Potential effects of climate change on Florida's Everglades peatlands

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Abstract

Restoration efforts in south Florida's Everglades include raising water levels and providing higher flow than currently exists. Because it is a peatland, the Everglades needs a surplus of inflow over evapotranspiration losses; if this surplus disappears under climate change, resulting droughts could challenge its long-term survival.

Using a regional hydrological model, we simulated combinations of a temperature rise of 1.5 º C, a ±10% change in rainfall, and a 0.46 m sea level rise relative to base conditions. The scenario of increased evapotranspiration and decreased rainfall (considered the worst case) produced median water depths that decreased by 5 cm to 114 cm, and inundation duration periods that decreased by 14% to 47%. Sea level rise caused increases in stage and inundation duration only in southern Everglades National Park. Ecologically significant decreases in water depths and inundation duration periods under the worst-case scenario would lead to severe alterations in the current ecosystems, including severe droughts, major peat losses and carbon emissions, wildfires, loss of the remaining unique patterns peatlands, large shifts in plant and animal communities, and increased exotic species invasions. Other scenarios produced less severe conditions.

This analysis highlights the importance of incorporating climate change into long-term restoration plans, current and future design of water management systems, and adaptive management practices. It is inappropriate to plan for unknown future hydrologic conditions assuming that past climate will resemble the future climate in south Florida. We also suggest some methods that may be more practical for restoration planning.

Key words: Climate change, Everglades, Everglades restoration, drought responses, peat loss, wetlands management

Introduction

The Everglades of south Florida (Fig. 1) is the subject of restoration efforts focused on preserving and restoring this unique wetland's natural landscape. 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 (124-132 cm) (Fernald and Purdum 1998) by 8 to 20 cm per year. Variability of annual rainfall is usually higher than annual evapotranspiration in the regional climate (Visher and Hughes 1969, Abtew et al. 2003, Abtew et al. 2007), but a long-term average water surplus has maintained the Everglades as a peatland.

Hydrologic restoration of appropriate depth, flow, and seasonality is the target of Everglades restoration (USACE and SFWMD 2002). Changes of even a few centimeters in water depth can have pronounced effects on wetland plant communities and peat accumulation (Craft and Richardson 2008, Bruland et al. 2006), 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 patterning was the product of seasonal and inter-annual variation in water depth and flow (Larsen et al 2010, Watts et al. 2010) and consists of open water sloughs with sawgrass ridges and tree islands aligned parallel to flow (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 drainage, have greatly altered the configuration of the original landscape (SCT 2003, Nungesser 2011, McVoy et al. 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 2011, Obeysekera et al. this issue). 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 by more uncertainty in rainfall predictions than in temperature increases. Consequently, Obeysekera et al. (this issue) 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. In this paper, we focus on the effects of climate change on the Everglades, the extensive natural wetland systems in south Florida. These individual studies are based upon climate change scenarios developed for southern Florida driving a regional hydrological model (the South Florida Water Management Model [SFWMM], SFWMD 2005). We used this model with altered climate regimes to explore hydrological implications of climate change on the water conservation areas (WCAs) and Everglades National Park (ENP) (Fig. 1). We analyzed the scenario results, focusing on the most probably and ecologically challenging scenario of increased temperature and decreased precipitation. The ecological implications of the scenario of increased evapotranspiration (ET), decreased precipitation, and sea level rise in the Everglades include peat loss, carbon emissions, drought, wildfires, ridge and slough pattern changes, vegetation community shifts, wildlife, and invasive exotic species, at a minimum. We then discuss implications of climate change for Everglades restoration planning and water management.

Methods

Climate change in south Florida was simulated using the SFWMM, as described by Obeysekera et al. (this issue). It is a legacy model developed over several decades to simulate hydrology of a heavily managed landscape; it uses climate drivers and applies operational rules that govern water management among square grid cells that are 3.22 km by 3.22 km in size (SFWMD 2005). Climate scenarios used were those developed in previously published work (Obeysekera et al. 2011) that used a Bayesian method (the Reliability Ensemble Average), derived from multi-model ensembles of GCMs, to produce monthly probability distributions of climate change in south Florida. These climate scenarios increased daily temperature 1.5°C, increased and decreased precipitation by 10%, and increased sea level by 0.46 m (Obeysekera et al. 2011), changes assumed to occur by the year 2060. These scenarios, relatively conservative within model ranges, were applied as an offset to historical values of ET and precipitation, adding 10% to or subtracting 10% from the daily rainfall recorded from 1965-2005, and adding 7% to the daily calculated ET [translation of a 1.5ºC temperature rise using a regionally derived temperature-based method (Abtew et al. 2003)]. The resulting scenarios included three included here: current rainfall and current ET (BASE), increased evapotranspiration /increased rainfall (+ET+RF), and increased ET/decreased rainfall (+ET-RF) (Table 1). Sea level rise of 0.46 m was included only 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 36 water stage gauges (Fig. 2) located from northern Water Conservation Area 1 (WCA-1) through southern Everglades National Park (ENP). Our analysis focuses on the cumulative hydrographs (stage-duration curves) for the base and climate change scenarios rather than on more detailed annual or seasonal values because the focus on more detailed values is unwarranted given the method used to generate the synthetic ET and precipitation. For this analysis, depths at the median (50%) line were used to represent the difference between scenarios and the BASE in median water depth differences (MDD) in cm and surface water inundation duration (SWD) in the percent of time water was above ground at each gauge. Median depths were used to represent the longer term changes in water depths, a statistic expected to be more robust under altered climate conditions than other statistical metrics for unknown future climates.

Although we discussed the +ET+RF scenario, it presents conditions that are similar to current climate as it was expressed om the Everglades landscape. Instead, we focused on the +ET-RF scenario because it is considered the most likely (Christensen et al. 2008, Meehl et al. 2008, Obeysekera et al. 2011) and because it represents the greatest challenge to the 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 was changes in storm frequencies or intensities, and third is flood and drought distribution, intensity, and duration.

Results

The two climate change scenarios produce very different hydrological responses from the BASE and from each other in the Everglades (Table 1). 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 by 1.5 to 9.4 cm. SWD was extended up to eight percent in most of the wetlands except near Florida Bay, where SWD increased up to 25% (Table 1), resulting from 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 (Table 1). Relative to the baseline, the +ET-RF scenario produced stage reductions ranging from 5.2 to 114.0 cm, and an increase at only one gauge. Most of the largest decreases of 40 cm or more occurred in the eastern-most conservation areas, where urban and agricultural urban demand are highest and seepage is highest. The most severe decline occurred in southern WCA-2B, where a combination of decreased precipitation, increased groundwater seepage, and increased groundwater withdrawals for human water supply caused water levels to decrease more than 1 m (Table 1, Fig. 4A). Another large decrease of almost 50 cm occurred in central WCA-3A, an area of particular importance for restoration. Sea level rise affected two gauges, NP-207, where median depth increased by 5.5 cm, and NP-67, which decreased by only 5.2 cm, suggesting that freshwater would be replaced by brackish 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, gauge SWD decreased from 6% to 47% relative to the BASE scenario (Table 1). Small decreases of only 6% occurred at gauge NP-67 near Florida Bay, again a response to sea level rise, and in northwestern WCA-3A where current peat depths are shallow (Johnson 2012). Gauge NP-207 inundation duration increased 8% because of its proximity to the coast and elevated sea level. The greatest decreases of 39% to 47% occurred at gauges affected by porous bedrock and high water supply demands in the eastern and southern portions of WCA-2B and WCA-3B. The greatest reduction in SWD occurred in east-central WCA-3B (-47%). Similar to the WCA-2B water depth reductions, the likely causes were decreased precipitation, increased groundwater seepage, and increased water supply withdrawals.

