Research Article

Dynamics of Mangrove–Marsh Ecotones in Subtropical Coastal Wetlands: Fire, Sea-Level Rise, and Water Levels

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ABSTRACT

Ecotones are areas of sharp environmental gradients between two or more homogeneous vegetation types. They are a dynamic aspect of all landscapes and are also responsive to climate change. Shifts in the position of an ecotone across a landscape can be an indication of a changing environment. In the coastal Everglades of Florida, USA, a dominant ecotone type is that of mangrove forest and marsh. However, there is a variety of plants that can form the marsh component, including sawgrass (*Cladium mariscus* [L.] Pohl), needlegrass rush (*Juncus roemerianus* Scheele), and spikerush (*Eleocharis* spp.). Environmental factors including water depth, soil type, and occurrence of fires vary across these ecotones, influencing their dynamics. Altered freshwater inflows from upstream and increasing sea level over the past 100 years may have also had an impact. We analyzed a time series of historical aerial photographs for a number of sites in the coastal Everglades and measured change in position of mangrove–marsh ecotones. For three sites, detailed maps were produced and the area of marsh, mangrove, and other habitats was determined for five periods spanning the years 1928 to 2004. Contrary to our initial hypothesis on fire, we found that fire did not prevent mangrove expansion into marsh areas but may in fact assist mangroves to invade some marsh habitats, especially sawgrass. Disparate patterns in mangrove–marsh change were measured at two downstream sites, both of which had multiple fires over from 1948 to 2004. No change in mangrove or marsh area was measured at one site. Mangrove area increased and marsh area decreased at the second of these fire-impacted sites. We measured a significant increase in mangrove area and a decline in marsh area at an upstream site that had little occurrence of fire. At this site, water levels have increased significantly as sea level has risen, and this has probably been a factor in the mangrove expansion.

Keywords: disturbance, Everglades, fire, hurricane, marl, peat, sea level, soil

Citation: Smith, T.J., III, A.M. Foster, G. Tiling-Range, and J.W. Jones. 2013. Dynamics of mangrove–marsh ecotones in subtropical coastal wetlands: fire, sea-level rise, and water levels. Fire Ecology 9(1): 66-77. doi: 10.4996/fireecology.0901066

INTRODUCTION

Ecotones are heterogeneous vegetation zones situated between two homogeneous plant communities (Risser 1995). Ecotones are found in virtually all terrestrial and aquatic landscapes (Naiman and Descamps 1990). They are important features of the landscape for several reasons, including their sensitivity to environmental change. For example, Weltzin and McPherson (2000) showed that a redistribution of precipitation would influence the position of savanna ecotones across the landscape. One factor that appears to influence a wide variety of ecotones is fire. Martin *et al.* (2007) showed that fire was a dominate factor in controlling the position of the pine forest–cloud forest ecotone in the mountains of the Dominican Republic. Brown and Sieg (1999) demonstrated that variability in fires over time resulted in a shift in the ponderosa pine–Great Plains prairie ecotone in South Dakota, USA. With a decrease in fire frequency, the pines invaded the prairie. As a last example, Boughton *et al.* (2006) found that suppression of fires over time resulted in sharply defined ecotones becoming very diffuse and difficult to discern in Florida scrub habitats.

Fire is also routinely used for habitat management, in both upland and wetland communities (Penfound and Hathaway 1938, Lynch 1941). In wetlands, fire is used to reduce the cover of undesirable vegetation, mainly shrubs and trees (Nyman and Chabreck 1995). Fire is a major management tool in one of the largest subtropical wetlands in the world, the Everglades of Florida, USA (Wade *et al.* 1980). The Everglades National Park has had an active fire management program since 1948, one year after the park was established (Bancroft 1976). Fire is used in all regions of the park, including upland pine forests, freshwater wetlands, and the saline coastal mangrove forests and their adjacent marshes (Taylor 1981). Three species of mangroves are found in the park, including the red mangrove (*Rhizophora mangle* L.), black mangrove (*Avicennia germinans* [L.] L.) and the white mangrove (*Laguncularia racemosa* [L.] C.F. Gaertn.). Numerous plant species are found in the coastal marshes of the Everglades, with the most common being sawgrass (*Cladium mariscus* [L.] Pohl) Gulf Coast spikerush (*Eleocharis cellulosa* Torr.), and sand cordgrass (*Spartina bakeri* Merr.).

The coastal mangroves and marshes are important for the goods and services they provide. Mangroves support both commercially and recreationally important fisheries (Odum *et. al.* 1982), sequester carbon (Breithaupt *et al.* 2012), and can attenuate some storm surges (Zhang *et al.* 2012). The coastal marshes are important feeding areas for a variety of wading birds (e.g., herons, egrets, and ibises) for which the Everglades are famous (Bancroft *et al.* 1994). Fire is used in the coastal Everglades for several reasons, including preventing mangrove encroachment into marshes and eliminating invasive exotics that frequently occur at the mangrove–marsh interface (e.g., Brazilian pepper [*Schinus terebinthifolius* Raddi] and small-leaf climbing fern [*Lygodium microphyllum* {Cav.} R. Br.]).

