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Shifting Ground: Landscape-Scale Modeling of Biogeochemical Processes under Climate Change in the Florida Everglades

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Abstract

Scenarios modeling can be a useful tool to plan for climate change. In this study, we help Everglades restoration planning to bolster climate change resiliency by simulating plausible ecosystem responses to three climate change scenarios: a Baseline scenario of 2010 climate, and two scenarios that both included 1.5 °C warming and 7% increase in evapotranspiration, and differed only by rainfall: either increase or decrease by 10%. In conjunction with output from a water-use management model, we used these scenarios to drive the Everglades Landscape Model to simulate changes in a suite of parameters that include both hydrologic drivers and changes to soil pattern and process. In this paper we focus on the freshwater wetlands; sea level rise is specifically addressed in prior work. The decreased rainfall scenario produced marked changes across the system in comparison to the Baseline scenario. Most notably, muck fire risk was elevated for 49% of the period of simulation in one of the three indicator regions. Surface water flow velocity slowed drastically across most of the system, which may impair soil processes related to maintaining landscape patterning. Due to lower flow volumes, this scenario produced decreases in parameters related to flow-loading, such as phosphorus accumulation in the soil, and methylmercury production risk. The increased rainfall scenario was hydrologically similar to the Baseline scenario due to existing water management rules. A key change was phosphorus accumulation in the soil, an effect of flow-loading due to higher inflow from water control structures in this scenario.

Keywords Scenarios modeling · Carbon · Peat · Phosphorus · Sulfate · Methylmercury

Introduction

Of all aquatic systems, wetlands are likely some of the most susceptible to climate change, particularly those dependent on precipitation (Burkett and Kusler 2000; Osland et al. 2016; Winter 2000). Strategies require sufficient adaptive capacity to allow for the development of achievable goals, the anticipation of future changes, and the overall design for self-sustainability. This is particularly salient in the case of the Everglades, where climate change will likely affect precipitation and evapotranspiration, sea level, and water-use management. Climate projections for Florida are further complicated by the coarse grid size of existing global circulation models relative to the narrow peninsular geography that drives Florida's climate (Obeysekera et al. 2011).

Millions of south Florida residents rely on the Everglades for ecosystem services including supporting recreational fisheries, providing protection from storms, and safeguarding drinking water from saltwater intrusion (Brown et al. 2018; SERES 2011). As one of the largest neotropical

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ecoregions in North America, the Everglades also is home to numerous rare, endangered, and threatened species, making it a critical resource for global biodiversity. The Everglades is an International Biosphere Reserve, a Ramsar Wetland of International Importance, and a World Heritage Site—one of only three places in the world given all three distinctions (Ramsar 2019; UNESCO 2019a; UNESCO 2019b).

Unfortunately, 150 years of human impacts have destroyed, fragmented, and degraded the ecosystem. In 2000, Congress launched the multi-billion dollar, multi-decade Comprehensive Everglades Restoration Plan (CERP) to restore the Everglades and to improve the ability of the ecosystem to meet both the human and natural needs (NRC 2016; USACE 1999). However, it is clear that the greatest threats are yet to come, as climate change is expected to fundamentally transform wetlands in the decades to come (Gabler et al. 2017; Osland et al. 2016), including the Everglades (Perry 2011). For the CERP to succeed, planners must pivot to building resiliency to these looming threats (NRC 2016).

Scenarios modeling offers a way to envision different plausible futures, providing a means of what-if analysis (Moss et al. 2010). A first step is to visualize how plausible climate scenarios may play out in the ecosystem in the absence of restoration, with a view to identifying restoration goals and strategies that are likely to be successful for a range of possible outcomes. Accordingly, in 2014, the U.S. National Research Council called for scenarios-based modeling that provides indications of the sensitivity of the Florida Everglades to temperature and precipitation changes in the coming decades (NRC 2014).

The current study is the latest to follow from climate change workshops organized by the Florida Atlantic University Center for Environmental Studies and the United States Geological Survey. In 2015, researchers from the South Florida Water Management District published climate scenarios simulations for south Florida, focusing on providing mid-century hydrologic outcomes based on a conservative set of climate change and sea level rise projections (Obeysekera et al. 2015). A series of what might be called thought-experiment papers extended these hydrologic modeling results by applying qualitative professional judgements to different aspects of the Everglades ecosystem (Aumen et al. 2015; Catano et al. 2015; Havens and Steinman 2015; Nungesser et al. 2015; Obeysekera et al. 2015; Orem et al. 2015; van der Valk et al. 2015).

One of these papers, Orem et al. (2015), developed a conceptual model of how climate change may affect elemental cycling in Everglades soils by applying insights from previously published studies of Everglades soils to the hydrologic results of Obeysekera et al. (2015). In brief, they envisioned that in a warmer but drier Everglades, large portions of Everglades soil would undergo extended dry-down, and loss of peat soil would be likely to exacerbate eutrophication and contamination downstream by releasing nutrients and contaminants such as nitrogen, phosphorus (P), sulfur, and mercury (Orem et al. 2014). For a warmer but wetter future, Orem et al. (2015) anticipated enhanced peat accretion in areas that are too dry today, and a faster flow of water that would in turn enhance the maintenance of landscape patterning. The caveat was that increased inflow through water structures that may accompany greater rainfall, may have the downside of further loading the Everglades with sulfate and P, in turn exacerbating eutrophication and methylmercury production. They concluded that future changes in precipitation would be a stronger driver of soil biogeochemical cycling than atmospheric warming because of the feedbacks among water availability, redox conditions, and organic carbon accumulation in soils.

Conceptual models or frameworks are usually the first step in any kind of modeling. A valuable next step is to compare the conceptual assessments of future soil changes in Orem et al. (2015) with numerical simulations by a hydro-ecological model. The Everglades Landscape Model (ELM) integrates a full suite of hydro-ecological processes on a regional scale, providing the ability to model and visualize hydro-ecological outcomes through space and time, both at local scales (Fitz and Sklar 1999) and regional scales (Fitz et al. 2011). The ELM has previously been used to compare alternative restoration scenarios in the Everglades (Fitz et al. 2011; Orem et al. 2014; Osborne et al. 2017). Flower et al. (2017) were the first to use the ELM to compare how alternative climate change scenarios combine with sea level rise to produce different effects on water levels and salinity, vegetation dynamics, peat accretion, and P dynamics in Everglades National Park (ENP). In the face of sea level rise, if rainfall decreased, salinity was much greater in the zone of saltwater encroachment, compared to the scenario of increased rainfall. A similar amount of freshwater marsh was lost to sea level rise in both scenarios, but more was converted to mangroves vs. open water in the decreased rainfall scenario compared to the increased rainfall scenario.