Other than at NP-207, reductions in Everglades National Park median water depths ranged from -5 cm to -38 cm (Table 1, Fig. 4C). Median depth differences at gauges in WCA-1 and WCA-2 ranged from -10 to -16 cm and from -7 to -16 cm, respectively, and from -10 cm to -49 cm in WCA-3A. The greatest loss of water depths were in WCA-2B of more than one meter (-114 cm) and in WCA-3B from -19 to -63 cm.

Overall, the +ET-RF scenario translated to lowered water levels throughout the Everglades so that water levels were above ground at the gauges on average only 59% of the time compared to 80% under the current (BASE) conditions. Median water levels decreased from an average of 27 cm for all gauges for the BASE to less than 1 cm under this worst case scenario. As noted above, large decreases occurred not only in the eastern sections of the WCAs, but also in central WCA-3A.

Rainfall differences were not the only cause of reductions in depths 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^3y^{-1}), relative to the

BASE ($3.6*10^6$ m^3y^{-1}) (see Obeysekera et al. this issue, Table 4). Therefore, the downstream wetland landscape received not only reduced rainfall and increased ET but also greatly reduced inflow from upstream sources.

Implications of hydrological changes on Everglades ecosystems

The large reductions in water available to the Everglades under a reduced rainfall regime directly conflicts with the goals of Everglades restoration. If rainfall increases substantially overall, restoration may still be possible in higher elevation areas unaffected directly by sea level rise.

The climate scenarios simulated here retained south Florida's past climatic variability; however, more extremes may occur in the future, including increased magnitudes or frequencies of flood and high water events. Increased variability was not included in the simulations, but even without it, conditions were poor for the peatlands when rainfall decreased by 10%. While occasional high water events may provide short term benefits to the system through drought relief, reduced precipitation is likely to lead to more severe and extended droughts over the upcoming decades. Expression of climate change is uncertain in timing; it could be relatively gradual or abrupt. Under either pattern, continued peat loss and ongoing drought would have serious ecological and water supply implications.

Following are brief overviews of the implications of the model results, beginning with the history of drainage effects 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 island oriented parallel to the flow direction (SCT 2003, McVoy et al. 2011), yet by 1940 when the first aerial photography was produced for the Everglades, large regions drained by the 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 (Nungesser 2011, McVoy et al. 2011, SCT 2003). 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 initial patterning was retained. The patterns rely on long term rise and fall of water levels and the annual flow velocities and directions of freshwater. When these hydropatterns are disrupted, ridge and slough patterns change in dimension and number of ridges per area (Nungesser 2011). Many of the greater decreases in SWD and MDD occur in central WCA-3A, the heart of the remaining ridge and slough landscape.

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). 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 patterning and potential conversion to an unpatterned landscape throughout the Everglades.

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 suggests the effects of reduced rainfall and increased ET on Everglades peatlands. 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. McVoy et al. 2011, Aich et al. 2011, 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 (McVoy et al. 2011, Davis 1943). 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, McVoy et al. 2011, Aich and Dreschel 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 1.3-7.7

cm/year) 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).

Other 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 a well-documented source of pre-drainage peat depths in the Everglades. 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 2). 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 subsequent 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 2). The estimated rates of peat loss were based on historic changes; 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 resulting increased oxidation.

In spite of major historic and current peat losses, these 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, and temperatures.

<u>Drought effects and methane emissions</u>. Droughts in Everglades freshwater peatlands elevate both CO_2 and methane (CH_4) emissions (Malone et al. 2013). Both greenhouse gases are concerns for climate change for their effects on warming and their longevity in the atmosphere. Experiments by Malone and colleagues (2013) simulating drought conditions in the Everglades indicated that reduced precipitation and increased drought occurrence and duration can turn freshwater wetlands from carbon sinks to sources following an extensive drought. Under the climate change scenarios, water availability is reduced and carbon emissions will increase.

While methanogenesis normally occurs at low rates in the Everglades, it increases with rising temperatures. Bachoon and Jones (1992) identified that both marl and sawgrass communities produce negligible concentrations of CO_2 and CH_4 under winter temperatures, which are generally below 25°C. When temperatures entered the range of 25° to 32°C, both vegetation communities produced detectable but low (<0.5 $\mu mol*ml^{-1}*h^{-1}$) emissions, and when temperatures exceeded 40°C, methane emissions increased to over 4.5 $\mu mol*ml^{-1}*h^{-1}$ (Bachoon and Jones 1992). This finding suggests that warmer summer temperatures may greatly increase CH_4 emissions from the Everglades through 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, producing poor nesting success for wading bird species such as wood storks that nest later in the dry season (Cook and Kobza 2011) and hypersaline (>40 psu) conditions in central Florida Bay for nearly 20 weeks.

<u>Peat fires and wildfires</u>. 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), the resulting dehydrated peat facilitated 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 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 to 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 to 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 to 15 cm below ground, depths which 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 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 0.01-0.14 $cm*yr^{-1}$ (Bernhardt et al. 2009; Willard et al., 2001) 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, controlled experiments indicate that both types of peat experience similar probabilities of peat combustion under controlled fire scenarios (Johnson 2012). Therefore, if fire conditions are right, the risk of peat fires is elevated and similar in all areas, regardless of moisture or organic content.

<u>Shifts in vegetation communities and wildlife</u>. Changes in hydrology and peat depths have already produced many vegetation changes in the Everglades. In much of the formerly patterned Everglades, ridges have expanded and flattened, sloughs have disappeared, willows have invaded, and upland wildlife species (including deer, opossums, foxes, and others) now inhabit 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 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 to 30 cm (Johnson 2012) above bedrock. In the southern Everglades Agricultural Area, some cropland has been lost through peat depletion, exposing 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 altering the habitat to one more similar to the Rocklands near Miami and Pine Rocklands in ENP, both of which lack peat.

Sea level rise and increased drought will alter plant community function, productivity, and processes (Saha et al. 2009, 2011, Ewe and Coronado 2009). Saha and colleagues (2011) reported that combined drought and sea level rise have already caused plant communities to shift in tree hammocks of southern Everglades National Park. The lack of freshwater resulting from upstream water management causes both seasonal drought and, combined with incursion of saltwater from sea level rise, physiological drought in plant communities, leading to vegetation shifts from freshwater to saltwater tolerant species. Increased salinity also threatens 21 rare coastal plants in ENP. Reduced rainfall and freshwater depths are expected to exacerbate similar community shifts and species losses, with associated shifts in animal communities from freshwater species to more marine species, as well as eliminating freshwater peat at those elevations.