During a previous research project that utilized historical maps and aerial photos, we discovered that there were areas where the mangrove–marsh ecotones had shifted position over time (Smith *et al.* 2010). There were also areas where no change in position had occurred. This observation led us to ask: what factors influence the position of the mangrove–marsh ecotones through time? In this paper, we examined changes in areal extent of mangrove forest and marsh as well as patterns of movement of mangrove–marsh ecotones over time. We specifically analyzed the roles of fire, sea level, and water levels in the positioning of mangrove–marsh ecotones.

METHODS

Study Areas

We determined the areal extent of mangrove and marsh habitats at three locations in the coastal Everglades: 2nd Onion Bay, SH5, and P35-SH1 (Figure 1). Second Onion Bay is located in the Lostmans River drainage and lies ~7.25 km upstream from the Gulf of Mexico. It is the largest drainage basin with the greatest freshwater discharge in the southwest coastal Everglades (Woods 2010). It has tidal amplitudes of ~1.0 m and floods only on the highest spring tides. SH5 is on the Harney River, the largest distributary of the Shark River Slough (Woods 2010). It is ~9.5 km upstream from the Gulf of Mexico. SH5 lies along the channel of a large tidal river. It has tidal amplitudes in excess of 2.0 m during spring tides. Both of these sites have mangrove forests along their shorelines that vary in width from 50 m to 200 m. Moving away from the river banks, the mangroves slowly thin and marsh vegetation becomes dominant. The P35-SH1 study location is in the main Shark River Slough drainage some 30 km upstream from the Gulf of Mexico. It is flooded throughout the wet season (May to October) and may have no standing water during the dry season (January to April). It differs from the other two sites in that tides are minimal. The fringing mangroves are narrow in width (<50 m). Finally, rather than a single tidal river channel, this site is a creek network. Because of the differences between sites, we did not consider them as replicates. They were chosen for this study because of previous work there by our research team (Smith 2004, Ward *et al.* 2006, Smith *et al.* 2009).

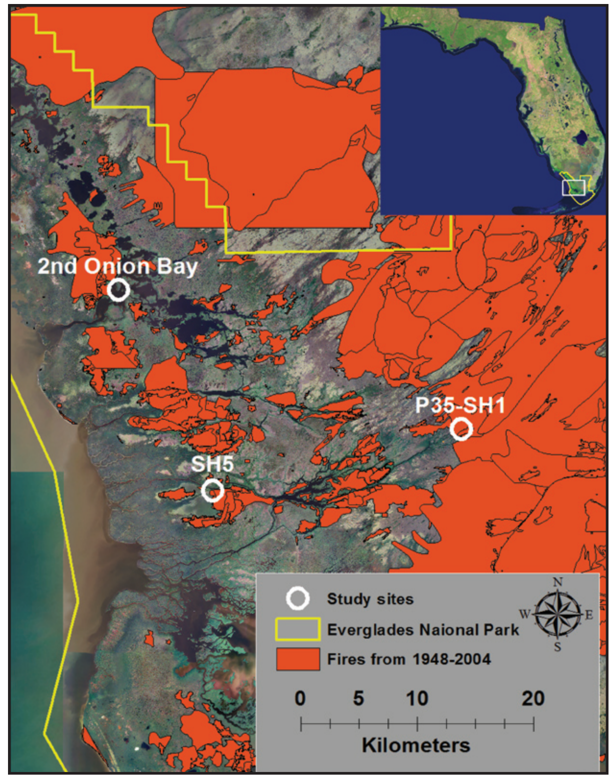

Figure 1. Our study region on the southwest coast of Florida within Everglades National Park is depicted. The background image is a mosaic of 2004 Digital Orthophoto Quarter Quads (DOQQs). Locations of the three study areas are indicated: 2nd Onion Bay, SH5, and P35-SH1. The bold yellow line is the boundary for Everglades National Park. Also shown are all fire polygons from the fire history database for the period 1948 to 2010 that occurred within this area.

Habitat Change Analyses

We established a 2 km radius circle around 2nd Onion Bay and SH5 within the ArcMap v10 GIS system (Environmental Systems Research Institute [ESRI] 2010). For 2nd Onion Bay, an arbitrary center point was chosen that lies approximately 175 m west of the western shoreline and approximately two-thirds of the way north from the southwest shore of the bay

(Figure 2a). For SH5, the circle was centered on the US Geological Survey (USGS) hydrology station that is located there (Figure 2b; and see Smith 2004). There are two hydrology stations located at P35-SH1. P35 is operated by the National Park Service (NPS) and SH1 by the USGS (Smith 2004). Here we created two circles, one centered on each gage, and merged them into a single shapefile (Figure 2c).

