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Potential Effects of Climate Change on Florida's Everglades

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Abstract Restoration efforts in Florida's Everglades focus on preserving and restoring this unique wetland's natural landscape. Because most of the Everglades is a freshwater peatland, it requires surplus rainfall to remain a peatland. Restoration plans generally assume a stable climate, yet projections of altered climate over a 50-year time horizon suggest that this assumption may be inappropriate. Using a legacy regional hydrological model, we simulated combinations of a temperature rise of 1.5 °C, a ± 10 % change in rainfall, and a 0.46 m sea level rise relative to base conditions. The scenario of increased evapotranspiration and increased rainfall produced a slight increase in available water. In contrast, the more likely scenario of increased evapotranspiration and decreased rainfall lowered median water depths by 5–114 cm and shortened inundation duration periods by 5–45 %. Sea level rise increased stages and inundation duration in southern Everglades National Park. These ecologically significant decreases in water depths and inundation duration periods would greatly alter current ecosystems through severe droughts, peat loss and carbon emissions, wildfires, loss of the unique ridge and slough patterns, large shifts in plant and animal communities, and increased exotic species invasions. These results suggest using adaptive restoration planning, a method that explicitly incorporates large climatic and environmental uncertainties into long-term ecosystem restoration plans, structural design, and management. Anticipated water constraints necessitate alternative approaches to restoration, including maintaining critical landscapes and facilitating transitions in others. Accommodating these uncertainties may improve the likelihood of restoration success.

Keywords Climate change · Everglades · Everglades restoration · Adaptive restoration planning

Introduction

The Everglades of South Florida (Fig. 1) is the subject of restoration efforts focused on preserving and restoring this wetland's unique natural character. The subtropical Everglades is a peatland, and so requires a surplus of water relative to evapotranspiration losses to support wetland structure and function (Stephens and Stewart 1942; Mitsch and Gosselink 1993). The primary source of water for the Everglades is precipitation, either directly as rainfall or indirectly as inflow from Lake Okeechobee. Annual precipitation (132–152 cm) has generally exceeded annual evapotranspiration (ET, 124–132 cm) (Fernald and Purdum 1998) by 8–20 cm year^{-1}, although rainfall is highly variable while ET is relatively constant (Visher and Hughes 1969; Abtew et al. 2003, 2007).

Hydrologic restoration of appropriate depth, flow, and seasonality is the target of Everglades restoration (USACE

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and SFWMD 2002). Changes of even a few centimeters in water depth can have pronounced effects on wetland plant communities and peat accumulation (Bruland et al. 2006; Craft and Richardson 2008), as well as the landscape ridge and slough patterning characteristic of many of the Everglades wetlands (McVoy et al. 2011; Nungesser 2011). This ridge and slough pattern, consisting of open water sloughs with sawgrass ridges and tree islands aligned parallel to flow, were the product of seasonal and inter-annual variation in water depth and flow (Larsen et al. 2011, Watts et al. 2010) and extended from south of Lake Okeechobee through what is now Everglades National Park (ENP) (SCT 2003; McVoy et al. 2011). Water depth affects rates of productivity, decomposition, and peat accumulation. Historical changes in water depth and seasonal hydroperiod since 1885, particularly from drainage, have greatly altered the configuration of the original landscape (SCT 2003; McVoy et al. 2011; Nungesser 2011). While sea level rise threatens coastal areas, climate change may threaten the long-term success of Everglades restoration, depending primarily on the magnitude and direction of changes in the relationship between precipitation and evapotranspiration.

General circulation models (GCMs) are well parameterized for projecting changes in regional temperature, which is a main driver of evapotranspiration and affects numerous biological processes. However, GCMs are not well suited to predicting rainfall with great certainty, particularly for peninsular Florida. In some GCMs, coarse grid cells barely cover Florida and most lack important dynamics associated with land–ocean-atmosphere interactions (Obeysekera et al. 2011, 2014). Because the sea breeze cycle is central to rainfall patterns in South Florida but poorly simulated in the GCMs, South Florida rainfall predictions are particularly uncertain. Until better regional climate models are available for South Florida, we are limited more by uncertainty in rainfall predictions than by uncertainty in temperature increases. Consequently, Obeysekera et al. (2014) have opted to use a scenario-based approach to simulating climate developed from current GCM projections and finer-scale climate data.

This paper is one of a series appearing in a special issue of *Environmental Management* addressing the potential effects of climate change in South Florida over the next 50 years. This paper focuses on the effects of climate change on the Everglades, the extensive heavily managed freshwater wetland ecosystems south of Lake Okeechobee south through ENP. Relatively conservative climate change scenarios were developed for southern Florida (Obeysekera et al. 2011, 2014) and incorporated into a regional hydrological model (the South Florida Water Management Model [SFWMM], SFWMD 2005) to assess hydrologic implications of climate change on the water conservation areas (WCAs) and ENP (Fig. 1). We analyzed the scenario results, focusing on the most probable and ecologically challenging scenario of increased temperature, decreased precipitation, and elevated sea level. The ecological implications of this scenario include, at a minimum, increased peat loss, elevated carbon emissions, longer and more severe droughts, wildfires and peat fires, degradation of ridge and slough patterns, shifts in vegetation and wildlife communities, and increased opportunities for exotic species invasions. We discuss implications of climate change for Everglades restoration planning and water management, and present possible options, including adaptive restoration planning, to address these challenges.