In the present paper, we provide process-based simulations and visualizations that offer new insight into soil biogeochemical outcomes under climate change scenarios. Although the model domain includes the ENP, we focus here on the Water Conservation Areas (WCAs) (Fig. 1). As Flower et al. (2017) has already focused on the ENP and the portion of our simulations that are directly affected by sea level rise, here we focus on the freshwater remnant that will be affected by climate change but not sea level rise. The WCAs deserve special attention because they are spatially and functionally central to the water management of the

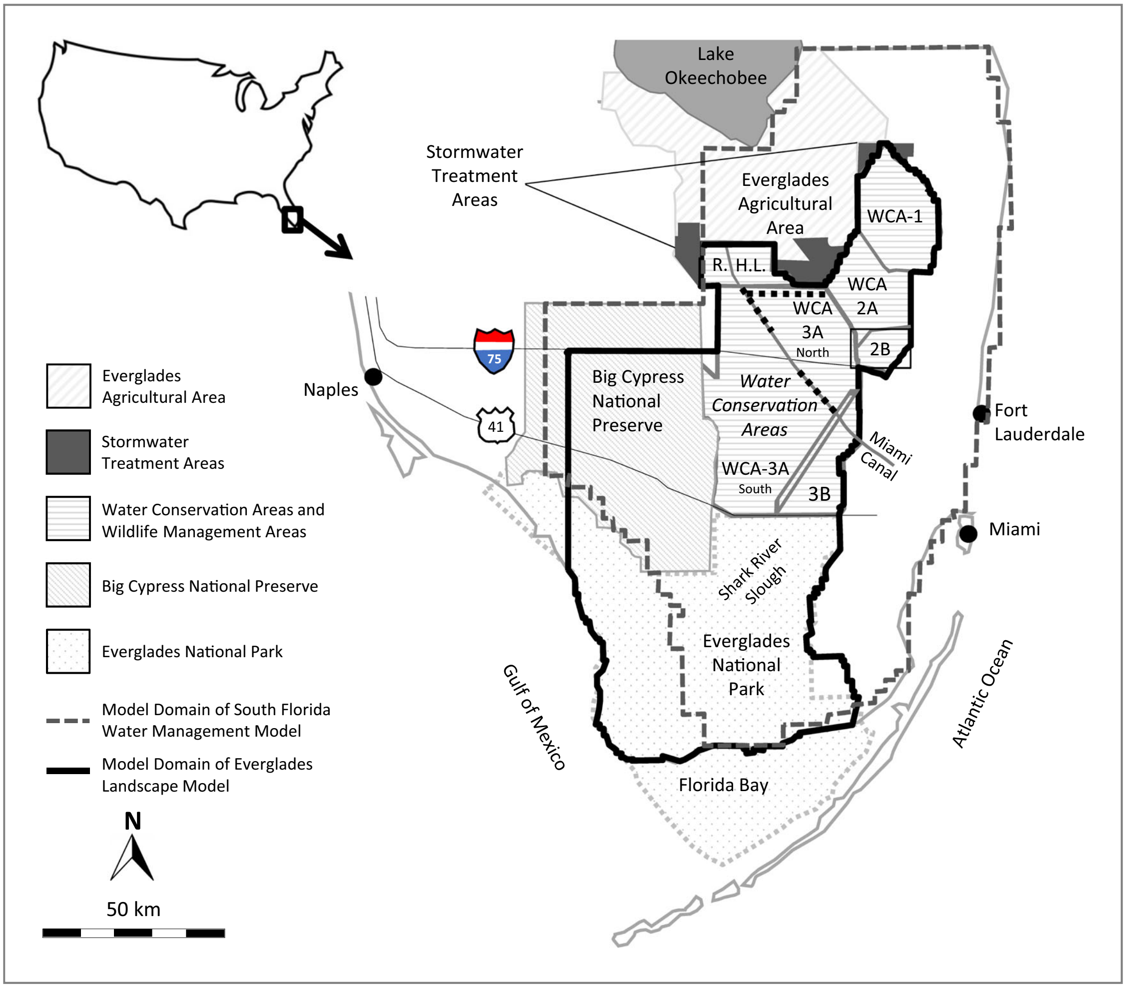

Fig. 1 Map of the Everglades Landscape Model (ELM) domain (delineated with a bold line) with respect to the domain for the South Florida Water Management Model (SFWMM, delineated with a dark gray dashed line). Inside the ELM domain, Water Conservation Areas (WCAs) and Wildlife Management Area (WMAs) are striped gray with sub-regions designated by name; Rotenberger WMA is designated with "R." and Holey Land WMA is designated with "H.L." Stormwater Treatment Areas are shaded in dark gray. Indicator Regions for our Muck Fire Index simulations are designated in WCA-3A with bold dotted lines

Everglades (Gunderson et al. 2010), and because they contain most of the last remnants of important freshwater habitats such as original sawgrass plain, wet prairie, and hardwood swamps outside of ENP (Light and Dineen 1994).

Our central question is: In the coming decades, how might soil biogeochemical processes respond to increases in temperature, increases in evapotranspiration, and increases or decreases in precipitation? Whereas Orem et al. (2015) identified trajectories of change without any numerical modeling of soil-related processes, the ELM allows us to spatially and temporally visualize possible future trajectories of nine parameters important for evaluating changes to the soil. First, we simulate three key hydrologic drivers of soil process and patterning: water flow volume, surface water depth, and surface water flow velocity. Next, we look at the effects of these drivers on soil process and patterning. Landscape patterning will be determined by surface water flow velocity. The amount of carbon storage as peat in the Everglades will depend on the peat accretion rate and the muck fire risk. Eutrophication will be determined by P availability (driven by water inflow volume) and may be seen most directly in the P accumulation in the soil. Sulfate concentration in the water (also driven by water inflow volume) will affect methylmercury production risk in the soil.

Although model results should not be interpreted to predict specific concentrations of chemical species at any particular location, they do provide an overall picture of the plausible effects of the climate model applied under different conditions and areas of the ecosystem most impacted by these changes. By providing visualizations and semi-quantitative projections of these key soil indicators, we aim to better inform adaptive planning efforts to bolster

Everglades resiliency to climate change and offer insights on approaches to planners worldwide of similar wetland ecosystems facing climate change.

Materials and Methods

Study Area

The greater Everglades of South Florida (Fig. 1) include neotropical estuaries, wetlands, and uplands. Historically, the abundant fresh water flowing southwesterly through the region flowed as a sheet due to the extremely flat ground surface extending from Lake Okeechobee to Florida Bay and the Gulf of Mexico with an elevation gradient of only 5 cm km^{-1}. The Everglades relies primarily on direct rainfall and rain-derived inflow from water control structures (see Baseline Scenario, Table 1).