There were four habitat types at each site, although habitats were not the same at all sites. We delineated mangrove forest, marsh, open water, and "pocs" at both 2nd Onion Bay and SH5. Pocs are small, roundish bodies of water

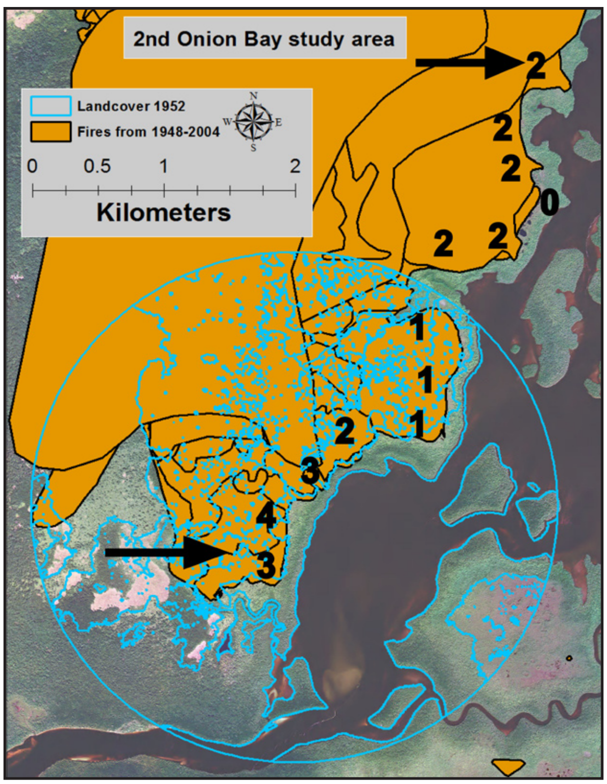

Figure 2a. The 2nd Onion Bay, Everglades National Park, Florida, USA, study area used for detailed mapping is shown here as the bright blue circle. The blue lines within the circle represent the various individual land covers (i.e., habitat) patches that were mapped. The black arrows indicate the mangrove fringe where change in the mangrove–marsh ecotone was measured. The numerals indicate the number of fires that occurred at that point. The orange polygons are fires that have burned at this study location.

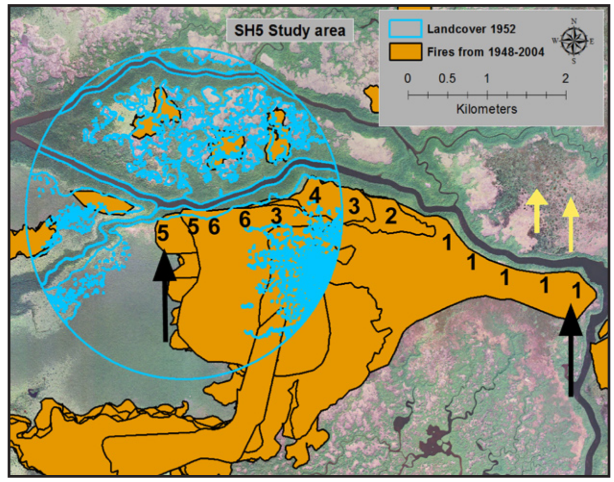

Figure 2b. The SH5 study area, Everglades National Park, Florida, USA, used for detailed mapping is shown here as the bright blue circle. The blue lines within the circle represent the various individual land cover (i.e., habitat) patches that were mapped. The black arrows indicate the mangrove fringe where change in the mangrove–marsh ecotone was measured. The numerals indicate the number of fires that occurred at that point. The yellow arrows show areas with a high density of pocs. The orange polygons are fires that have burned at this study location.

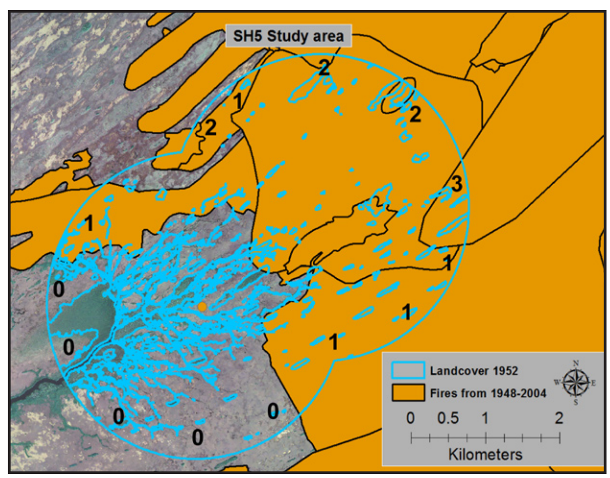

Figure 2c. The P35-SH1 study site, within Everglades National Park, Florida, USA, is shown here. The black and yellow dots give the location of the SH1 and P35 hydrology platforms, respectively. Numerals indicate the number of fires at that location. The blue lines within the circles represent the various individual land covers (i.e., habitat) patches that were mapped. The orange polygons are fires the have burned in the study area.

that are embedded within the larger marsh matrix (Figure 2b). Mangroves, marsh, open water, and tree islands were present at P35-SH1. Maps and photos available for 1928, 1940, 1952, 1964, 1987, and 2004 had previously been georeferenced and imported into the GIS (e.g., Smith *et al.* 2002*a*, 2002*b*). The ecotones between the various habitat types were digitized and total area for each habitat for each time was calculated. Changes in area for each habitat type were derived for five time periods: 1928 to 1940, 1940 to 1952, 1952 to 1964, 1964 to 1987, and 1987 to 2004. These values were then divided by the number of years in the period to yield a yearly rate of change.