Methods

Climate change in South Florida was simulated using the SFWMM, as described by Obeysekera et al. (2014). It is a legacy model developed over several decades to simulate hydrology of the heavily managed landscapes of South Florida. The model is a complex coupled surface–groundwater model that uses climate drivers and applies operational rules that govern water management among 3.2 by 3.2 km square grid cells (SFWMD 2005). Climate scenarios were developed previously (Obeysekera et al. 2011), derived from multi-model ensembles of GCMs that used a Bayesian method (a Reliability Ensemble Average) to produce monthly probability distributions of climate change in South Florida. These distributions indicated daily temperatures that increased by 1.5 °C and precipitation that increased or decreased by 10 % (Obeysekera et al. 2011), changes assumed to occur over a 50 year time frame (by the year 2060). These scenarios, relatively conservative within model ranges, were applied as an offset to historical values of ET and precipitation. The offsets added 10 % to or subtracted 10 % from daily rainfall recorded from 1965 to 2005, and added 7 % to the daily calculated ET [translation of a 1.5 °C temperature rise using a regionally derived temperature-based method (Abtew et al. 2003)]. The resulting scenarios included three that are included here: current rainfall and current ET (BASE), increased ET/increased rainfall (+ET+RF), and increased ET/decreased rainfall (+ET−RF). Sea level rise of 0.46 m was included in the non-BASE simulations and was based upon projections used for regional climate and sea level rise planning efforts of the South Florida Regional Climate Change Compact (SFRCC 2011).

Model output for the Everglades was produced for 35 water stage gauges (Fig. 2) located from northern WCA-1 through southern ENP. Our analysis focuses on the cumulative hydrographs (stage–duration curves, Fig. 3) for the base and climate change scenarios rather than on more detailed annual or seasonal values. More detailed scrutiny

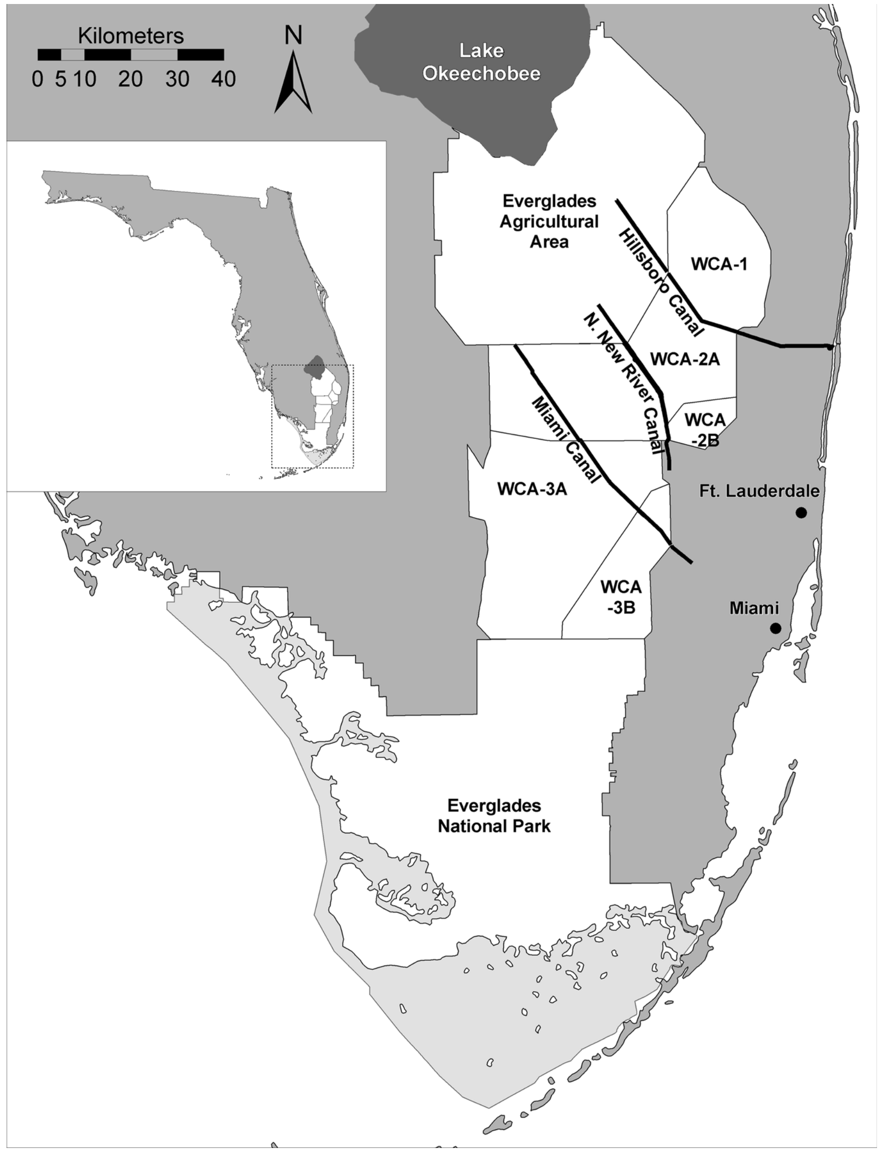

Fig. 1 The Everglades in South Florida, including the water conservation areas (WCAs) and Everglades National Park (ENP)

is unwarranted because synthetic ET and precipitation are simple offsets and do not account for the many other climatological changes likely to occur. For this analysis, depths at the median (50 %) line were used to represent the difference between the scenarios and the BASE for median water depth differences (MDD, cm) and surface water inundation duration (SWD, percent). Median depths represent the longer term changes in water depths, a statistic expected to be more robust under altered climate conditions than other statistical metrics for uncertain future climates. SWD indicates the percent of time that water remains above ground, helping to conserve peat.

Although we assessed the +ET+RF scenario, it presents conditions that are similar to or slightly better than current conditions in the Everglades landscape (e.g., see Fig. 3) and would not present inordinate challenges to restoration. Instead, we focused on the +ET-RF scenario because it is considered the most likely (Christensen et al. 2007; Meehl et al. 2007; Obeysekera et al. 2011) and because it presents great challenges to preserving and restoring Everglades ecosystems. Several important climate components are not incorporated into these scenarios because they are unknown at the present: one is potential altered seasonality, another is changes in storm frequencies and intensities, and a third is flood and drought distribution, intensity, and duration. The simulated climate retains the current patterns with a simple offset; as better forecasts of climate become available, they can be used to drive appropriate hydrological models.