More than 50% of the historical Everglades has been lost to agricultural and urban development (Light and Dineen 1994). The remaining Everglades wetlands have been bisected by two main east-west trending roads, I-75 ("Alligator Alley") and State Road 41 ("Tamiami Trail") (Fig. 1). Much of the remnant Everglades that lies north of Tamiami Trail has been compartmentalized and bisected by canals in a system of basins known as WCAs and Wildlife Management Areas (WMAs). The northernmost of these is WCA-1 (the Arthur R. Marshall Loxahatchee National Wildlife Refuge), then WCA-2A and -2B to the south, with WCA-3A adjacent to the west, WCA-3B at the southeastern corner. South of Tamiami Trail, the ENP comprises the remnant southern Everglades and most of Florida Bay. Together the ENP and WCAs are designated via the Everglades Forever Act (1994) the 900,000 ha (2,200,000 acres) Everglades Protection Area (EPA). The present study focuses on the freshwater part of the EPA. To the east of the EPA is a densely populated urban area that includes Miami (Fig. 1). Immediately south of Lake Okeechobee is the Everglades Agricultural Area, a 300,000 ha (700,000 acre) agricultural zone, which is the main source of surface water inflow to the EPA (Abtew and Khanal 1994; Abtew and Obeysekera 1996; Scheidt and Kalla 2007).

Surface water flow into and out of WCAs occurs through water control structures and canals. Timing and volumes are determined by the South Florida Water Management District and the Army Corps of Engineers based on multi-objective water management decisions that balances the needs of the EPA with the water supply demands and protection from flooding required by the agricultural and urban sectors. Surface water enters the ENP by passing below Tamiami Trail from the WCAs (Fig. 1). In this study, the main part of the ENP that we will focus on is the Shark River Slough, which is the main flow-way which drains to the Gulf of Mexico.

Scenarios

To extend the recent advances of prior climate-scenarios work (Flower et al. 2017; Obeysekera et al. 2015), we used the same Baseline scenario and scenarios of plausible future climate change (Table 2). The period of simulation was set for mid-21st-century (2050–2060) because Everglades restoration commonly uses 50 years as the planning horizon (Obeysekera et al. 2015). The CERP was approved by congress in 2000, with projects expected to be completed in 30 years. However, restoration has been slow, and is now estimated to take 50 years to implement.

The Baseline scenario is based on 2010 climate conditions, and represents a four decade future period under current climate conditions (Obeysekera et al. 2015). The

Table 1 Simplified water budget for the freshwater system (i.e., excluding tidal exchanges) represented as monthly means (in millions of cubic meters) for direct rainfall input, loss from evapotranspiration, and water control structure inflow

Scenario	Direct rainfall input	Loss from evapotranspiration	Surplus (rainfall minus evapotranspiration)	Structure inflow
Baseline	1140	977	163	228
−RF	1026	1025	1	146
+RF	1254	1109	146	252

Scenarios are existing condition (Baseline), 10% reduction (−RF), or increase (+RF) in rainfall

Table 2 Model scenarios used in this paper, based on precipitation, air temperature, evapotranspiration, and sea level rise climate change model scenarios of Obeysekera et al. (2015)

Scenario	Precipitation	Temperature	Evapotranspiration	Sea level rise
Baseline	No change	No change	No change	No change
−RF	−10%	+1.5 °C	+7%	+0.46 m
+RF	+10%	+1.5 °C	+7%	+0.46 m

Annual means are from the 36-year period of simulation for the Baseline and climate change scenario simulations. Flower et al. (2017) focuses on the consequences to the Everglades of the sea level rise part of the two climate change scenarios

Baseline scenario uses climate data from 1965 to 2000 to capture the effects of inter-annual variability, and the two climate change scenarios were constructed by modifying the Baseline scenario with appropriate changes to climate and sea level. The two climate change scenarios were derived from a synthesis of downscaled data (Obeysekera et al. 2015; Obeysekera et al. 2011). We used projections for 2060 that are conservative for warming (1.5 °C), and subsequent evapotranspiration (+7%), (Table 2) (Carter et al. 2014; Melillo et al. 2014; Obeysekera et al. 2011; SFRCCC 2015). Although the climate change scenarios included sea level rise (0.46 m), its effect is primarily on the coastal Everglades and was examined in a prior study (Flower et al. 2017). In this study we focus exclusively on the freshwater remnant. The only difference in the two climate change scenarios is whether rainfall increases or decreases by 10%; hereafter, we refer to them simply as "+RF scenario" and "–RF scenario," respectively. A simple ±10% allows us to evaluate the sensitivity of the ecosystem to alternative rainfall outcomes in the face of increased warming and evapotranspiration, which may be magnified if the change exceeds 10%.

All of the scenarios for this study assume current (ca. 2012) water management infrastructure, rules, and operational criteria for flood protection, water supply or ecological water deliveries. No CERP projects were accounted for (Obeysekera et al. 2015).

Hydrologic Boundary Conditions

For surface water flow into and out of the ELM model domain through control structures and canals, and for water levels at the domain boundaries we used the hydrologic simulations of Obeysekera et al. (2015) wherein the South Florida Water Management Model (SFWMM) was run with the climate scenarios from Table 2. The SFWMM is a hydrologic model that simulates altered water level distributions and daily flows through water control structures throughout south Florida's urban, agricultural, and natural systems. It uses climate input and a built-in complex regional water management decision framework that includes agricultural and urban water demand (Obeysekera et al. 2015; SFWMD 2005; Tarboton et al. 1999). The SFWMM is often referred to as the "2 × 2" model because it uses a 2 × 2 mi (3.2 × 3.2 km) grid across the model domain (delineated by a dark gray dashed line in Fig. 1).

Everglades Landscape Model

The ELM is a dynamic regional-scale integrated model that simulates how changes in temperature and precipitation may alter a complex, living system. The first publicly released ELM version was Open Source with an extensive documentation report (Fitz and Trimble 2006). Subsequent improvements to the present ELM (versions 2.8 and 2.9) were also fully documented, with the Open Source code, data, and documentation being available at http://www.ecolandmod.com, which should be consulted for a hierarchy of detailed information on all aspects of the model and its assumptions (Fitz et al. 2004; Fitz 2009; Fitz 2013; Fitz and Paudel 2012; Fitz and Trimble 2006).

The ELM performance has been calibrated using extensive field data (Fitz and Trimble 2006), and both calibration and validation continue as new data become available. Model calibration and validation has been conducted mainly by comparing modeled vs. observed values at almost 80 stations through the system. The most recent (ELM v2.8.4; same in v2.8.6 and v2.9.0) marsh surface water P concentrations have a median modeled vs. observed difference of 0 μg L^{-1} (Fitz and Paudel 2012). Hydrologic flow was validated using chloride as a conservative tracer, with a median bias of 8 mg L^{-1} (Fitz and Trimble 2006). The ELM soil module was largely calibrated using data from the WCAs (Fitz and Sklar 1999; Fitz and Trimble 2006). Sulfate modeled vs. observed values (ELM v2.8.6) differed by a median of 0 mg L^{-1} (Fitz 2013). Extensive documentation reports (model structure, performance, etc) for incremental model versions are available at http://www.ecolandmod.com/publications/.