The 1928 photoset did not extend upstream to the P35-SH1 study area and were available only for 2nd Onion Bay and SH5. The 1940 photos did not completely cover the SH5 study area. This missing portion was 16 % of the total. We assumed that the missing area had the same proportion of habitats as that shown in the photo and we adjusted the areal values accordingly.

Mangrove–Marsh Ecotone Change

We measured changes in the position of the mangrove–marsh ecotone at 2nd Onion Bay and SH5. At both sites, a 6 km length of shoreline was delineated (Figures 2a, 2b). The position of the ecotone was determined for 1928 and 2004 at 500 m intervals along the shore. The distance from the shoreline to the ecotone was measured as a straight line normal to the shoreline. The difference was determined by subtracting the 1928 value from the 2004 value. Thus, a positive value indicated that the ecotone had moved inland, and a negative value indicated it had moved shoreward. These methods parallel those of Ross *et al.* (2000).

Fire Occurrence, Water Level, and Sea-Level Data

The number of fires that had occurred along the ecotones was determined from the Everglades fire history geodatabase. Briefly, the fire managers at Everglades National Park have been collecting fire occurrence data since 1948 (Taylor 1981). Locations of fires have been recorded and fire perimeters mapped. These data are available in a GIS database. We queried the database to determine the number of fires and their locations relative to our three study sites for the period 1948 to 2004.

Monthly average water level data for station P35 (Figure 3) were extracted from the Everglades' "DataForEVER" database (SFNRC 2011). Sea-level data (Figure 3) were collected from the National Oceanic and Atmospheric Administration's database for Key West (NOAA 2012). The Key West record is the longest in the United States (Maul and Martin 1993). The rate of mean water-level and sea-level rise was determined for the same five time periods as for habitat change.

Statistical Analysis

Patterns in mangrove and marsh area over time at each site were examined using simple linear regression. We did not examine area of pocs or open water because our interest was in the mangrove–marsh interaction. Additionally, we examined change in mangrove and marsh area in relation to the slope of sea-level rise for the five time periods, again with linear regression. The change in width of the mangrove fringe was analyzed separately for 2nd Onion Bay and SH5 with linear regression. All analyses were conducted using the S-Plus statistical package (®Tibco Spotfire S+, Somerville, Massachusetts, USA). Also, it must be noted that habitat areas are correlated with one another, such that if one type is increasing over time, some of the others must be decreasing.

RESULTS

Patterns in Mangrove and Marsh Area

Marsh area was greater than that of mangroves at 2nd Onion Bay in 1928 (622 ha vs.

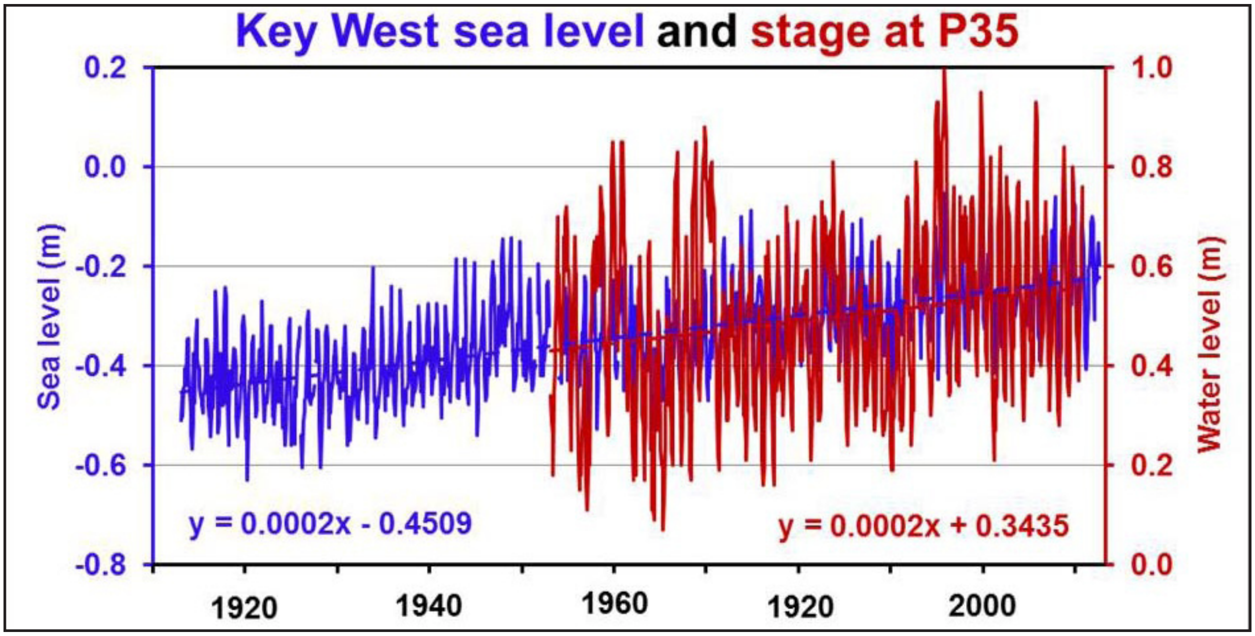

Figure 3. The patterns of monthly mean Key West, Florida, USA, sea level and stage at NPS gage P35 are shown here. Both time series are in meters and in the North American Vertical Datum of 1988.