Results

The two climate change scenarios produce very different hydrological responses from the BASE and from each

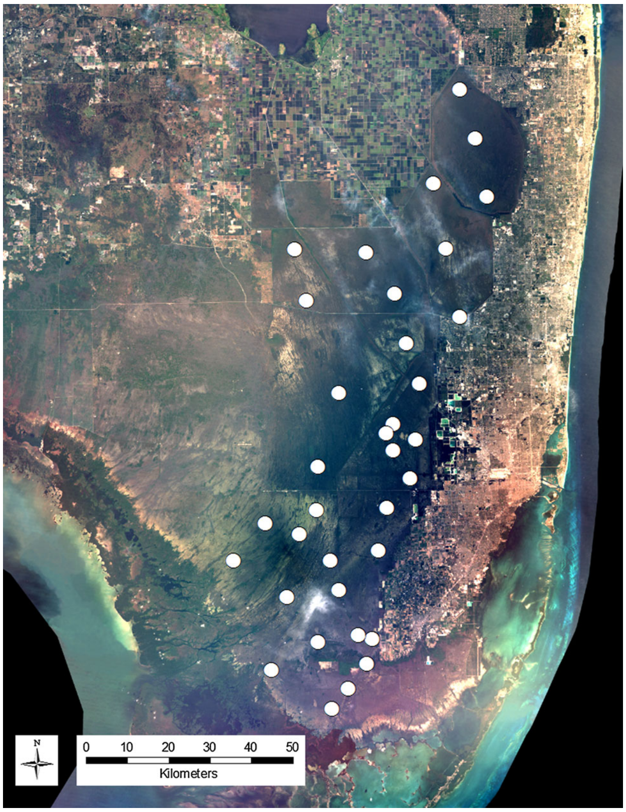

Fig. 2 Gauge locations used in the analysis of hydrological effects of climate change scenarios in the Everglades

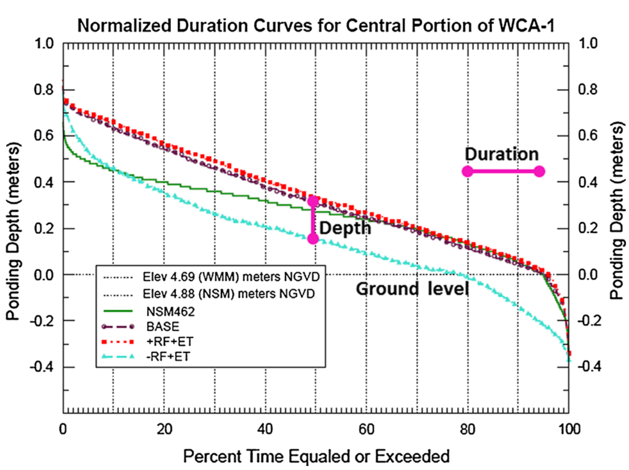

Fig. 3 Details of stage-duration hydrographs to compare climate change scenarios in the Everglades. "Depths" and "Duration" indicate the depth and duration differences between the +ET−RF and the BASE scenarios. Shown is gauge 7, centrally located in WCA-1 (Fig. 1). A full set of hydrographs are available from the corresponding author upon request

other. Water levels in the +ET+RF scenario were consistently slightly above BASE water levels because increases in ET were matched or exceeded by increases in precipitation. Under this scenario, gauge water depths increased slightly by 1.5–9.4 cm. A larger effect was in SWD, which increased up to eight percent in most of the wetlands except near Florida Bay, where SWD increased up to 25 % as a result of increased rainfall, inflow, and tidal action. Under the +ET+RF scenario, hydrological conditions in the Everglades would experience overall higher stages and longer SWD than those in the BASE and +ET −RF scenarios.

In contrast, the +ET−RF scenario produced substantially shallower surface water in the Everglades, both in depths (MDD, Fig. 4) and in duration (SWD, Fig. 5). Relative to the baseline, the +ET−RF scenario produced stage reductions ranging from 6 to 114 cm, and an increase at only one gauge (Fig. 4). A reduction of only 9 % in SWD at the southern end of WCA-1 suggests that ponding would continue to occur because eastward flow is prevented by higher land elevations to the east and northeast in this conservation area. Most of the greatest depth decreases of 40 cm or more occurred in the eastern-most conservation areas, where urban and agricultural urban demands are great and seepage is high. The greatest decline in water depth occurred in southern WCA-2B, where a combination of decreased precipitation, increased groundwater seepage,

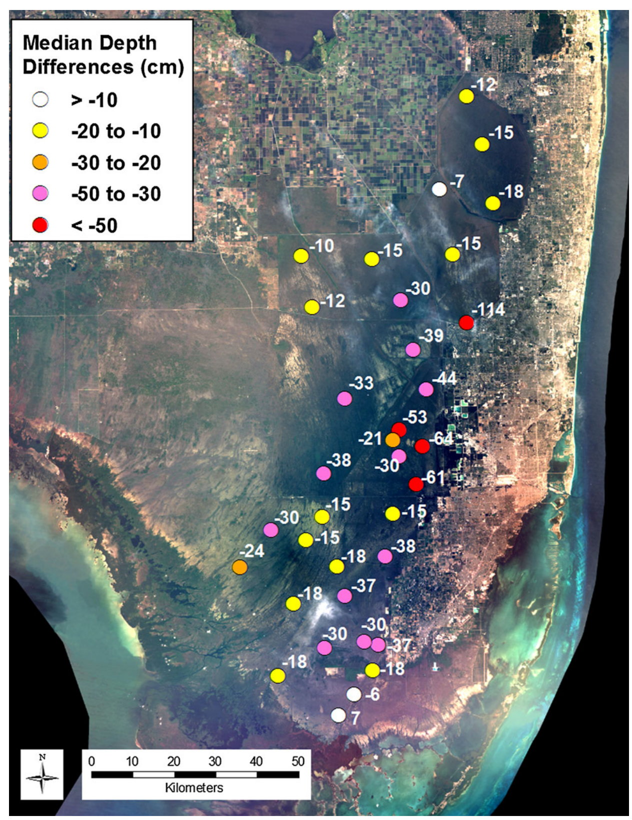

Fig. 4 Changes in median water depth differences (MDD, cm) for the +ET−RF scenario relative to the BASE scenario in the Everglades