The ELM has been reviewed by an independent scientific review panel (Mitsch et al. 2007), and has been formally approved by the U.S. Army Corps of Engineers for project-specific planning perspectives dealing with water quality. Therefore, the ELM has been widely used to evaluate changes throughout the Everglades including: water quality and ecological outcomes from different decompartmentalization alternative strategies in WCA-3A (CERP 2012; Fitz et al. 2011), water sulfate and soil methylmercury patterns that may result from alternative approaches to Aquifer Storage and Recovery (Orem et al. 2014), and soil responses to different CERP restoration alternatives as part of the Synthesis of Everglades Research and Ecosystem Services (SERES) Project (Osborne et al. 2017). Most recently the ELM was used to consider hydro-ecological responses to climate and sea level rise scenarios for the first time in a project focused on ENP (Flower et al. 2017).

For this project we set a multi-decadal period of simulation starting with 2015 as time zero and running for 36 years. We used the regional (10,394 km^2) ELM v2.9 application at 0.25 km^2 grid resolution, which is 40 times finer resolution than the SFWMM. The model domain of the ELM (delineated by a bold line in Fig. 1) is largely encompassed by the SFWMM domain and includes the EPA, the eastern part of Big Cypress National Preserve, Rotenberger and Holey Land (HL) WMAs.

The ELM is driven by hydrologic output from the SFWMM model, and we used SFWMM output that was derived from the same climate scenarios we are using in this study (Table 2). The SFWMM domain inlcudes the ELM domain and supplies daily flow through water management structures and canals in the ELM domain and water levels along the ELM boundary. Within the model domain, the ELM dynamically distributes those flows in canals and through model grid cells, integrating surface water/groundwater interactions, and using scenario-based climate spatial time series input data to determine volumes of direct rainfall input and direct output by evapotranspiration.

The ELM fully integrates many of the components of an ecosystem including hydrology, water quality, soils, and macrophyte productivity and organic matter turn-over. Here we briefly describe the hydro-ecological modules used in this study. We emphasize that the model documentation reports referenced above provide definitive details regarding the model structure and performance.

Hydrologic dynamics involve a suite of modules that involve overland, groundwater, and canal fluxes, including their interactions. Those are relatively complex, and their description is beyond the scope of this manuscript, but available in the above referenced documentation and other ELM publications referenced above. However, we note that the overland flow velocity Performance Measure we use in this study is simply the cumulative, net, inflow-outflow volume flux in four grid-cell directions on a daily basis (involving a 36-min spatial flux time step), with that flux volume expressed as a linear flux across the 500 m grid-cell width across the daily time period. Thus, that velocity Performance Measure provides a grid-cell net flux velocity at "coarse" spatio-temporal scales, but no direction (which may be inferred by map visualization).

Phosphorus is a variable that is conserved within the course of its transit from the surface (or porewater) column into incorporation by live periphyton and macrophytes, with variable stoichiometry of phosphorus:carbon ratios relative to the pertinent community type. P limits the maximum growth rate of the plant/periphyton communities, along with other water and density-dependent constraints. Upon mortality, P and organic matter/carbon are consolidated into either the floc or the consolidated soil matrix.

The soil module of the ELM is encoded to include feedbacks among hydrology, biology, and eutrophication, with a variety of spatial trends throughout the system. The vertical accretion of organic soil, and the carbon and P that are thus stored, derives from the growth and mortality of periphyton and macrophytes, both above and below-ground, which are simulated in two other respective modules. Growth and mortality of these primary producers are driven by a variety of factors, including water availability and chemistry. Because the Everglades ecosystem is highly P-limited, higher P loads generally increase plant productivity and turnover, thereby enhancing peat accumulation (Armentano et al. 2006; Gaiser et al. 2005; Osborne et al. 2014). This is consistent with field observations from within and without WCA-2A where cattail-infested P-enriched areas were found to have three to five times higher soil accretion rates compared to unenriched areas (Craft and Richardson 1993).

Water availability is important to the soil module in part because excessive water depths and excessive dry-down periods decrease plant productivity and turnover, thereby diminishing peat accretion. Water availability also determines the relative contribution of aerobic vs. anaerobic decomposition rates (DeBusk and Reddy 1998) for the two state variables for peat: the floc and the consolidated soil. Under flooded conditions, the (slower) anaerobic rate prevails. Under dry-down conditions, the aerobic rate is applied to the unsaturated zone, and anaerobic rate is used below that depth.

The ELM has been encoded with a Muck Fire Index is based on a study by Smith et al. (2003), which evaluated the risk of peat fire in the Florida Everglades based on a suite of measurable risk factors (including surface water depth, duration of dry-out, and water level relative to ground surface). The ELM Muck Fire Index is measured in days, corresponding to cumulative number of consecutive days that the unsaturated zone extended deeper than 15 cm below the land surface, and had unsaturated soil moisture of $<50\%$ (Fitz et al. 2011). Because of the ephemeral nature of muck fire risk, we chose to exhibit a time series rather than a map, since each map would be limited to a snapshot in time or an average for the period of simulation. Evaluating fire risk requires "high temporal resolution" modeling, so we chose daily data rather than monthly or an average value for the period of simulation.

Muck fire risk also exhibits great spatial variability, and for simple examples to demonstrate the important temporal variability, we provide results from several regions that represent a range from dry to wet hydrologic regimes. For the Muck Fire Index we used a set of model grid cells (which we refer to here as Indicator Regions) encompassing local areas where change was considered likely due to changes in known flow pathways. In this study, the outputs for given Indicator Regions are provided as time series of the daily mean values for all of the constituent cells. The Indicator Regions are examples of dry and wet extremes and are designated with bold dotted lines within WCA-3A in Fig. 1: (1) a relatively dry section adjacent and parallel to the northern boundary (21.75 km^2); (2) another relatively dry section that includes the northern part the Miami Canal (21.25 km^2); and (3) a relatively wet section that includes the southern part of the Miami Canal.

The Sulfate Transport and Fate module incorporates a first order, net settling rate equation, and includes sulfate boundary conditions, a net settling rate map, and observed data for calibrating model performance. Statistical and graphical assessments of model performance were consistent with other ELM-simulated water quality variables (e.g. phosphorus). Details on calibration and validation can be found in Fitz (2013) and Orem et al. (2014). Associated with the Sulfate module is the (post-processed) empirical relation of the (0-1) methylmercury production risk assessment defined by Orem et al. (2014). Methylmercury production risk is higher at sulfate concentrations that are intermediate, rather than very high or very low. When surface water sulfate concentrations are very low, methylmercury production tends to be low, and they increase with increasing sulfate concentrations. However, there's a limit. As sulfate concentrations get too high, excess sulfide (a byproduct of sulfate reduction) begins to inhibit further increases in methylmercury production (Orem et al. 2011). The range of surface water sulfate concentrations that coincide with peak methylmercury production vary depending on wetland conditions: it is estimated to be near 10 mg/L surface water sulfate concentrations in the WCAs, and closer to 2 mg/L in the ENP (Fitz et al. 2011).