347 ha). However, marshes declined significantly and mangroves increased significantly at this site, such that in 2004, mangroves occupied the greatest area (579 ha vs 376 ha; Figure 4). Marshes occupied almost twice as much area at SH5 than did mangrove forest (823 ha vs. 374 ha) in 1928. There were no significant changes in the area of these two

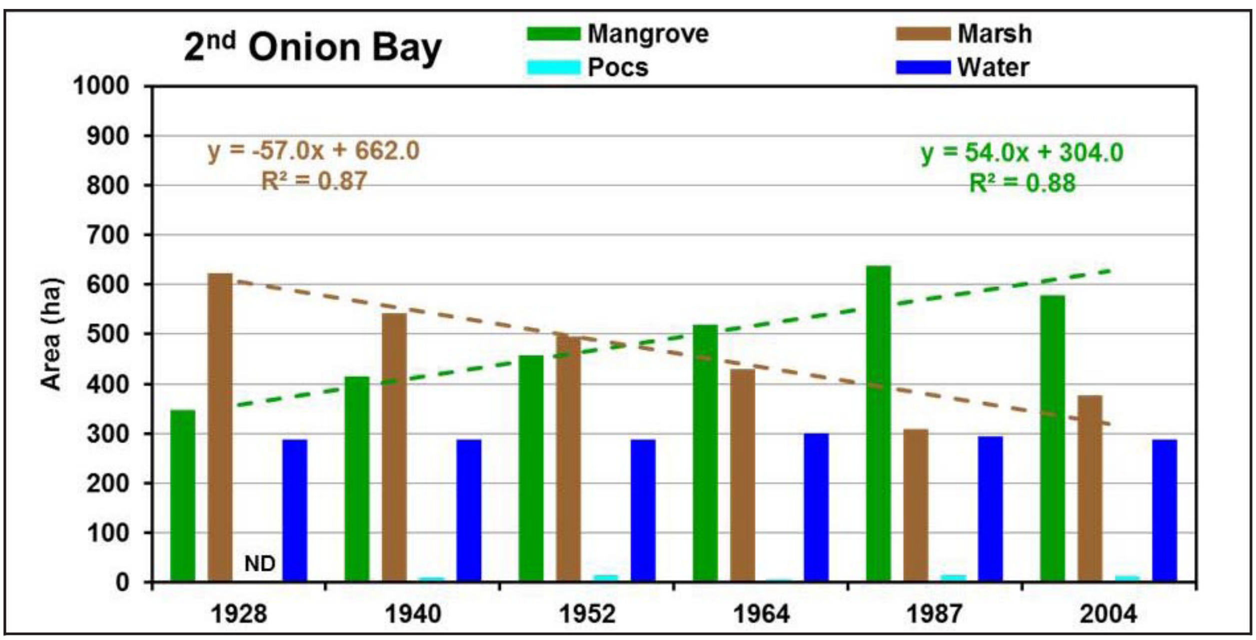

Figure 4. Change in area over time of four habitats at the 2nd Onion Bay study site, within Everglades National Park, Florida, USA. For marsh and mangroves, significant change was measured ($P \leq 0.05$ for both). ND = no data.

habitat types over time at this site (Figure 5). Significant changes in mangrove and marsh areas were also measured over time at P35-SH1. Marsh area declined from 1832 ha in 1940 to 1663 ha in 2004, whereas mangrove area increased from 106 ha to 290 ha over the period from 1940 to 2004 (Figure 6).