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, 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). With additional drought stress, native species may be outcompeted for habitat by invasive exotic plants and animals. Lower water levels and lower variability in seasonal and annual water depths in the Everglades have been associated with increasing likelihood of invasion by an aggressive climbing vine, *Lygodium microphyllum* (Nungesser unpub.).

Paleoecology. The extent of droughts resulting from the +ET-RF scenario appears to exceed any previously occurring in Everglades history. Fossil pollen and seeds suggest that the Everglades has remained wet since its early development period beginning approximately 5000 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). Paleoecological records indicate that 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, Givnish et al. 2008, Powers 2005, Lockwood et al. 2003, Saunders unpubl. data). Evidence from radiometrically dated peat cores from northeast and southwest Shark River Slough indicate that over this time period, two multi-millenial periodicities (Bernhard and Willard 2009, Gleason and Stone 1994, Saunders et al. 2008, Willard et al. 2006) of dryer and wetter conditions tied to the Intertropical Convergence Zone (Haug et al. 2001) and the El Niño Southern Oscillation (Rodbell et al. 1999) have caused long-term shifts in vegetation. Yet the vegetation changes suggested by these analyses indicate that these areas had never before experienced the magnitude of changes observed under 20th century drainage. The even drier conditions of the +ET-RF climate change scenario would present even harsher conditions, so there are no prior comparable periods to serve as proxies.

Implications for Everglades restoration and water supply

While these scenarios represent a first attempt to anticipate the challenges that a changing climate is likely to pose to the Everglades, they should be used primarily as initial indicators of the possible magnitude and direction of hydrologic changes under altered climate. Even though climate change has been anticipated for a quarter of a century, climate change has not yet figured 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/docs_51_cepp_draft_pir.aspx). Flows, volumes, structures, reservoirs, and stormwater treatment areas are being sized for planning purposes assuming that historic climate adequately represents the climate for the future five or six decades. This assumption, called stationarity (Milly et al. 2008), is no longer appropriate for plans to address long-term (multi-decadal) restoration and water supply in south Florida. Given the scenarios presented here, assuming stationarity will probably overestimate the benefits of restoration projects by anticipating unrealistically high water availability without a very high increase in rainfall. If rainfall decreases or increases only slightly 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 the plans for restoration may proceed as they currently stand. A scenario that retains the current rainfall-ET ratio allows for an entirely different suite of options than a scenario that produces chronic drought and lower rainfall-ET ratios. However, if rainfall decreases relative to ET, then the Everglades will face increasing droughts, probably in frequency and duration, and the resulting suite of changes described above will include replacement of peatlands with mesic or xeric ecosystems. Questions arise whether it is reasonable to continue to plan for restoration of the Everglades as they were either historically or recently if water supply is inadequate.

In general then, restoration planning needs to implement the following to adequately address uncertainties posed by a changing climate that is in transition and unpredictable:

1) It is inappropriate to continue using previous climate history to represent the future climate. Instability and uncertainty are too great to evaluate performance of particular landscape-scale structures and operational changes without including the uncertainties of the next 50 to 100 years into the decision-making process.

2) It is essential to incorporate the uncertainties of water supply and ecosystem responses into planning, perhaps by using multiple climate scenarios. Reasonable scenarios could be included in the modeling to determine system performance (and identify preferred alternatives) under versions of at least the three scenarios simulated here: 1) if existing water balances (e.g., ET and rainfall) are maintained, 2) if rainfall increases beyond increased ET, producing an excess of water, and 3) if rainfall decreases substantially relative to ET, producing severe water deficits. Additional scenarios could be developed as well to accommodate potential changes that are considered to be appropriate. Whatever scenarios are used, they should reflect the reality of the finer scale climate drivers of south Florida (such as the sea breeze cycle and heat balance influences of extensive natural areas with and without surface water). Scenarios of future climatic conditions should reflect the best estimates of what climate change will mean in south Florida. These climate scenarios can be modified adaptively as information improves.

3) Rather than planning for a single configuration of structures and operations that have been reasonable under a predictable future, new planning paradigms that anticipate less predictability in natural ecosystems are called for. Perhaps modular structures or adaptive structures and more flexible operations can become an inherent part of restoration planning and engineering. While more complex than the usual alternatives evaluations required by the National Environmental Policy Act, these may provide a much more cost effective means of accommodating significant uncertainties while still leading to restoration success.

Another and more controversial restoration effort would be to prioritize restoration based upon realities of a limited water supply. Priorities can be established based upon a suite of values that range from full restoration to maintenance to transition facilitation. Rather than facing a potentially unreachable goal of full restoration all of the remaining Everglades, sub-areas can be rated based upon the expense and benefits of full restoration versus maintenance of existing conditions. For other areas where full degradation appears probable, these places can be consciously facilitated to achieve a smoother transition than would happen otherwise. All plans should consider that future conflicts may arise between advocates for water for natural systems and those for human economic activities (agriculture, urban land uses) as water becomes a scarce resource.

Summary

The somewhat wetter (+ET+RF) and much drier (+ET-RF) alternatives pose very different challenges for Everglades restoration and management. Wetter conditions, were they to occur, would greatly benefit Everglades restoration and water supply, providing adequate water to keep the peatlands hydrated and water flow through the WCAs and ENP.

Dryer conditions appear to be of much greater concern. Large decreases in median water depths and surface water inundation duration damage peatlands and threaten their existence. The significant negative effects of increased ET and decreased rainfall on the Everglades should be addressed in planning and in water management strategies by assessing plans for their performance under major drought conditions. The Everglades are unlikely to survive significantly drier average annual conditions and the extensive ongoing droughts predicted in the +ET-RF simulations. These changes 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 emissions of carbon and methane. It is not too soon to consider alternative approaches to restoration of the Everglades that incorporate options for managing smaller areas than are now addressed.

If realized, climate change as described by the +ET-RF scenario will pose numerous challenges to restoration efforts. At this time, planning for Everglades restoration relies on historic climate patterns rather than an altered and probably unstable climate. Modeling scenarios that integrate climate shifts into restoration planning will provide a perspective from which to identify the biggest challenges and ways to mitigate the worst impacts. Perhaps more flexible structural designs and operations can manage the natural systems in a way that increases their resilience and accommodate increases or decreases in rainfall as temperatures increase.

These scenarios should trigger discussions and motivate further investigation of the impacts of climate change on the Everglades ecosystems. Everglades research is needed that focuses on the effects of combined temperature increases and precipitation changes on ecosystem types, as well as the recent increased focus on the effects of sea level rise.

