in the literature (Loveless 1959, Gunderson and Snyder 1994). However, wetter conditions create far greater variability with longer mean periods to PBC (Figure 3A, node 3). When looking at depths (specifically maximum depth between fire and green-up, MAXf2g) combined with depth variability (σ), the data (Figure 3B) suggest that most fires ($n = 20$) reached PBC within one to four years (node B3). Fires in wetter locations where water depths during green-up are high (>26.5 cm), and fires in drier locations that nonetheless typically experience large fluctuations in water depth (>27.8 cm), will tend to take longer to replenish fuel loads and may support less frequent burning by management. The variability of DTP times seen in Figure 3B, nodes 4 and 5, is high, ranging from as few as 2.9 to as many as 7.7 years. In contrast, DTP times in node 3 ranged from 1.1 to 5.7 years.

Upon detailed analysis, the developed monitoring techniques provided diagnostic information on wetland fire ecology and independent assessment of management practices on post-fire vegetation condition. This was afforded by careful interpretation of no-cost, repeat moderate resolution satellite data (i.e., Landsat) systematically collected over long time periods. Because any Landsat data in the archive are freely available, wetland burn scar and the post-fire land cover change metrics described here can be derived for any fires >1.6 ha in size in any wetland. This pilot work will be extended over a larger portion of the Greater Everglades and longer time frames to yield a richer database for similar and other Everglades fire ecology research. The resulting data are the foundation for on-going research focused on the development of automated techniques for burn scar delineation and, most important, digitally based monitoring of post-fire land cover dynamics.

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LITERATURE CITED

Bowman, D., Y. Zhang, A. Walsh, and R.J. Williams. 2003. Experimental comparison of four remote sensing techniques to map tropical savanna fire-scars using Landsat-TM imagery. International Journal of Wildland Fire 12: 341-348. doi: 10.1071/WF03030

Cassidy, L. 2007. Mapping the annual area burned in the wetlands of the Okavango panhandle using a hierachical classification approach. Wetlands Ecology and Management 15: 253-268. doi: 10.1007/s11273-006-9026-2

Duncan, B.W., G. Shao, and F.W. Adrian. 2009. Delineating a managed fire regime and exploring its relationship to the natural fire regime in east central Florida, USA: a remote sensing and GIS approach. Forest Ecology and Management 258: 132-145. doi: 10.1016/j.foreco.2009.03.053

Fuller, D.O. 2000. Satellite remote sensing of biomass burning with optical and thermal sensors. Progress in Physical Geography 24: 543-561.

Gunderson, L.H., and J.R. Snyder. 1994. Fire patterns in the southern Everglades. Pages 291-306 in: S.M. Davis and J.C. Ogden, editors. The Everglades ecosystem and its restoration. St. Lucie Press, Delray Beach, Florida, USA.

Jones, J.W., J.C. Thomas, and G.B. Desmond. 2001. South Florida Everglades. USGS IMAP 2742, US Geological Survey, Reston, Virginia, USA.

Jones, J.W. 2011*a*. Wetland fire remote sensing research—the Greater Everglades example. USGS Fact Sheet 2012-3133, US Geological Survey, Reston, Virginia, USA.

Jones, J.W. 2011*b*. Remote sensing of vegetation pattern and condition to monitor changes in Everglades biogeochemistry. Critical Review in Environment and Technology special edition 41(S1): 64-91.

Jones, J.W., G.B. Desmond, C. Henkle, and R. Glover. 2012. An approach to regional wetland digital elevation model development using a differential global positioning system and a custom-built helicopter-based surveying system. International Journal of Remote Sensing 33: 460-465. doi: 10.1080/01431161.2010.533212

Lodge, T.E. 2005. The Everglades handbook: understanding the ecosystem. Second edition. CRC Press, Boca Raton, Florida, USA.

Loveless, C.M. 1959. A study of the vegetation of the Florida Everglades. Ecology 40: 1-9. doi: 10.2307/1929916

Noble, C.V., R. Evans, M. McGuire, K. Trott, M. Davis, J. Ellis, and J. Clairain. 2002. A regional guidebook for applying the hydrogeomorphic approach to assessing wetland functions of flat wetlands in the Everglades. US Army Corps of Engineers Report ERDC/EL TR-02-19. US Army Engineer Research and Development Center, Vicksburg, Mississippi, USA.

Olmsted, I., L.L. Loope, and R.E. Ritz. 1980. A survey and baseline analysis of aspects of the vegetation of Taylor Slough, Everglades National Park. Report T-586, South Florida Research Center, Everglades National Park, Homestead, Florida, USA.

Olmsted, I., and T.V. Armentano. 1997. Vegetation of Shark Slough, Everglades National Park. National Park Service SFNRC Technical Report 97-001, South Florida Natural Resources Center, Everglades National Park, Homestead, Florida, USA.

RECOVER. 2004. CERP monitoring and assessment plan: part 1. Monitoring and supporting research. Comprehensive Everglades Restoration Plan, US Army Corps of Engineers South Florida Restoration Office, West Palm Beach, Florida, USA.

Salvia, M., D.C. Ceballos, F. Grings, H. Karszenbaum, and P. Kandus. 2012. Post-fire effects in wetland environments: landscape assessment of plant coverage and soil recovery in the Paraná River Delta marshes, Argentina. Fire Ecology 8(2): 17-37. doi: 10.4996/fireecology.0802017

Scheidt, D.J., and P.I. Kalla. 2007. Everglades ecosystem assessment: water management and quality, eutrophication, mercury contamination, soils and habitat: monitoring for adaptive management: a REMAP status report. US Environmental Protection Agency, Athens, Georgia, USA.

Strobl, C., A.-L. Boulesteix, A. Zeileis, and T. Hothorn. 2007. Bias in random forest variable importance measures: illustrations, sources and a solution. BMC Bioinformatics 8(25): 21.

Strobl, C., T. Hothorn, and A. Zeileis. 2009. Party on! A new, conditional variable importance measure for Random Forests available in the party package. Technical Report Number 050, Department of Statistics, University of Munich, Germany.

Telis, P.A. 2006. The Everglades Depth Estimation Network (EDEN) for support of ecological and biological assessments. USGS Fact Sheet 3087, US Geological Survey, Reston, Virginia, USA.

US Fish and Wildlife Service. 1999. Freshwater marshes and wet prairies. Pages 3-399 to 4-454 in: south Florida multi-species recovery plan. US Fish and Wildlife Service, Atlanta, Georgia, USA.

US Geological Survey. 2012. USGS global visualization viewer. <http://glovis.usgs.gov>. Accessed 12 December 2012.

Wade, D.D., J.J. Ewel, and R.H. Hofstetter. 1980. Fire in south Florida ecosystems. USDA Forest Service General Technical Report SE-17. Southeastern Forest Experiment Station, Asheville, North Carolina, USA.

Welch, R., and M. Madden. 1999. Vegetation map and digital database of south Florida's National Park Service lands. Final report to the US Department of Interior, National Park Service, Athens, Georgia, USA.

Zahina, J.G. 1998. Plant communities and species distribution in Water Conservation Areas 2A and 2B of the northern Everglades. Page 10 in: D.T. Jones and B.W. Gamble, editors. Florida's garden of good and evil: proceedings of a joint conference of the Exotic Pest Plant Council and the Florida Native Plant Society. South Florida Water Management District, West Palm Beach, Florida, USA.