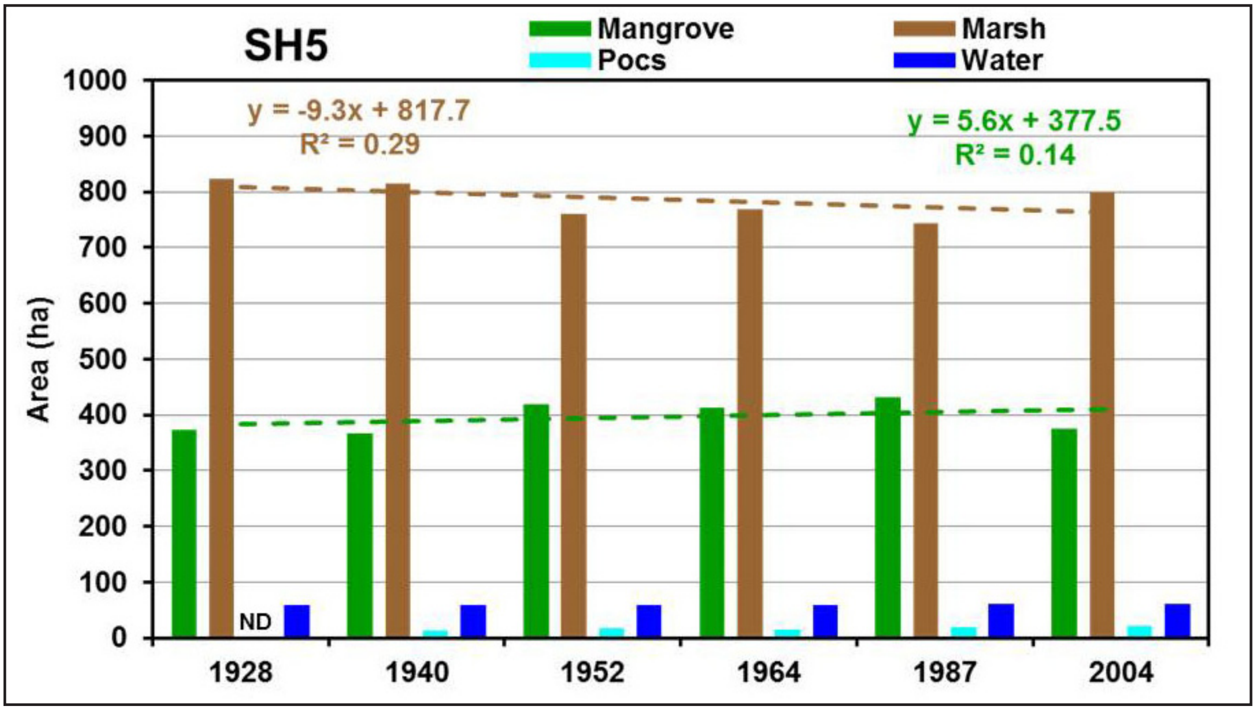

Figure 5. Change in area over time of four habitats at the SH5 study site, within Everglades National Park, Florida, USA. No significant changes were measured over time at this site. ND = no data.

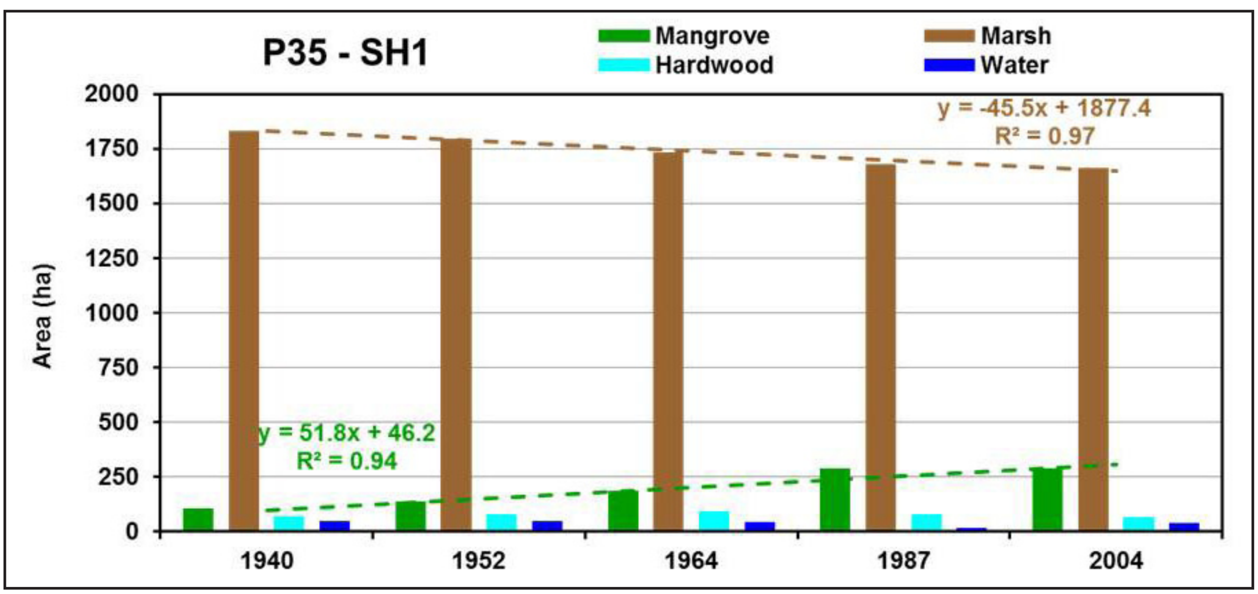

Figure 6. Change in area over time of four habitats at study site P35-SH1, within Everglades National Park, Florida, USA. Significant changes for both mangroves and marshes were measured over time ($P \leq 0.01$ for both). Note change in scale on the *y*-axis between this and figures 4 and 5.

Mangrove and Marsh Change in Relation to Water and Sea Level

The rates at which mangrove and marsh areas changed also differed over the five time periods (Figure 7). Over the first four time intervals, mangroves were expanding at 2nd Onion Bay, and at P35-SH1, mangroves expanded over the first three periods. Similarly, marsh area was decreasing during the first four time intervals at 2nd Onion Bay and for the first three intervals at P35-SH1. The patterns were reversed during the last time interval. For the 1987 to 2004 period, mangroves were lost (and marshes gained) at 2nd Onion Bay and SH5. At P35-SH1, there was little change in either marsh or mangrove for the last time interval. There was no relationship between rates of mangrove area change and sea level at Key West (t = 0.428, P < 0.67). Similarly, there was no significant relation between mangrove change and water level at P35 (t = 1.881, P < 0.102).