Results

All of the simulation maps (Figs 2–4, 6, and 7) exhibit outcomes as an average over the entire period of simulation. Black isolines on difference maps represent approximate confidence intervals, which vary by parameter and are based largely upon our own expert opinion derived from development and implementation of the ELM. Where colored shading is visible below these isolines, interpretation should be made with caution, because differences are small and they may not represent real differences between the Baseline and climate scenario runs.

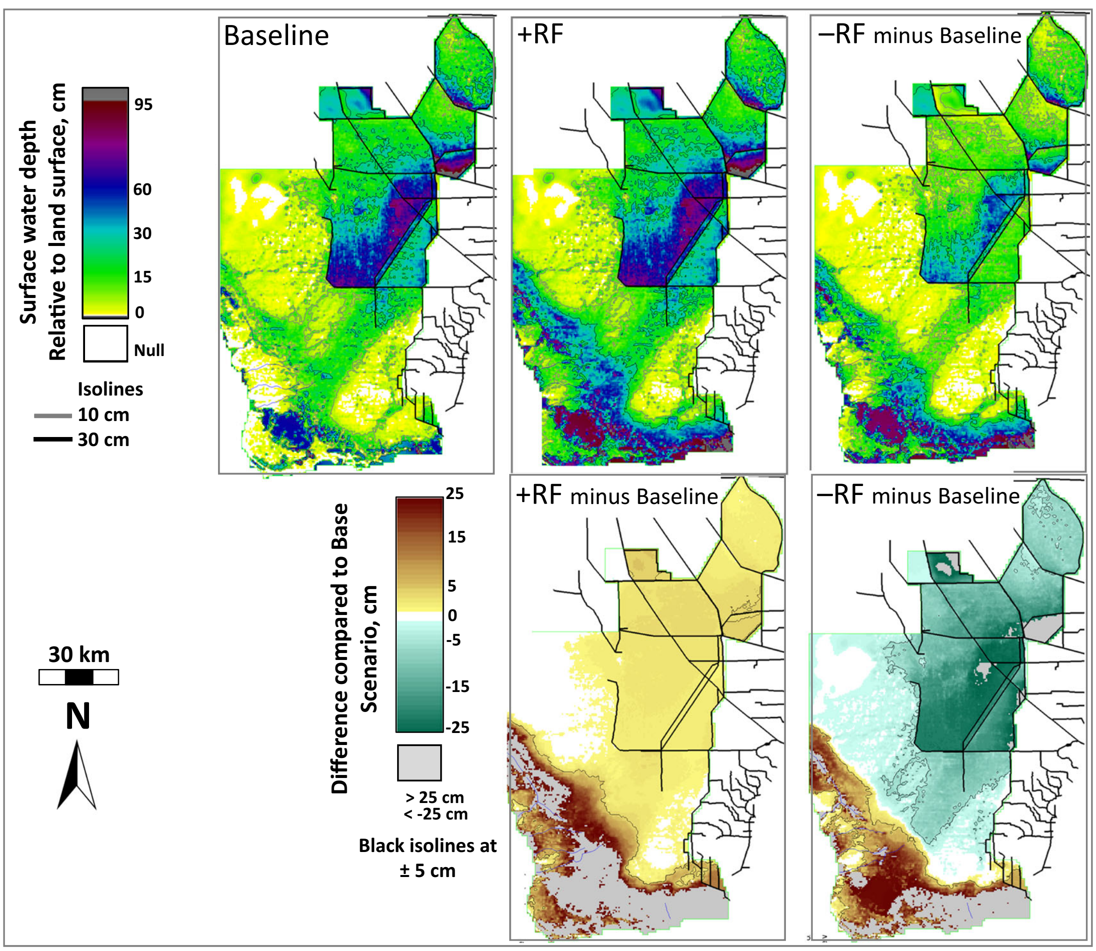

Fig. 2 Daily mean surface water depth simulation maps for the period of simulation for the Baseline scenario (top left), +RF scenario (top center), and –RF scenario (top right). For each model variable exhibited in map form, we offer what might be termed a "difference map" that shows the difference of the climate change scenario compared to the Baseline scenario, for +RF scenario (bottom left) and for the −RF scenario (lower right). Sea level rise deepens coastal waters in both of the climate change scenarios, as discussed in detail in Flower et al. (2017)