Acknowledging the likelihood of reduced water availability may encourage more creative and flexible water management in the near future. In a report on the progress of restoration, the National Research Council indicated that pending climate change and sea level rise should present incentives to take actions to increase the resilience of the Everglades through restoration projects (NRC 2008). It will be important to continue adaptive management or its equivalent as an ongoing practice, not only in ecological restoration but in all aspects of water supply planning.

The uncertainties of ecosystem adaptation and resilience to climate change can be assessed through determining the limits of ecosystem stability and tipping points. Ecosystems may respond in many ways to increased temperatures and changes in relative water availability. If possible, water managers need to consider ways to deliver more water to minimize ecosystem damage to the extent feasible, and to work with scientists to identify highest restoration priorities. Integrating climate change into restoration projects and management plans is essential for present and future planning efforts for Everglades restoration. Ignoring the ongoing shifts in climate may render restoration impossible or unsuccessful.

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References

Abtew W, Obeysekera J, Irizzary-Ortiz M, Lyons D, Reardon A (2003) Evaporation estimation for south Florida, Tech. Paper EMA#407, South Florida Water Management District, West Palm Beach, FL

Abtew W, Huebner R, Pathak C (2007) Hydrology and Hydraulics of South Florida. World Environmental and Water Resources Congress 2007

Aich S, Dreschel TW (2011) Evaluating Everglades peat carbon loss using geospatial techniques. Fla Sci 74(1):63-71.

Aich S, McVoy CW, Dreschel TW, Santamaria F (2013) Estimating soil subsidence and carbon loss in the Everglades Agricultural Area, Florida using geospatial techniques. Agric Ecosyst and Environ171:124-133.

Bachoon D, Jones RD (1992) Potential rates of methanogenesis in sawgrass marshes with peat and marl soils in the Everglades. Soil Biol. Biochem. 24(1):21-27

Bender GJ (1943) The Everglades Fire Control District. Soil Sci Soc Fl 5-A:149-152

Bernhardt CE, Willard DA (2009) Response of the Everglades ridge and slough landscape to climate variability and 20th-century water management. *Ecological Applications* 19: 1723-1738

Bestor HA (1942) The principal elements of a long time soil and water conservation plan for the Everglades. Soil Sci Soc. FL 4-A:90-99

Bruland GL, Grunwald S, Osborne TZ, Reddy KR, Newman S (2006) Spatial distribution of soil properties in water conservation area 3 of the Everglades. Soil Sci Soc Am 70: 1662-1676

Christensen JH, Hewitson B, Busuioc A et al. (2007) Regional climate projections, Climate Change, 2007: The Physical Science Basis. Contribution of Working group 1 to the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change, University Press, Cambridge, Chapter 11. ISBN: 978-0-521-88009-1.

Cook MI, Kobza M (eds) (2011) South Florida Wading Bird Report (17). South Florida Water Management District, West Palm Beach, FL

Cornwell G, Hutchinson EC (1974) An ecological analysis of an Everglades township in southwestern Palm Beach County, Florida. Ecoimpact, Gainesville, FL

Craft CB, Richardson CJ (1993) Peat accretion and N, P, and organic C accumulation in nutrient-enriched and unenriched Everglades peatlands. Ecol App 3:446–458.

Craft CB, Richardson CJ (2008) Soil characteristics of Everglades peat. 59-74. In Richardson CJ, The Everglades Experiments. Springer Science+Business Media LLC. New York

Davis JH (1943) The natural features of southern Florida: Especially the vegetation, and the Everglades. Geol Bull 25, Florida Geological Survey, Tallahassee, FL

Doren RF, Volin JC, Richards JH (2009) Invasive exotic plant indicators for ecosystem restoration: An example from the Everglades restoration program. Ecol Indic 9(6):S29-S36

Dukes JS, Mooney HA (1999) Does global change increase the success of biological invaders? TREE 14(4):135-39.

Ewe SML (2001) Ecophysiology of *Schinus terebinthifolius* contrasted with native species in two South Florida ecosystems. Dissertation, University of Miami.

Ewe SML, Coronado C (2009) Tree island ecophysiology as a measure of stress. White paper report, South Florida Water Management District, West Palm Beach, FL

Fennell M, Murphy JE, Gallagher T, Osborne B (2012) Simulating the effects of climate change on the distribution of an invasive plant, using a high resolution, local scale, mechanistic approach: challenges and insights. Glob Ch Biol 19(4):1262-1274

Fernald EA, Purdum ED (1998) Water Resources Atlas of Florida. Institute of Science and Public Affairs, Florida State University, Tallahassee, FL

Givnish TJ, Volin JC, Owen VD, Volin VC, Muss JD, Glaser PH (2008) Vegetation differentiation in the patterned landscape of the central Everglades: Importance of local and landscape drivers. Glob Ecol Biogeo 17: 384–402

Gleason PJ, Stone P (1994) Age, origin, and landscape evolution of the Everglades peatland. 149-198. *in* Davis, SM, JC Ogden, Everglades: the Ecosystem and its Restoration, Delray Beach, FL, St. Lucie Press

Gordon DR (1998) Effects of invasive, non-indigenous plant species in ecosystem processes: lessons from Florida. Ecol Appl 8:975-989

Haug GH, Hughen KA, Sigman DM, Peterson LC, Rohl U (2001) Southward migration of the Intertropical Convergence Zone through the Holocene. Science 293:1304-1308.

Johnson J (2012) Estimating the Vulnerability of Everglades Peat to Combustion. Master's Thesis, Environmental Sciences Program, Florida Atlantic University.

Light SS, Dineen JW (1994) Water control in the Everglades: A historical perspective. 47-84, *in* Davis, S.M. and Ogden, J.C, Everglades: the Ecosystem and its Restoration. Delray Beach, FL, St. Lucie Press

Lockwood JL, Ross MS, Sah JP (2003) Smoke on the water: the interplay of fire and water flow on Everglades restoration. Front Ecol Environ 1:462-468.

Malone SL, Starr G, Staudhammer CL, Ryan MG (2013) Effects of simulated drought on the carbon balance of Everglades short-hydroperiod marsh. Global Change Biology doi: 10.1111/gcb.12211.

Mayo N (1940) Possibilities of the Everglades (revised). Bulletin 61 new series. Fl Dept of Agriculture, Tallahassee, FL 91 pp.

McVoy CW, Park WA, Obeysekera J, VanArman J, Dreschel TW (2011) Landscapes and Hydrology of the Pre-drainage Everglades. University Press of Florida, Gainesville

Meehl GA, et al. 2007. Global Climate Projections. Pages 747–845 in Solomon S, Qin D, Manning M, Chen Z, Marquis M, Avery KB, Tignor M, Miller HL (eds), Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on

Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, New York, USA.

Milly PCD, Bettencourt J, Falkenmark M, Hirsch RM, Kundezewicz ZW, Lettenmaier DP, Stouffer RJ (2008) Stationarity is dead-Whither water management. Science 319:573-574. DOI:10.1126/science.1151915.

Mitsch WJ, Gosselink JG (1993) Wetlands. Wiley, New York.