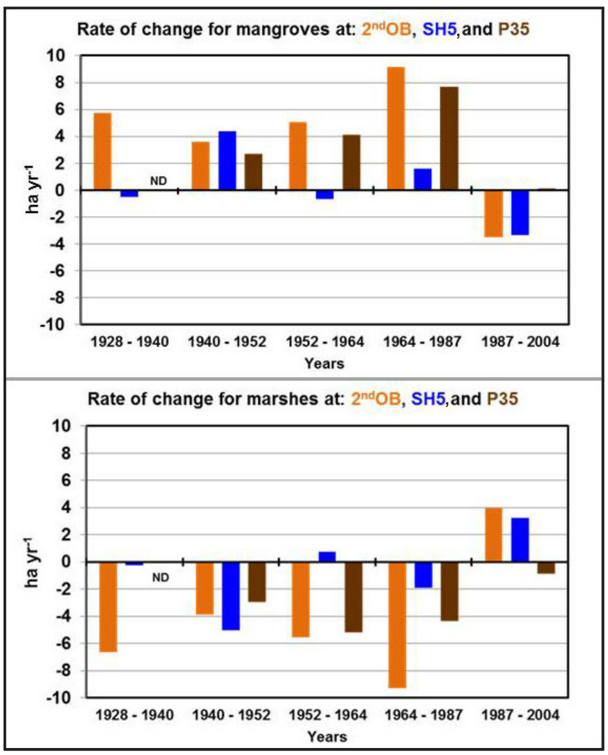

Figure 7. Rate of change in area for mangroves (upper) and marshes (lower) over time for the three study sites in Everglades National Park, Florida, USA: 2nd Onion Bay (orange), SH5 (blue), and P35-SH1 (brown) over the four time intervals. ND = no data.

Patterns of Mangrove–Marsh Ecotone Movement and Fire

There was no relationship between number of fires and ecotone movement at the 2nd Onion Bay study site (t = 1.532, P < 0.158). A highly significant relationship was found at SH5 (t = 4.312, P < 0.005). Areas with the most fires had shifted the greatest distance along the SH5 mangrove–marsh ecotone (Figure 8).

DISCUSSION

At two of our three study sites, we measured significant increases in mangrove area and concomitant decreases in marsh area. This is what we would predict given increases in sea level in South Florida. As sea level increases at upstream locations, salinity also increases. Mangroves are salinity tolerant, whereas the freshwater marsh plants are not. At the third study site, no change was measured, which was counter to our expectations. When rates of areal change were examined, we found no relationships between sea level or marsh water levels. Again this was counter to our expectations.

When examining the pattern of mangrove–marsh ecotone movement, we also had counter-intuitive results. Ecotones did not show a uniform pattern of movement over time. Some ecotones had expanded >100 m, whereas others had not shifted (Figure 9). A significant positive relationship between ecotone movement and fire was found at one study site, but not the other two. The greatest ecotone movement occurred for the area with the largest number of fires.

In our analyses, we only looked at number of fires. We did not examine fire intensity, time of year, or water depth when the fire oc-

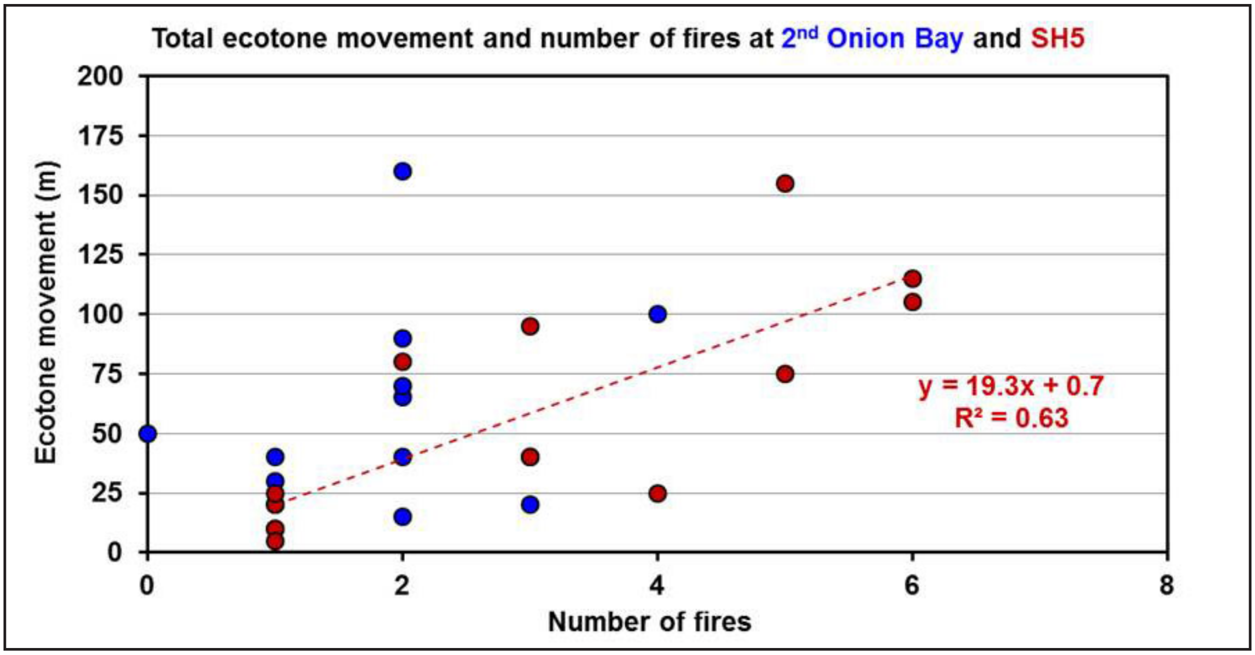

Figure 8. Total ecotone movement as a function of the number of fires for the period of 1940 to 2004 at the 2nd Onion Bay and SH5 study sites.