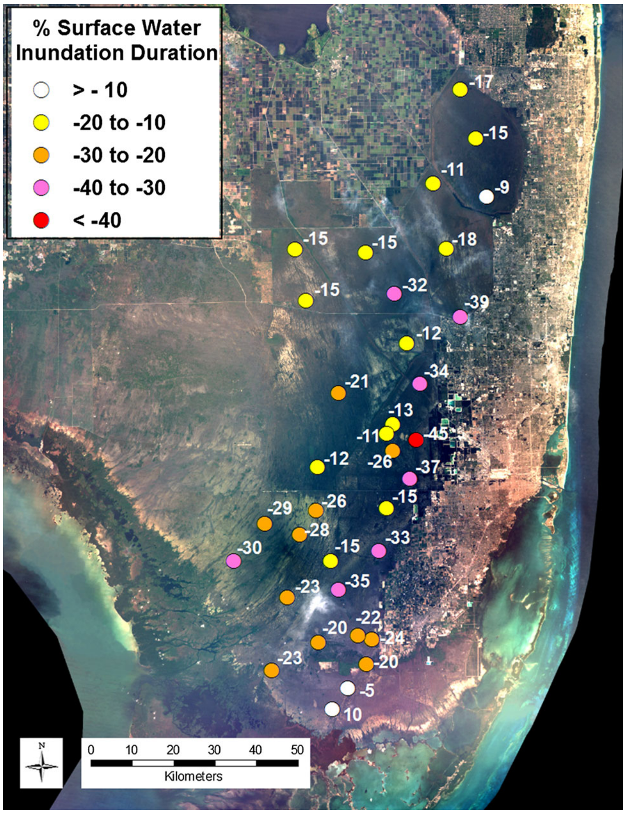

Fig. 5 Changes in surface water inundation duration (SWD, percentages) from the +ET−RF scenario relative to the BASE scenario in the Everglades

and increased groundwater withdrawals for human water supply caused water levels to decrease more than 1 m. Sea level rise affected two gauges at the southern end of ENP (Fig. 4) where median depth increased by 7 cm at one and decreased by only 6 cm at the other, suggesting that freshwater would be replaced by brackish water or saltwater. Other gauges appeared to be unaffected by a 0.46 m sea level rise because of their distance from the coast.

Under the +ET−RF scenario, SWD decreased from 5 to 45 % relative to the BASE scenario (Fig. 5). Small decreases of only 5 % and an increase of 10 % occurred at two gauges near Florida Bay, again in response to sea level rise. Similar to changes in MDD, the greatest decreases of 39–45 % occurred at the gauges affected most by porous bedrock and high water supply demands in the eastern and southern portions of WCA-2B and WCA-3B. The likely causes were decreased precipitation, increased groundwater seepage, and increased water supply withdrawals.

Overall, the +ET−RF scenario translated to lowered water levels and reduced inundation durations throughout the Everglades. Reductions in noncoastal ENP MDD ranged from −15 to −38 cm (Fig. 4). Conservation area MDD ranged from −12 to −18 cm in WCA-1, from −7 to −15 cm in WCA 2A, and from −10 to −38 cm in WCA-3A. The greatest reductions in water depths occurred in WCA-2B, more than one meter (−114 cm), and in WCA-3B, −21 to −64 cm. Water levels were above ground at the gauges on average only 59 % of the time compared to 80 % under the current (BASE) conditions. For all gauges, median water levels decreased from the BASE's average of 27 cm to less than 1 cm under this scenario. All of these changes are in directions contrary to those desired when planning for Everglades restoration.

Rainfall differences were not the only cause of reductions in MDD and SWD. Annual mean structure flow from upstream sources into the WCAs was reduced by 43 % under the +ET−RF scenario (2.0×10^6 m^3 $year^{-1}$) relative to the BASE (3.6×10^6 m^3 $year^{-1}$) (Obeysekera et al. 2014, Table 4). Therefore, not only did the downstream wetland landscape experience reduced rainfall and increased ET but also received 44 % less inflow from upstream sources because these sources also were subject to major reductions in water supply.

Discussion

The simulations conducted for this analysis do not include some of the features likely to occur under a less stable and shifting climate. While the climate scenarios simulated here retained south Florida's past climatic variability, it is more realistic to assume that more extremes may occur in the future, including increased magnitudes or frequencies of flood and high water events and increased variability. Even without these conditions, the outlook is poor for the peatlands subjected to a rainfall reduction of 10 %. While occasional high water events may provide short term drought relief, reduced precipitation is likely to lead to more severe and extended droughts over the upcoming decades. The timing of climate change is also uncertain; changes could occur gradually or abruptly. Under either pattern, continued peat loss and ongoing drought would have serious ecological and water supply implications. Large reductions in water availability directly conflicts with the goals of Everglades restoration and will require a major rethinking of restoration goals and methods. In contrast, if rainfall increases substantially overall, the increased water supply will facilitate restoration, including areas affected by sea level rise.