National Research Council (NRC) (2008) Progress Toward Restoring the Everglades: The Second Biennial Review, 2008. Committee on Independent Scientific Review of Everglades Restoration Progress, National Research Council, National Academies Press, ISBN: 0-309-12575-8

Nungesser MK (2011) Reading the landscape: temporal and spatial changes in a patterned peatland. Wetl Ecol and Manag DOI 0.1007/s11273-011-9229-z.

Nungesser MK, Ewe SML, Vega JF Submitted. A landscape approach to identifying the hydroecology of *Lygodium microphyllum*, an invasive exotic species.

Obeysekera J, Barnes J, Nungesser M (this issue) Predicting response of the greater Florida Everglades to climate change and future hydrologic regimes: climate sensitivity runs and Regional hydrologic modeling. Envir Mgmt

Powers, 2005 M.S. Thesis, Univ. FL;

Robertson WB (1953) A survey of the effects of fire in Everglades National Park. US Dept of Interior, National Park Service, Everglades National Park, Homestead, FL 169 pp.

Rodbell DT, Seltzer GO, Anderson DM, Abbott MB, Enfield DB, Newman JH (1999) An ~15,000-year record of El Niño-driven alluviation in southwestern Ecuador. Science 283:516-520.

Sah, AK, Sternberg LSLO, Miralles-Wilhelm F (2009) Linking water sources with foliar nutrient status in upland plant communities in the Everglades National Park, USA. Ecohydrol 2:42-54.

Saha K, Saha S, Sadle J, Jiang J, Ross MS, Price RM, Sternberg LSLO, Wendelberger KS (2011) Sea level rise and South Florida coastal forests. Clim Chang DOI 10.1007/s10584-011-0082-0.

Saunders C, Jaffe R, Gao M, Anderson W, Lynch JA, Childers D (2008) Decadal to millennial dynamics of ridge-and-slough wetlands in Shark Slough, Everglades National Park: integrating paleoecological data and simulation modeling. Final Report (GA) 5280-00-007, National Park Service, Miami.

Schmitz DC, Simberloff D, Hofstetter RH, Haller W, Sutton D (1997) The ecological impact of nonindigenous plants. In Simberloff D, DC Schmitz, TC Brown (eds) Strangers in Paradise: Impact and Management of Nonindigenous Species in Florida. Island Press, Washington, DC pp 39-61

Science Coordinating Team (SCT). 2003. The Role of Flow in the Everglades Ridges and Slough Landscape. Report to the South Florida Ecosystem Restoration Task Force Working Group, West Palm Beach, FL, USA.

Simberloff D (1997) The biology of invasions. In Simberloff D, Schmitz DC, Brown TC (eds) Strangers in Paradise: Impact and Management of Nonindigenous Species in Florida. Island Press, Washington, DC pp 3-17

Snyder G.H. (2005) Everglades Agricultural Area Soil Subsidence and Land Use Projections. In the 64thProceedings of the Soil and Crop Science Society of Florida, Gainesville, FL.

South Florida Regional Climate Change Compact (SFRCC) (2011) A Unified Sea Level Rise Projection for Southeast Florida, Southeast Florida Regional Climate Change Compact, http://www.southeastfloridaclimate compact.org/pdf/Sea%20Level%20Rise.pdf

South Florida Water Management District (SFWMD) (2005) Documentation of the South Florida Water Management Model Version 5.5. South Florida Water Management District, West Palm Beach, FL

South Florida Water Management District (SFWMD) (2011) Biweekly status report 6-15, Water Shortage Report. SFWMD, West Palm Beach, FL, USA.

Simpson CT (1920) In Lower Florida Wilds. GP Putnam’s Sons, NY. 404 pp.

Sklar F, Cline E, Cook M, Dreschel T, Coronado C, Gawlik DE, Gu B, Hagerthey S, Lantz S, McVoy C, Miao S, Newman S, Richards J, Rutchey K, Saunders C, Scinto L, Shuford R, Thomas C (2008) Soil profiles of macrofossils, Chap. 6 of 2008 South Florida Environmental Report, South Florida Water Management District, West Palm Beach, FL, pp. 6-75 to 6-77.

Sklar FH, van der Valk A (2002) Tree Islands of the Everglades. Kluwer Academic Publishers, The Netherlands

Southeast Florida Regional Climate Change Compact Counties. 2012. A Region Responds to a Changing Climate. Regional Climate Action Plan, Southeast Florida Regional Climate Change Compact Counties.

Stephens JC, Speir WH (1969) Subsidence of organic soils in the U.S.A. Pub. 89, Assn Intern. of Hydro Sci, Colloque de Tokyo

Stephens JC, Stewart EH (1942) Effect of climate on organic soil subsidence. Agricultural Research Service, USDA, Fort Lauderdale and Fort Pierce, FL.

U.S. Army Corps of Engineers (USACE) and South Florida Water Management District (SFWMD). 2002. Final Central and Southern Florida Project Comprehensive Everglades Restoration Plan, Project Management Plan, WCA-3 Decompartmentalization and Sheetflow Enhancement Project, Part 1. USACE, Jacksonville, FL. http://www.evergladesplan.org/pm/pmp/pmp_docs/pmp_12_wca/decomp_main_apr_2002.pdf

Visher FN, Hughes GH (1969) The difference between rainfall and potential evaporation in Florida, 2"d Ed. Florida Bureau of Geology Map Series 32, Tallahassee, FL.

Vitousek PM (1986) Biological invasions and ecosystem properties: can species make a difference? In: Mooney HA, JA Drake (eds) Ecology of Biological Invasions of North America and Hawaii. Ecological Studies. Springer-Verlag, New York pp 163-177

Wade D, Ewel J, Hofstetter R (1980) Fire in South Florida Ecosystems. US Department of Agriculture, Forest Service Technical Report SE-17

Watts DL, Cohen MJ, Heffernan JB, Osborne TZ (2012) Hydrologic modification and the loss of self-organized patterning in the ridge-slough mosaic of the Everglades. Ecosys 13:813-827

Willard DA, Bernhardt CE, Holmes CW, Landacre B, Marot M (2006) Response of Everglades tree islands to environmental change. Ecol Monog 76:565-583.

Willard DA, Holmes CW, Weimer LM (2001) The Florida Everglades ecosystem: climatic and anthropogenic impacts over the last two millennia. Pages 41-55 in Wardlaw BR (ed). Bull Amer Paleon

Wyatt MG, Curry JA (2013) Role for Eurasian Arctic shelf sea ice in a secularly varying hemispheric climate signal during the 20th century. Clim Dyn, DOI 10.1007/s00382-013-1950-2

Figures

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

Fig. 2. Gauge locations used in the analysis 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. 4. Subset of stage-duration hydrographs for the Everglades other than gauge 7 (Fig. 3). Full set available from senior author upon request.

Fig. 5. Changes in median water depths (MDD, cm) for the +ET-RF scenario relative to the BASE scenario in the Everglades.