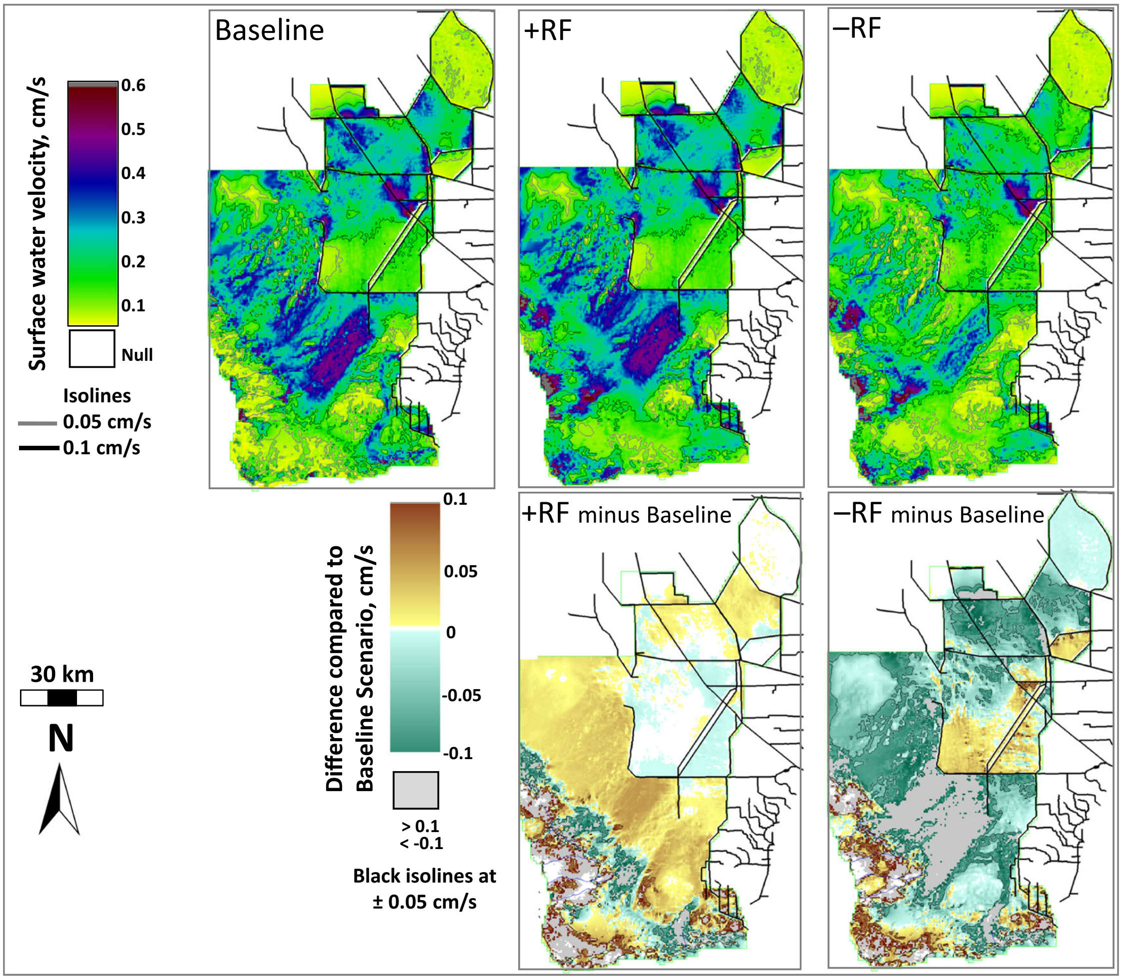

Fig. 3 Daily mean velocity of surface water flow for the period of simulation; simulation maps for the Baseline scenario (top left), +RF scenario (top center), and −RF scenario (top right). Difference maps compare the +RF scenario (bottom left) and −RF scenario (lower right) to the Baseline scenario

Domain-Wide Water Budgets

Baseline scenario

Direct rainfall within the model domain is high, but 85% of it was lost to evapotranspiration, leaving a modest surplus (rainfall minus evapotranspiration) (Table 1).

+RF scenario

The net water budget was similar to the Baseline scenario, with a marginal increase in surplus freshwater (rainfall minus evapotranspiration) and structural inflow. However, the balance of water sources shifted: surplus from internal supply (surplus) decreased by 10% compared to the surplus in the Baseline scenario, and structural inflow increased by about 10%.

−RF scenario

Rainfall is essentially canceled out by evapotranspiration within the model domain, reducing surplus by 100% (Rainfall minus Evapotranspiration is close to zero). Structural inflow declined by 36% (from 185 to 118 million cubic meters).

Surface Water Depth Distribution

Baseline scenario

Daily mean water depth exhibited a distinctive pattern of deepening to the south, with shallowest water in most sub-basins in their northern section, and deepest water along its southern boundary where the water is impounded (Fig. 2). The shallowest water (<10 cm) was limited to a large patch in northern WCA-1, small patches in other WCAs, and the marl

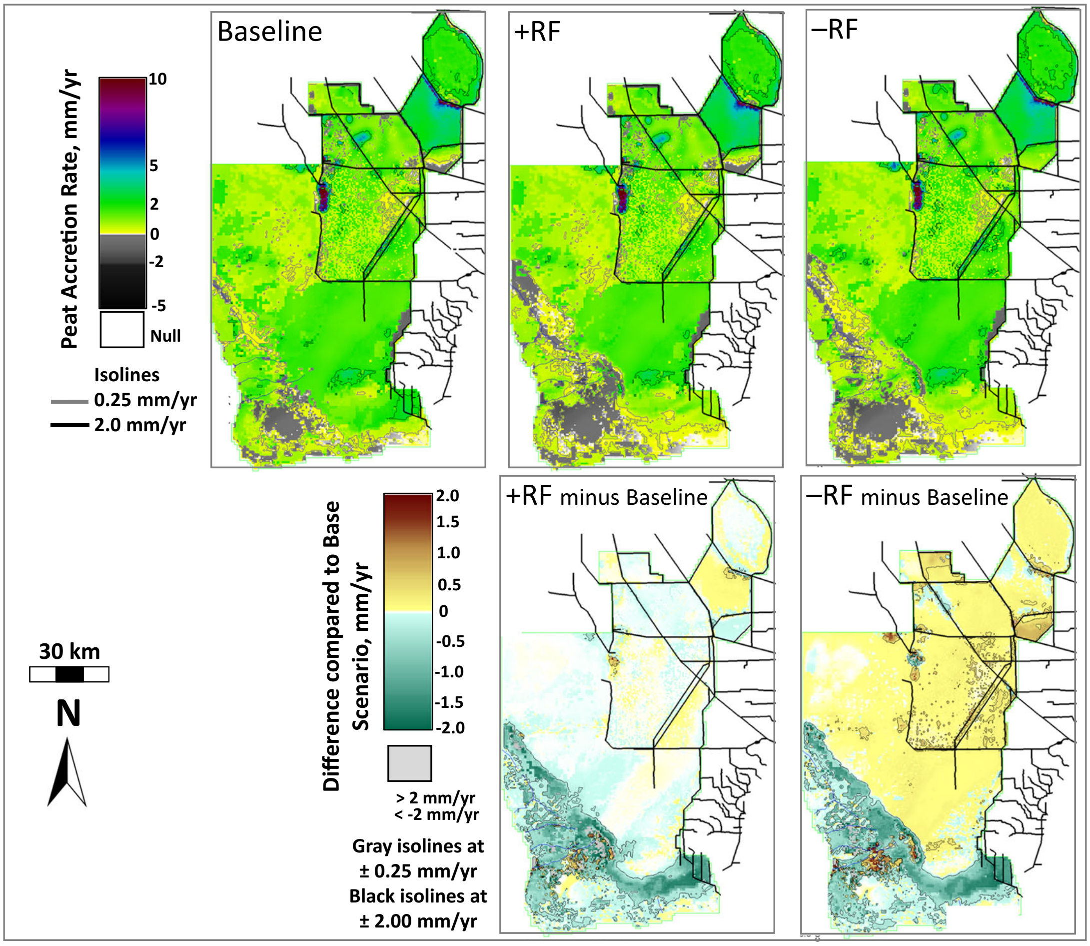

Fig. 4 Average peat accretion rate simulation maps for the period of simulation for the Baseline scenario (top left), +RF scenario (top center), and −RF scenario (top right). Difference maps compare the +RF scenario (bottom left) and −RF scenario (lower right) to the Baseline scenario

prairies in ENP. The north and central parts of the WCAs exhibited relatively shallow water (<30 cm), as did the Shark River Slough in ENP. Very deep water (>50 cm, and in some places >100 cm) was exhibited in a large swath of WCA-3A South, along its southern and eastern boundaries, and throughout most of WCA-2B. In addition, all sub-basins exhibited at least small areas of very deep water along their southern boundaries (eastern boundary for WCA-3B).

+RF scenario

Because of (SFWMM) water management rules that attempt to minimize excess water depths by moderating structural inflows, surface water depths were within 5 cm of the Baseline scenario except in two places: WCA-2B and HL WMA where increases exceeded 5 cm.