Following are brief overviews of the implications of the decreased precipitation scenario to the Everglades, beginning with the history of drainage effects in the Everglades. Because the Everglades differs from most other ecosystems and even other peatlands, we have focused on research that has been conducted in the Everglades. An in-depth literature review of the effects of climate change and sea level rise on the Everglades is beyond the scope of this paper;

however, the examples below suggest some of the probable consequences of the +ET−RF scenario in the Everglades.

Loss of Patterning

The Everglades was originally extensively patterned (SCT 2003; McVoy et al. 2011) but much of that patterning has disappeared. Early surveys and notes described the Everglades as linear open water sloughs, elongated sawgrass ridges and tree islands oriented parallel to the flow direction (Davis 1943; SCT 2003; McVoy et al. 2011) yet by 1940 when the first aerial photography was produced for the Everglades, large regions drained by early canals and water management structures showed significant pattern degradation, expressed as loss of linear sloughs, expansion of sawgrass into the sloughs, and loss of tree islands (SCT 2003; McVoy et al. 2011; Nungesser 2011). Ongoing pattern degradation and losses appeared where canal drainage dominated local hydrology and later where compartmentalization lowered surface water in the northernmost sections of the water conservation areas (SCT 2003; McVoy et al. 2011; Nungesser 2011). Where water levels were maintained above ground, the original patterning was retained. Disruption of the long-term rise and fall of water levels and the annual flow velocities and directions changed the ridge and slough patterns in their dimensions and densities (Nungesser 2011).

Similarly, losses of tree islands have been identified in locations that were heavily drained and burned in the WCAs and in ENP's Shark River Slough (Sklar and van der Valk 2002). Historically, peat losses have been reported throughout the Everglades in ridges and tree islands, as well as in the areas now defined as marl prairie and pine rocklands (McVoy et al. 2011). The +ET−RF scenario would lead to ongoing loss of tree islands, degradation of ridge and slough patterns, and potential broad-scale conversion of the Everglades to an unpatterned landscape.

Historic Peat Loss in the Everglades

The Everglades has a long history of water levels lowered by drainage that led to peat loss and altered peat quality (SCT 2003; McVoy et al. 2011). This history provides an analog of the effects of reduced rainfall and increased ET on Everglades peatlands. It is likely that under the +ET−RF scenario, these losses will continue and escalate as peat is subjected to lower water levels, higher temperatures, and subsequent increased oxidation.

Because peat is composed of organic material, it oxidizes as it dries, causing soil loss, emission of carbon, and peat subsidence from compaction and dewatering. Drainage began in the late 1800s with canals dug to connect Lake Okeechobee to the coasts, followed by later efforts in the early 1900s to drain the Everglades for agricultural uses (McVoy et al. 2011). Original peat depths were reported to be much deeper than they are today (e.g., Aich and Dreschel 2011; McVoy et al. 2011; Aich et al. 2013), with losses caused by drainage, fire, and cultivation.

These deep drainage canals eliminated the normal annual flows that supported peat accumulation and wetlands habitat and instead lowered water levels, leading to major peat loss through microbial oxidation and peat fires (Davis 1943; McVoy et al. 2011). In the middle 20th century, subsequent construction of water conservation areas further disrupted flows and water levels, but reduced peat subsidence and fires (Bestor 1942; McVoy et al. 2011).

Several estimates have been made of the extent of historic peat loss from drainage and agriculture. Starting in the mid-1920s, drainage of the deep peats immediately south of Lake Okeechobee (Stephens and Stewart 1942; Aich and Dreschel 2011; McVoy et al. 2011; Aich et al. 2013) allowed cultivation of the peat. In the 1970s, Stephens and Stewart (1942) reported that Everglades organic soils were subsiding at an average of 4.2 cm annually (from 1.3 to 7.7 cm year^{-1}) in areas drained for agriculture. Cultivated land continues at present to lose peat, sometimes exposing bedrock where ongoing drainage and agricultural use occur (Snyder 2005).

Areas outside of the Everglades Agricultural Area (EAA) also lost significant amounts of peat through drainage. Early surveys and extensive recent analyses (McVoy et al. 2011) have provided well-documented sources of pre-drainage peat depths. Aich and Dreschel (2011) and Aich et al. (2013) estimated losses of total carbon and total CO_2 emitted between 1875 and 2005 to be 1.6 billion metric tons (Table 1). The detailed temporal and spatial histories of peat loss are poorly known; however, using the decidedly unsatisfying assumption of a steady rate of peat oxidation, these losses average 12 million metric tons of CO_2 per year. Peat loss probably was highest initially, soon after construction of the canals, and lower following compartmentalization, with occasional spikes from drought and peat fires. At present, few data exist on the current rate of peat loss from the Everglades, but the greatest peat loss has occurred in the EAA (Table 1). The estimated rates of peat loss were based on historic changes.

In spite of major historic and contemporary peat losses, Everglades CO_2 emissions are not included in regional estimates of anthropogenic carbon emissions (Southeast Florida Regional Climate Change Compact Counties 2012). The values above suggest that anthropogenic peat loss from the natural ecosystems may account for an additional 18 % (i.e., 12 million metric tons of CO_2 per year) over the amounts estimated for all other anthropogenic sectors. Future loss rates could easily exceed this 12 million metric ton estimate, depending on the severity of drought duration, extent, temperatures, and water demands.