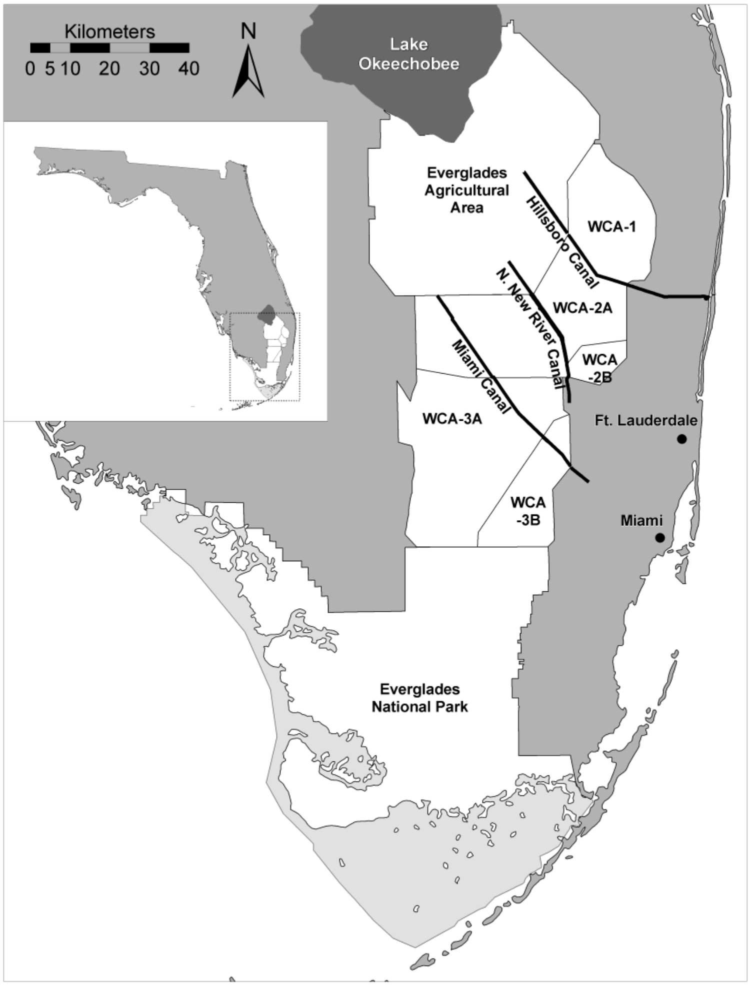
Fig. 6. Changes in surface water depth duration (SWD, percentages) from the +ET-RF scenario relative to the BASE scenario in the Everglades.

Table 1. Climate change scenario results. BASE scenario results at gauges for median water depths and surface water inundation duration (SWD) and changes relative to the BASE for +ET+RF and +ET-RF scenarios.

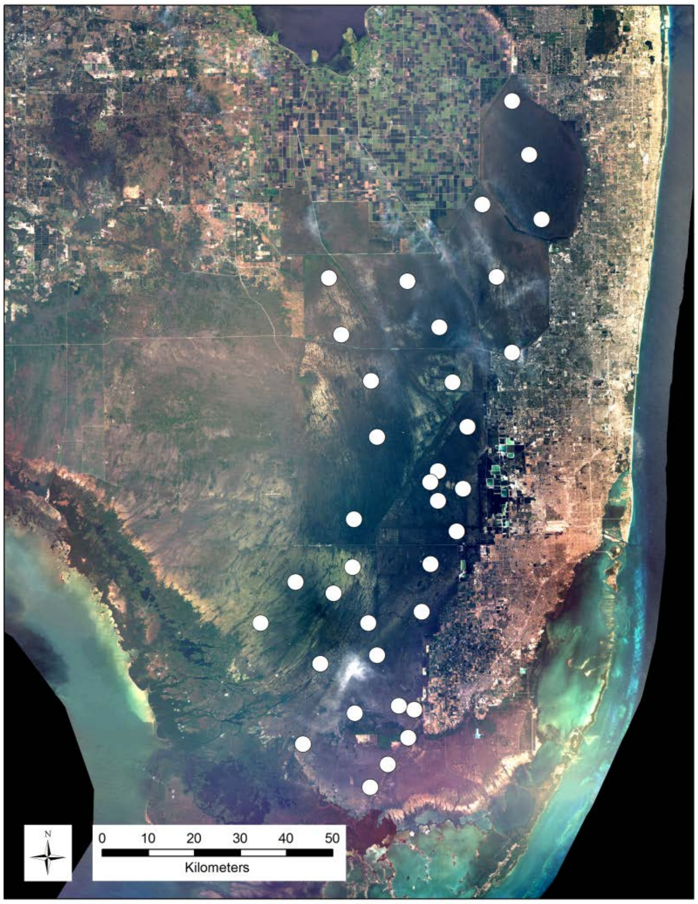
	BASE		**+ET+RF**		**+ET-RF**	
Gauge	Median depth (cm)	SWD (%)	Median depth diffs (cm)	SWD diff (%)	Median depth diffs (cm)	SWD diff (%)
1-7	30.8	95	2.4	1	-15.5	-16
2A-17	25.3	88	1.8	1	-16.5	-19
2A-N	20.4	94	1.5	1	-7.3	-10
2B-S	89.9	86	8.8	4	-114.0	-40
3A-2	44.2	98	2.1	0	-10.4	-6
3A-NE	28.7	92	2.7	2	-14.9	-16
3A-28	53.3	98	4.6	1	-36.0	-13
3A-3	33.2	90	4.3	1	-28.7	-33
3A-4	40.8	94	4.9	1	-31.7	-22
3A-C	81.4	99	4.6	0	-48.8	-13
3A-NW	29.6	94	1.8	1	-10.7	-16
3B-2	35.1	98	5.5	1	-19.2	-11
3B-29	44.5	81	5.8	3	-62.8	-47
3B-S	47.2	94	5.2	2	-31.4	-26
3B-N	43.9	92	5.2	2	-34.4	-30
3B-NC	36.6	98	6.4	0	-20.7	-12
3B-SC	47.2	94	5.2	2	-31.4	-26
3B-SE	56.1	84	4.9	4	-61.6	-39
1-N	16.2	85	1.5	2	-10.1	-18
1-S	59.7	99	2.4	0	-16.2	-9
G-3273	1.5	53	3.7	8	-38.4	-33
G-620	13.7	79	4.6	2	-14.6	-30
NESRS-2	35.1	94	1.5	1	-15.5	-16
NP-201	7.9	72	4.9	2	-12.5	-27
NP-205	2.1	56	1.8	6	-32.6	-28
NP-206	6.4	68	2.7	6	-33.8	-35
NP-207	-5.5	42	9.4	25	5.5	8
NP-33	28.0	91	3.4	1	-15.5	-16
NP-34	10.1	72	4.3	3	-24.1	-31
NP-36	25.6	89	3.7	1	-18.0	-23
NP-38	16.2	83	3.0	3	-13.7	-24
NP-44	-17.4	34	5.5	6	-26.8	-19
NP-67	9.8	69	3.4	11	-5.2	-6
NTS-1	4.0	55	4.6	8	-35.7	-25
R-3110	-19.8	36	8.8	7	-31.4	-21

Table 2. Estimates of total period of record (1875 through 2005) loss of CO_2 from the Everglades peatlands. Source: Aich and Dreschel 2011, Correction; Aich et al. 2013).