−RF scenario

Surface water depths decreased over most of the landscape. Depth was substantially reduced in the deeper areas by more than 20 cm, including WCA-2B, WCA-3A South, and HL WMA. Shallow areas underwent a smaller magnitude of depth reduction, however the net effect was a significant expansion of the total area subjected to the same shallow surface water found drier areas today (~10–30 cm, as found in the WCA-3A North in the Baseline scenario. Relatively large areas appeared with mean surface water depth <10 cm above ground surface, including northern WCA-1, northern WCA-2A, northern WCA-3A North, northeastern WCA-3A South, and southern and eastern HL WMA. Shark River Slough is projected to narrow significantly.

Velocity of Surface Water Flow

Baseline scenario

Only small isolated areas exceeded 0.5 cm/s surface water flow rate, mainly near the southern part of the Miami Canal in northeastern WCA-3A South (Fig. 3). Approximately half of the northern part of the system exceeded a mean annual surface water flow rate of 0.1 cm/s, especially WCA-3A North, the northern part of WCA-3A South, and WCA-2A.

The other half of the northern Everglades exhibited a mean annual surface water flow rate of <0.1 cm/s, including the too wet areas of southeast WCA-3A South and WCA-2B, as well as WCA-1 and northeastern WCA-3A North. In the ENP, surface water flowed at 0.1-0.5 cm/s.

+RF scenario

No significant difference was exhibited compared to the Baseline, although WCA-2A flow rates increased slightly (<0.05 cm/s).

−RF scenario

Water flow slowed by >0.05 cm/s over large areas, particularly in WCA-3A North and most of WCA-2A, and most dramatically in Shark River Slough (>0.1 cm/s). The –RF scenario also accelerated surface water flow by 0.05–0.10 cm/s in some of the too wet areas of WCA-3A South and WCA-2B, and WCA-3B.

Peat Accretion Rate

Baseline scenario

The soil accretion rate was 0.25–2 mm/year across much of the landscape (Fig. 4). The only significant patches of little to no soil accretion (<0.25 mm/year) were in the eastern WCA-3A South and most of WCA-2B, which correspond with large areas of deep surface water (Fig. 2). Faster accretion rates (>2 mm/year) are visible across most of WCA-2A, the perimeter of WCA-1, and at key water inflow points in the WCAs.

+RF scenario

Soil accretion rate was nearly identical to the Baseline scenario. Accelerated soil accretion (compared to the Baseline scenario) only occurred in two small areas adjacent to water inflow points (in northern WCA-2A and western WCA-3A South).

–RF scenario

The areas that show accelerated peat accretion above the gray isoline of 0.25 mm/year were the same places that were also relieved of excess water depths in this scenario: most of WCA-2A and many discrete spots in southern and eastern WCA-3A South, as well as northern HL WMA and much of WCA-3B. Areas adjacent to key inflow structures, noted for faster accretion rates in the Baseline scenario, exhibited significant changes from the Baseline scenario. Although much of the freshwater. Everglades shows a slight increase in peat accretion indicated by yellow coloring, most of this is below the gray 0.25 mm/year isoline, and thus not appreciably different from the Baseline condition.

Muck Fire Risk Index

Baseline scenario

In the three multi-cell Indicator Regions we examined in WCA-3A (Fig. 5), we found that the two locations in WCA-3A North (which corresponded to shallow surface water in Fig. 2) exhibited elevated muck fire risk in a relatively high proportion of days (12 and 20% for Indicator Regions 1 and 2 respectively). The risk was very low (4%) in the deeper part of WCA-3A South (Indicator Region 3).

+RF scenario

Muck fire risk was 4% lower than the Baseline scenario in Indicator Region 2, the region that had the highest muck fire risk of the three locations in the Baseline scenario. In the other two locations, the risk was the same or slightly lower than the Baseline scenario most of the time.

−RF scenario

Muck fire risk was more than twice as high as the Baseline scenario in the two locations WCA-3A North, reaching 31 and 49% of the period of simulation for Indicator Regions 1 and 2, respectively. The northern part of the Miami Canal (Indicator Region 2), exhibited 2 years with almost 300 days each of elevated muck fire risk. Around 2040, a cluster of several dry years bore little or no break from muck fire risk even during the wet season. In the lower Miami Canal area in eastern WCA-3A South (Indicator Region 3), which corresponds to one of the large deep areas in Fig. 2, dry years had up to 50 consecutive days of elevated muck fire risk at a time. Muck fire risk was elevated 19% of the time for the period of simulation, making it similar to the region that had the highest muck fire risk of the three locations in the Baseline scenario.

Phosphorus

Baseline scenario

Phosphorus accumulation rate in the soil (Fig. 6a), P concentrations in soil pore water (Fig. 6b), and P

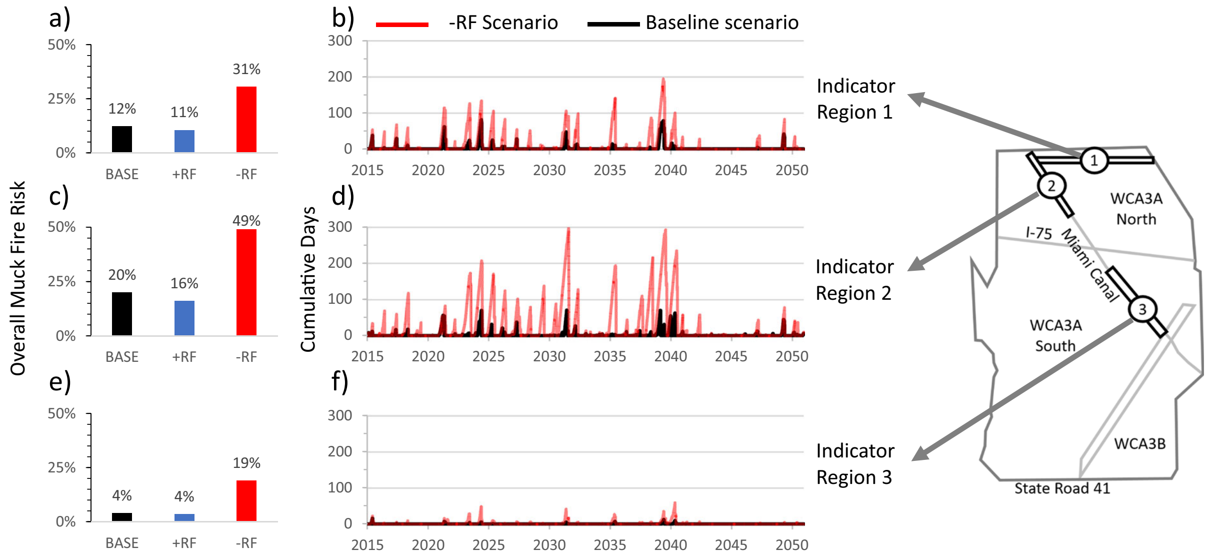

Fig. 5 Muck Fire Risk shown for WCA-3A Indicator Regions 1 (**a**, **b**), 2 (**c**, **d**), and 3 (**e**, **f**), with locations depicted in the map insert. In the left panel Muck Fire risk is shown as percent of days with elevated risk for the period of simulation for the Baseline scenario (black), +RF scenario (blue), and –RF scenario (red) In the right panel, the time series is shown as the cumulative number of consecutive days of risk for –RF scenario (red) and the Baseline scenario (black).The +RF scenario was omitted from the time series because it overlaps almost entirely with the Baseline scenario