Table 1 Estimates of total period of record (1875 through 2005) loss of CO_2 from the Everglades peatlands

Source	m^3 of peat volume lost	WCAs: Grams lost per square meter per hour (using data from Snyder, 1994 for bulk density and carbon content)	Total Metric tons of CO_2 lost (using data from Snyder, 1994 for bulk density and carbon content)	Average Subsidence in m from the m^3 of peat volume lost and the area of the region
WCA-1	2.2×10^8	0.18	1.1×10^8	0.4
WCA-2A	2.1×10^8	0.23	1.1×10^8	0.5
WCA-2B	1.1×10^8	0.41	4.9×10^7	0.9
WCA-3A	1.3×10^9	0.30	6.2×10^8	0.6
WCA-3B	2.5×10^8	0.30	1.2×10^8	0.6
ENP	1.2×10^8	0.02	6.1×10^7	0.01
EAA	4.9×10^9	0.9	2.3×10^9	1.7

Source Aich and Dreschel 2011, *Correction* Aich et al. 2013

Drought Effects on Carbon Dioxide and Methane Emissions

Both CO_2 and methane (CH_4) are emitted in the Everglades. Droughts in Everglades freshwater peatlands elevate emissions of both (Bachoon and Jones 1992; Malone et al. 2013). These greenhouse gases are concerns for climate change because of their effects on warming and their longevity in the atmosphere. Experiments by Malone et al. (2013) simulating drought conditions in the Everglades indicated that reduced precipitation and increased drought can turn freshwater wetlands from carbon sinks to carbon sources following an extensive drought. Methanogenesis normally occurs at low rates in the Everglades, particularly in sawgrass peat (Bachoon and Jones 1992), but CH_4 emissions increase with rising temperatures. Both marl and sawgrass communities produce negligible concentrations of CO_2 and CH_4 under winter temperatures, generally below 25 °C. Under temperatures between 25 and 32 °C, both vegetation communities produced detectable but low (<0.5 μmol ml^{-1} h^{-1}) emissions, and when temperatures exceeded 40 °C, CH_4 emissions increased to over 4.5 μmol ml^{-1} h^{-1} (Bachoon and Jones 1992). This finding suggests that warmer summer temperatures may greatly increase CH_4 emissions from the Everglades during droughts and increased air and water temperatures, again acting as positive feedbacks to the climate system.

Recent droughts illustrate conditions that may become common under climate change. During the dry season (November through May) of 2010–2011, water fell below ground surface throughout the WCAs and ENP; by early June, surface water had disappeared except for small areas in southernmost WCA-3A (SFWMD 2011). Consequences included water levels 67 cm below ground in central western WCA-3A (gauge 64, over one meter lower than the median BASE water level) where the best remaining ridge and slough patterning exists. The drought produced poor nesting success for wading bird species such as wood storks that nest later in the dry season (Cook and Kobza 2011) and nearly 20 weeks of hypersaline (>40 psu) conditions in central Florida Bay.

Peat Fires and Wildfires

With higher frequency droughts under the +ET−RF scenario, wildfires and peat fires are expected to increase in frequency and magnitude. Historical evidence provides a perspective on effects of severe droughts on fires. Following construction of the Miami, Hillsboro, and North New River canals in the early 20th century (Fig. 1), water levels in the peat fell several feet below ground, facilitating numerous and extensive peat fires with associated region-wide ash fall and soil loss (Simpson 1920; Mayo 1940; Bender 1943; Cornwell and Hutchinson 1974). According to Bender (1943), extensive peat fires burned areas from 30 to 300 km^2 beginning in the 1920s and again in the 1950s (Cornwell and Hutchinson 1974), smoldering for months to years even through multiple wet seasons. Peat fires were reported to have burned 7–30 cm of peat in depth and destroyed up to one-third of an unnamed county's peat area (Bender 1943). In 1920, peat on tree islands had burned out from under the trees in WCA-3, and tree islands near the eastern border of the Everglades were burned and totally destroyed (Simpson 1920). In 1940, Mayo (1940) wrote that some areas as large as 518 km^2 had lost all peat and muck, and reported that some estimates claimed that as much as 20–25 % of the 5,180,000 km^2 suitable for agriculture were destroyed by peat fires. Cornwell and Hutchinson (1974) noted that peat fires occurred when water depths were only 10–15 cm below ground, depths that are commonplace today in the dry season. During the recent drought of 2010–2011, lightning-sparked surface fires burned over 15,380 ha in Big Cypress Preserve and another 27,640 ha in WCA-3B in late May and early June. With low water levels and warm temperatures, these surface fires could readily become peat fires.

Peat fires can smolder for long periods of time, leading to extended periods of carbon emissions and permanent loss of existing peat. Peat accumulates slowly, particularly in older, stable layers at rates generally from 0.01 to 0.14 cm $year^{-1}$ (Willard et al. 2001; Bernhardt and Willard 2009) and takes centuries to millennia to accumulate naturally. While one might expect Everglades peat to vary in its risk of wildfire depending on moisture content and organic content, Johnson (2012) has determined that peat flammability is similar throughout WCA-3A in spite of differences in peat quality across the landscape. In general, historically low water levels and extended annual oxidation in northern WCA-3A have produced peat with lower moisture content and organic content (81 %) than peat in central WCA-3A, where nearly perennial hydration has preserved peat with higher moisture content and organic content (90 %). In spite of these differences in soil properties, both types of peat experience similar probabilities of combustion under simulated fire scenarios (Johnson 2012). Therefore, if fire conditions were right, the risk of peat fires in the Everglades water conservation areas would be elevated and similar in all areas.

Shifts in Vegetation Communities and Wildlife

Changes in hydrology and peat depths have already produced many vegetation changes in the Everglades. Modified hydrology has caused ridges to expand and flatten, sloughs to disappear, willows to invade, and upland wildlife species (including deer, opossums, foxes, and others) to colonize former perennial wetlands. Plant communities where extended annual drought occurs (at the north ends of the WCAs and ENP) have become more xeric, with invasions of woody species. These habitats reduce or eliminate habitat for aquatic species such as alligators, native fish, crayfish, amphibians, and aquatic invertebrates. Transitions from wetlands to xeric uplands have been documented in locations with shallow peat. Early peat fires in Miami-Dade County burned down to the bedrock of Miami oolite (McVoy et al. 2011), creating the pine rocklands (Robertson 1953). In some parts of northwestern WCA-3A, similar losses can be anticipated where peat depths are only 10–30 cm (Johnson 2012) above bedrock. In the southern EAA, peat depletion has exposed bedrock in farm fields (Snyder 2005). Peat fires or continued oxidation in northern WCA-3A and other areas with shallow peat could expose bedrock, permanently converting the habitat to one more similar to the Rocklands near Miami and Pine Rocklands in ENP, both of which lack peat cover.