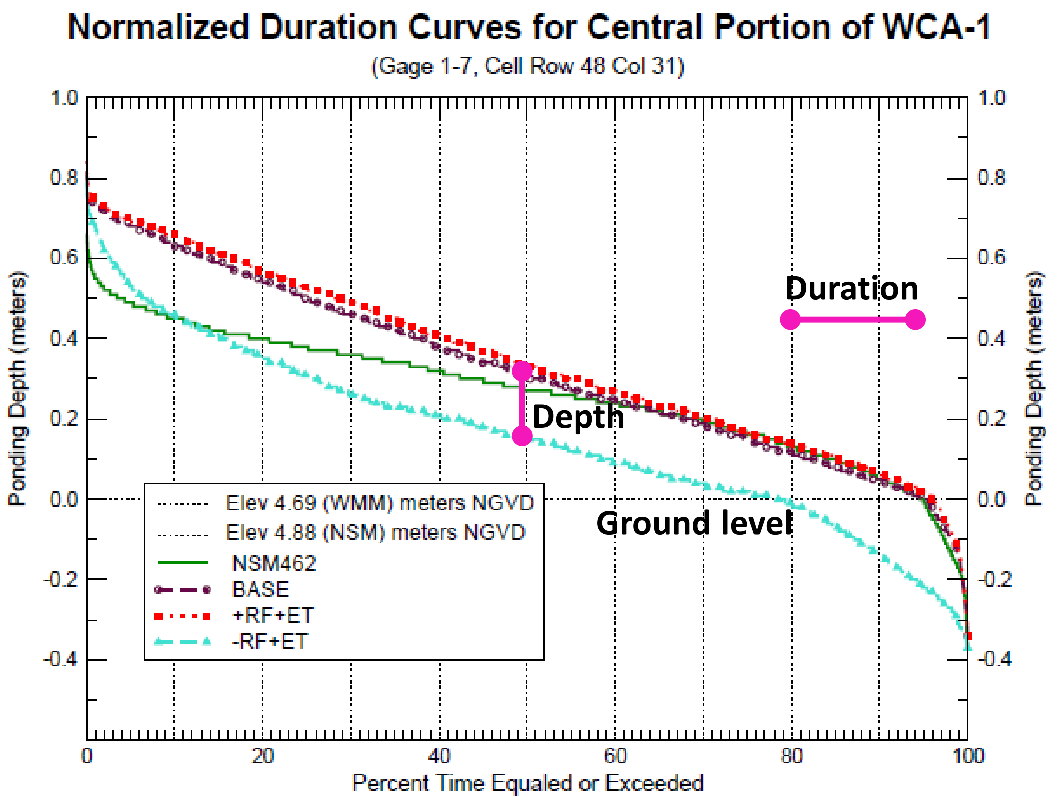
Source	m^3 of peat volume lost	WCAs: Grams lost per square meter per hour (using data from Snyder, 1994 for bulk density and carbon content)	Total Metric tons of CO_2 lost (using data from Snyder, 1994 for bulk density and carbon content)	Average Subsidence in m from the m^3 of peat volume lost and the 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



Kilometers
0 5 10 20 30 40
N
Lake Okeechobee
Everglades Agricultural Area
Hillsboro Canal
WCA-1
N. New River Canal
WCA-2A
WCA -2B
Miami Canal
WCA-3A
WCA -3B
Ft. Lauderdale
Miami
Everglades National Park



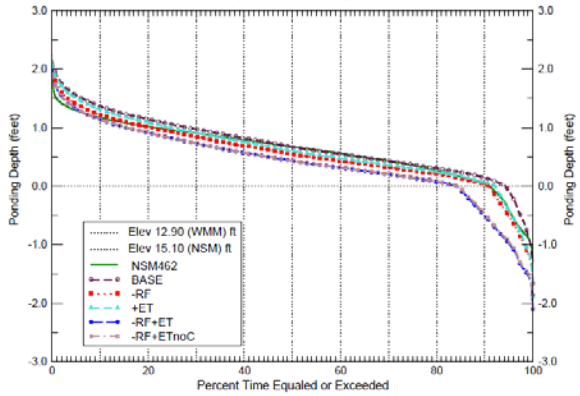
N
0 10 20 30 40 50
Kilometers



Normalized Duration Curves for Central Portion of WCA-1
(Gage 1-7, Cell Row 48 Col 31)
Ponding Depth (meters)
Percent Time Equaled or Exceeded
Elev 4.69 (WMM) meters NGVD
Elev 4.88 (NSM) meters NGVD
NSM462
BASE
+RF+ET
-RF+ET
Duration
Depth
Ground level

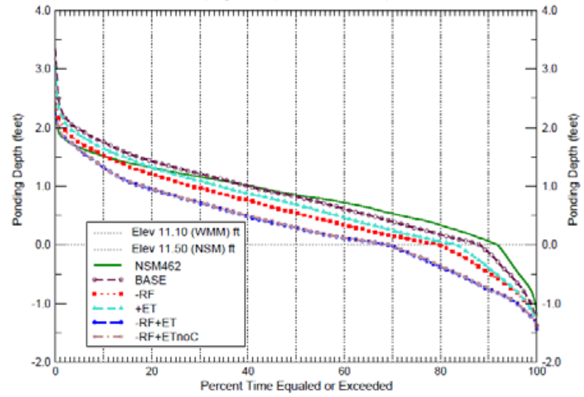
Normalized Duration Curves for North End of WCA-2A

(Cell Row 45 Col 28)



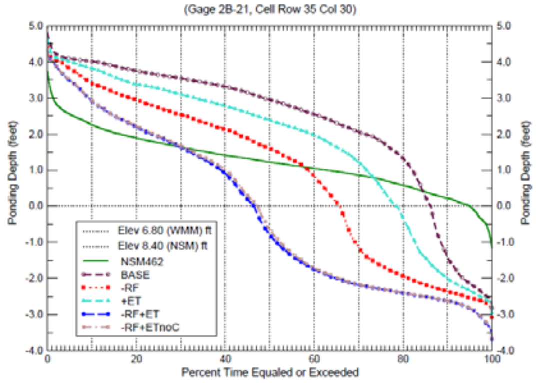
Normalized Duration Curves for Central Portion of WCA-2A

(Gage 2A-17, Cell Row 40 Col 29)