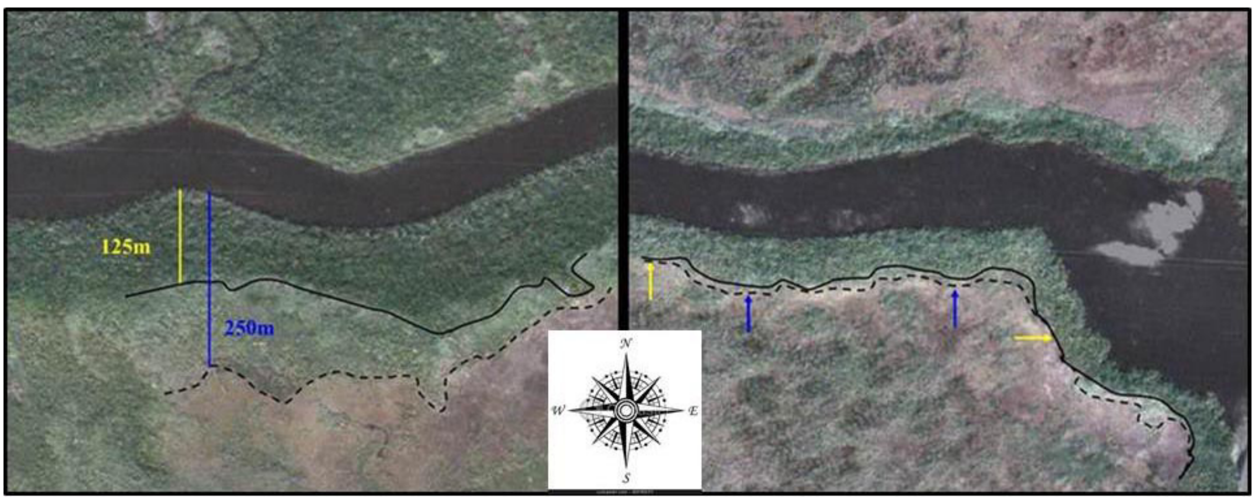

Figure 9. Close-up of the SH5 study sites' western (left) and eastern (right) ends. A 1940 aerial image is overlain on the 2004 photos. The mangrove–marsh ecotone in 1940 is shown by the solid line, and in 2004 by the dashed line. The ecotone at the west end has shifted by 125 m whereas on the eastern end there has been hardly any change.

curred. All of these factors could influence the impact of a fire at the mangrove–marsh ecotone. For example, mangrove seedlings that are found in the marsh might be under water during a wet season fire and thus not affected. During a dry season fire, any mangrove seedlings in the marsh would most likely be killed.

Soil type is another factor that we did not examine. Soils vary tremendously across the coastal Everglades. Mangroves can build highly organic peats that reach to 7 m or more in depth (McKee *et al*. 2007). Both 2nd Onion Bay and SH5 have the deep peat soils characteristic of the coastal Everglades (Spackman *et* *al*. 1966, Cohen and Spackman 1967). Sawgrass and needlerush also produce peat soils (Cohen and Spackman 1967). Marl soils, composed of large fractions of calcium carbonate, are common along the upstream freshwater mangrove and marsh ecotone (Jones 1948). Marl soils were present at our upstream study site, P35-SH1. It is known that dry season fires can burn peat and alter the local hydrology (Jones *et al*. 2013). However, wetlands having marl soils rarely burn, as shown by the number of fires for our P35-SH1 study site. This study site is similar to the southeast saline Everglades region examined by Egler (1952). A characteristic of these sites is relatively low vegetation density and biomass, both of which result in a lower occurrence of fire. Our continuing research will address these factors with more detailed field observations and experiments.

ACKNOWLEDGMENTS

This research has been supported by a variety of funding sources over the years, including: the Critical Ecosystems Studies Initiative from Everglades National Park, the Greater Everglades Priority Ecosystem Studies program, the National Climate Change and Wildlife Science Center, and the FISCHS project (Past and Future Impacts of Climate Change on Coastal Habitats and Species in the Everglades) of the USGS. A. Garfield, U. Nash, D. Palacio, and S. Quail assisted with the massive amount of digitizing required during this project. We thank the staff of the Everglades National Park's South Florida collection management center for loaning us the aerial photographs. This material was developed in collaboration with the Florida Coastal Everglades Long-Term Ecological Research program under National Science Foundation Grant Nos. DEB-9910514 and DBI-0620409.

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