Sea level rise with increased drought will alter plant community function, productivity, and processes (Ewe and Coronado 2009; Saha et al. 2009, 2011). Saha et al. (2011) reported that combined drought and sea level rise have already caused shifts in plant communities in tree hammocks of southern ENP. The lack of freshwater resulting from upstream water management causes both seasonal drought and, with incursion of saltwater from sea level rise, physiological drought in plant communities; these combined stresses lead to vegetation shifts from freshwater to saltwater tolerant species. Increased salinity also threatens 21 rare coastal plants in ENP (Pearlstine et al. 2009; Saha et al. 2011) and would eliminate freshwater peat where it occurred. Similar plant community shifts and species losses would produce associated shifts in animal communities from freshwater species to more marine species (Pearlstine et al. 2009).

Invasive Exotic Species

As native communities grow increasingly drought stressed under the +ET−RF scenario, opportunities are likely to expand for invasive species to establish (Dukes and Mooney 1999; Pearlstine et al. 2009; Fennell et al. 2012). Under current climatic conditions, south Florida already experiences significant negative impacts from invasive exotic species which displace native species, reduce community diversity, and alter ecosystem geomorphology, biogeochemistry, and hydrology (Vitousek 1986; Schmitz et al. 1997; Simberloff 1997; Gordon 1998; Ewe 2001; Doren et al. 2009). Additional drought stress may facilitate invasion of exotic plants and animals. Lower water levels and lower variability in seasonal and annual water depths in the Everglades are associated with increasing likelihood of invasion by an aggressive climbing vine, *Lygodium microphyllum* (Coronado et al. 2011).

Paleoecology

Paleoecological records analyzed for the Everglades suggest that the extent of droughts produced by the +ET−RF scenario exceeds any occurring previously in Everglades history. Fossil pollen and seeds suggest that the Everglades has remained wet since its early development period beginning approximately 5,000 years ago (Gleason and Stone 1994). Over that time, Everglades hydrology and vegetation have varied as regional and global climate have grown alternately wetter or drier (Willard et al. 2006; Bernhardt and Willard 2009), but while there have been long-term variations in water levels in the Everglades that included extensive droughts, the region has remained wetlands and peatlands (Gleason and Stone 1994; Lockwood et al. 2003; Powers 2005; Givnish et al. 2008; Saunders unpubl. data). Radiometrically dated peat cores along the historic flowpath of Shark River Slough indicate that two multi-millenial periodicities occurred over this 5,000 year period (Gleason and Stone 1994; Willard et al.

2006; Saunders et al. 2008; Bernhardt and Willard 2009) with drier and wetter conditions tied to the Intertropical Convergence Zone (ITCZ; Haug et al. 2001) and the El Niño Southern Oscillation (ENSO; Rodbell et al. 1999). While long-term shifts in vegetation appear in concert with these shifts, they are not of the magnitude of vegetation changes observed under twentieth century drainage.

Contemporary landscape surveys have demonstrated the absence of nymphaeid water lily communities in the majority of Shark River Slough (ENP) (Scheidt 2000) starting in the early twentieth century where the wetlands were drained. In contrast, over the last 2,000 years, nymphaeid communities have remained abundant, even during drier conditions of the Little Ice Age and Medieval Warm Periods. While the temporal resolution of paleoecological data may be limited (Willard et al. 2001), it appears that modern conditions are as dry as or drier than any pre-drainage period. The even drier conditions of the +ET−RF climate change scenario would present conditions not previously experienced by the Everglades.

Implications for Everglades Restoration and Water Supply

These scenarios represent only a first attempt to anticipate the challenges that a changing climate is likely to pose to the Everglades and should be used primarily as initial indicators of the possible magnitude and direction of hydrologic changes under altered climate. Even though it has been anticipated for a quarter of a century, climate change has not yet figured prominently into planning for Everglades restoration. Sea level rise and climate change have been given only cursory attention even in the last few years of restoration planning (http://www.evergladesplan.org/pm/projects/proj_51_cepp.aspx#final_eis). Flows, volumes, structures, reservoirs, and stormwater treatment areas are being sized for planning purposes for the next five or six decades assuming that historic climate represents future climate for that planning horizon. This assumption, called stationarity (Milly et al. 2008), is no longer appropriate for multi-decadal restoration and water supply plans. Given the scenarios presented here, assumptions of stationarity will probably overstate the benefits of restoration projects by overestimating water availability. If rainfall decreases or only slightly increases from recent historic levels, then the likelihood of achieving restoration targets is low.

If the current relationship between rainfall and ET (with a ratio slightly over 1.0) holds over the next five decades, then plans for restoration may achieve the expected results. A scenario that retains the current rainfall-ET ratio allows for an entirely different suite of options than a lower rainfall-ET ratio that produces chronic drought. However, if rainfall-ET ratios decline, then the Everglades will face longer and more frequent droughts and the resulting suite of changes described above will include replacement of peatlands by mesic or xeric ecosystems. How then can we increase the odds of successfully planning for restoration as climate changes?