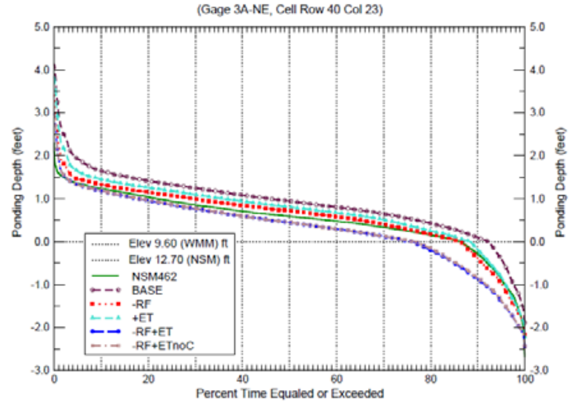
Normalized Duration Curves for South End of WCA-2B

(Gage 2B-21, Cell Row 35 Col 30)



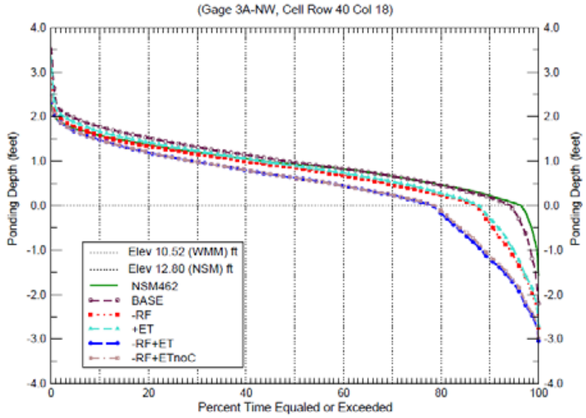
Normalized Duration Curves for North-East End of WCA-3A

(Gage 3A-NE, Cell Row 40 Col 23)



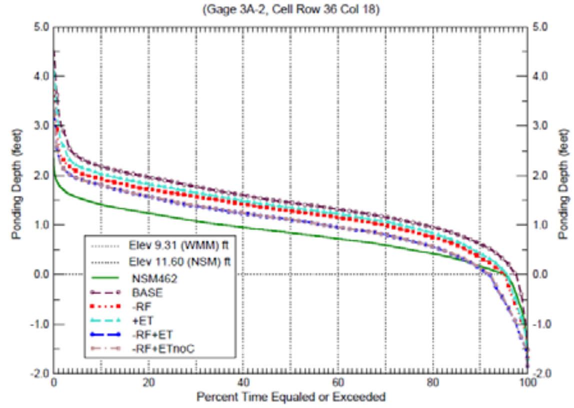
Normalized Duration Curves for North-West End of WCA-3A

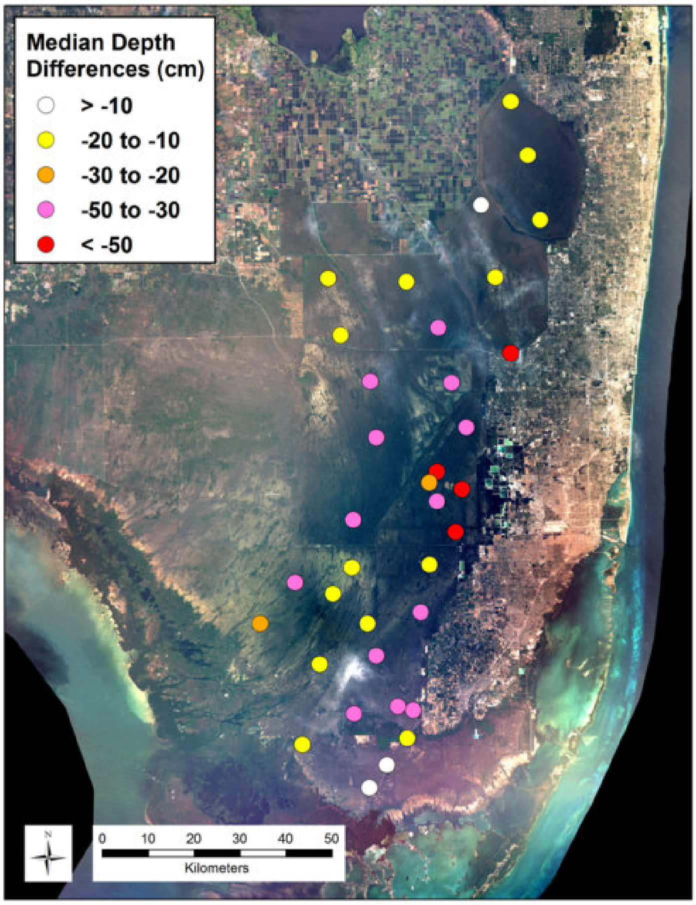
(Gage 3A-NW, Cell Row 40 Col 18)

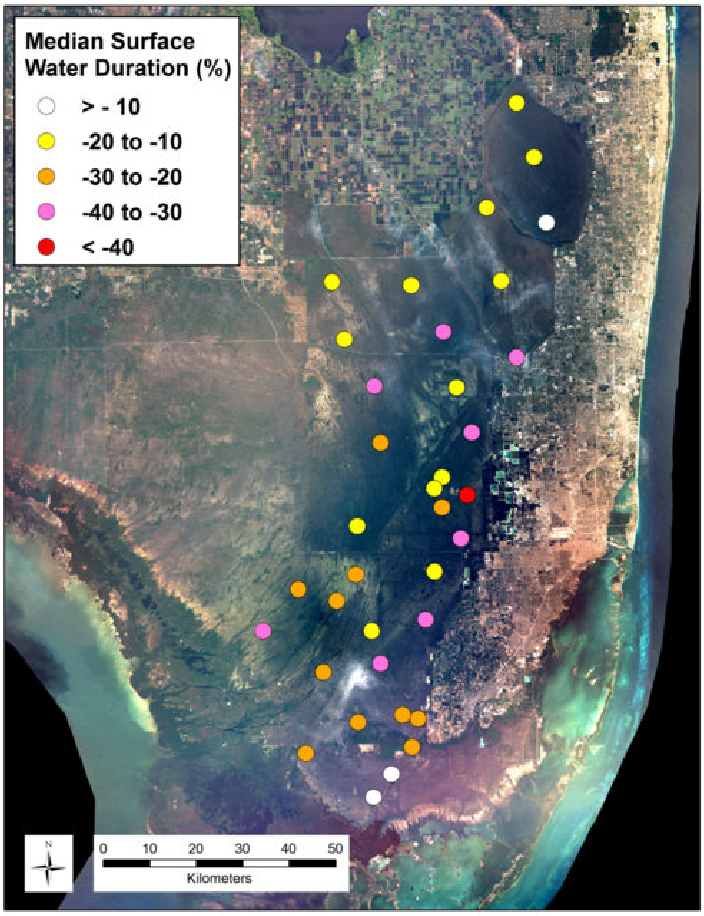


Normalized Duration Curves for North End of WCA3A

(Gage 3A-2, Cell Row 36 Col 18)




Median Depth
Differences (cm)
> -10
-20 to -10
-30 to -20
-50 to -30
< -50
N
0 10 20 30 40 50
Kilometers


Median Surface
Water Duration (%)
> - 10
-20 to -10
-30 to -20
-40 to -30
< -40
N
0
10
20
30
40
50
Kilometers