Because of these radically different implications, the influence of divergent climate change scenarios on restoration should be considered explicitly in a process that can be termed "Adaptive Restoration Planning," which differs from adaptive management, a process currently integrated into restoration planning in the Everglades. Adaptive management is an iterative process that uses monitoring data over time to reduce uncertainty in decision making (Holling 1978). Adaptive management occurs after the project is completed and is usually constrained by prior decisions and construction of structures, facilities, and operations. In contrast, Adaptive Restoration Planning directly incorporates these major uncertainties into the planning process from its initiation rather than assuming that climate or other fundamental environmental drivers will remain constant. Assumptions that rainfall will equal or exceed the increases in ET may suggest one set of structures and operations, whereas assumptions that rainfall will decrease relative to ET may require a very different set of structures and operations. Similarly, climate variability may increase relative to historic ranges. Failure to account for these climatic extremes may reduce restoration success. It is not only possible, but likely, that optimizing for one scenario may preclude choices that accommodate the other. Therefore, to account for the wider but unknown ranges of future altered climate, Adaptive Restoration Planning should consider the following questions to adequately address uncertainties posed by a climate that is in transition and probably unpredictable:

(1) How can climate uncertainties expected over 50–100 years be considered when evaluating performance of landscape-scale structures, hydrological patterns, and operational changes? Are there conditions that justify use of historic climate for restoration planning?
(2) Is it possible to incorporate uncertainties into restoration planning by using multiple climate scenarios? Reasonable modeling scenarios for identifying preferred alternatives could include the three types of scenarios simulated in this study. Additional scenarios can be developed to accommodate other anticipated changes in climate such as increases in extremes in rainfall (high and low) and temperatures. These scenarios should also reflect the most current understanding of the effects of increased temperature and altered precipitation regimes on the sea breeze

cycle and the thermal influences of extensive natural areas that contain and lack surface water (e.g., see Pielke et al. 1999).

(3) Can new planning paradigms explicitly incorporate expectations of higher unpredictability? Perhaps modular or adaptable structures and more flexible operations can become an integral part of restoration planning and engineering. While more complex than the usual alternatives evaluations required by the National Environmental Policy Act (NEPA), these options may provide a much more cost effective means of accommodating climatic uncertainties while still leading to restoration success.

(4) Should restoration targets be prioritized under the assumption of a more limited water supply, which appears more likely at this time? Rather than facing a potentially unreachable goal of fully restoring all of the remaining Everglades to historic conditions, sub-areas could be rated according to the cost-effectiveness and benefits of full restoration versus maintenance of existing conditions. For other areas where full degradation appears probable, facilitated succession in these places can be adopted to achieve a smooth transition. All plans should consider the types of future water conflicts that may arise between natural and human systems (agriculture, urban land uses) as water becomes a scarcer resource in South Florida.

Conclusions

The somewhat wetter (+ET+RF) and much drier (+ET−RF) alternatives pose opposite and very different challenges for Everglades restoration and management. Wetter conditions, were they to occur, would greatly benefit Everglades restoration and water supply as they are currently proposed, providing adequate water to keep the peatlands hydrated and sustain water flow through the WCAs and ENP into Florida Bay. The climate change scenarios indicate that the additional volume is slightly higher than that of the baseline scenarios, upon which current Everglades planning is based. Therefore, planning for a somewhat wetter climate represents a relatively minor modification of current plans to accommodate higher temperatures and possible greater extremes in rainfall events.

Drier conditions pose much greater challenges for restoration. Large decreases in water depths and surface water inundation duration threaten survival of the Everglades peatlands and its other ecosystems. The significant risk of increased ET and decreased rainfall on the Everglades should be addressed in restoration plans and water management strategies by assessing their performance under major drought conditions. The Everglades is unlikely to survive in its current state under significantly drier average annual conditions and extensive ongoing droughts. Ecosystem changes, as described above, would be accompanied by loss of habitat, loss of peat, conversion of wetland habitats to uplands, shifts in plant and animal communities, increased peat fires, increases in extent and numbers of invasive exotic species, and large-scale increased emissions of carbon and methane. It is time to consider alternative approaches to Everglades restoration that begin with assumptions that differ from those that have guided planning over the last several decades.

Adaptive Restoration Planning will inherently assume an altered and probably unstable climate. Modeling scenarios that integrate variable future climate scenarios will provide a more realistic suite of alternatives to achieve restoration targets under anticipated new and transient climate regimes. Perhaps more flexible structural designs and operations can manage the natural systems in ways that increase their resilience and better accommodate climate instabilities and changes.

The scenarios used for this analysis motivate further investigation of the impacts of climate change on the Everglades ecosystems. Research focusing on more detailed consequences of sea level rise, temperature increases, and precipitation changes on Everglades ecosystems is a priority. Acknowledging the likelihood of reduced water availability may lead to more creative and flexible future water management options that have not been considered previously. The National Research Council has indicated that pending climate change and sea level rise present incentives to take actions to increase the resilience of the Everglades through restoration projects (NRC 2008). It will be important to define and implement adaptive restoration strategies for ecological restoration and for water supply planning.

Significant uncertainty exists not only in the nature of the future climate, but also in the responses of South Florida's natural and managed ecosystems to this altered climate. The uncertainties of ecosystem adaptation and resilience to climate change can be assessed by determining the limits of ecosystem stability and associated tipping points related to increased temperatures and changes in water availability and distribution patterns. We urge scientists and stakeholders to identify restoration priorities in the natural systems and to collaborate with water managers to determine how water can be delivered to minimize ecosystem damage.

Ultimately, the ability to anticipate challenges from unstable and altered climates will determine whether

Everglades restoration will succeed and the nature of the future Everglades. Adaptive Restoration Planning, with climate change integrated into its foundation, should be adopted now to guide the long-term design and implementation of structures and water management. Although details of climate and ecosystem responses are unknown at this time, it is important to incorporate these large uncertainties into planning to accommodate the multi-decadal planning horizons of these large projects. Ecosystem responses to altered climates should be addressed soon in funded research programs. While it may not be realistic to expect restoration to historic conditions in light of regional and global change, Adaptive Restoration Planning may improve our abilities to manage landscape-scale changes and to maintain healthy ecosystems in South Florida.

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