concentrations in surface water (Fig. 6c) all exhibited high values in localized areas associated with high antecedent soil P (and internal loading), downstream of significant inflows (with some western WCA-3A inflows not treated by Stormwater Treatment Areas). Particularly high soil P accumulation rates (>50 mg/m^2/year, and in some cases >200 mg/m^2/year) are observed in a large swath encompassing in the western parts of WCA-3A North and South, in large plumes emanating from boundary canals of WCA-2A, and encircling WCA-1 (>100 mg/m^2/year). The ENP had low soil P accumulation rate (<50 mg/m^2/year), with negative values along portions of the eastern levee that are very dry, with substantial groundwater outflows to the east. Drier areas tended to have higher porewater P concentrations, reflecting higher soil decomposition and internal P cycling.

+RF scenario

The areas noted for particularly high soil P accumulation rates in the Baseline scenario accelerated by more than 25 mg/m^2/year. Soil pore water P concentrations slightly increased, and there was no change in surface water P concentration compared to the Baseline scenario.

−RF scenario

The same areas noted for increases in the +RF scenario, decreased by more than 25 mg/m^2/year. In smaller portions of the same zones, soil pore water P concentrations decreased, and even smaller zones (closer to structural inflow points) exhibited decreased surface water P concentrations.

Sulfur

Baseline scenario

Surface water sulfate concentrations exhibited an overall pattern of higher values in the northern part of the system and decreased southward (Fig. 7a). Sulfate-enriched water (>10 mg/L concentration) was visible in four main locations: (1) along the perimeter canals of WCA-1, (2) in plumes extending outward from the northern Miami Canal in WCA-3A North, (3) at inflow structures at the western edge of WCA-3A, and (4) at inflow structures along the perimeter of WCA-2A. In WCA-2A surface water sulfate concentrations exceeded 10 mg/L nearly everywhere except in the center of the basin. Although the ENP exhibited lower surface water sulfate concentrations compared to the WCAs, two large plumes >2 mg/L sulfate concentration extend southwest along flow paths in Shark River Slough and the smaller slough matrix to the northwest of Shark River Slough.

+RF scenario

Sulfate concentration in surface water showed little indication of change compared to the Baseline scenario.

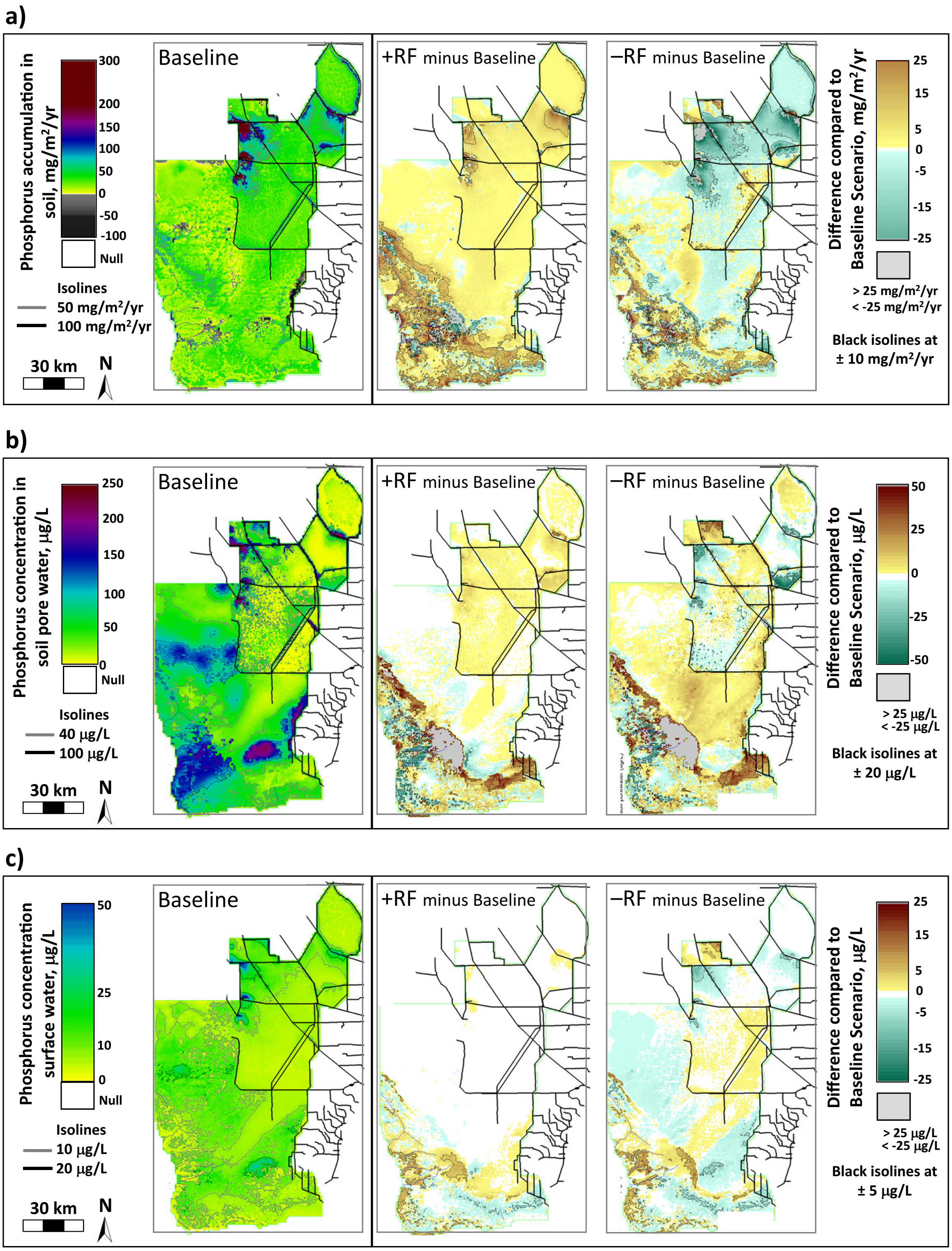

Fig. 6 Daily mean values for the period of simulation for **a** phosphorus accumulation rate in the soil, **b** phosphorus concentration in soil pore water, and **c** phosphorus concentration in the surface water; simulation maps are provided for the Baseline scenario (maps on the left). Difference maps compare the+ RF scenario (bottom left) and –RF scenario (lower right) to the Baseline scenario

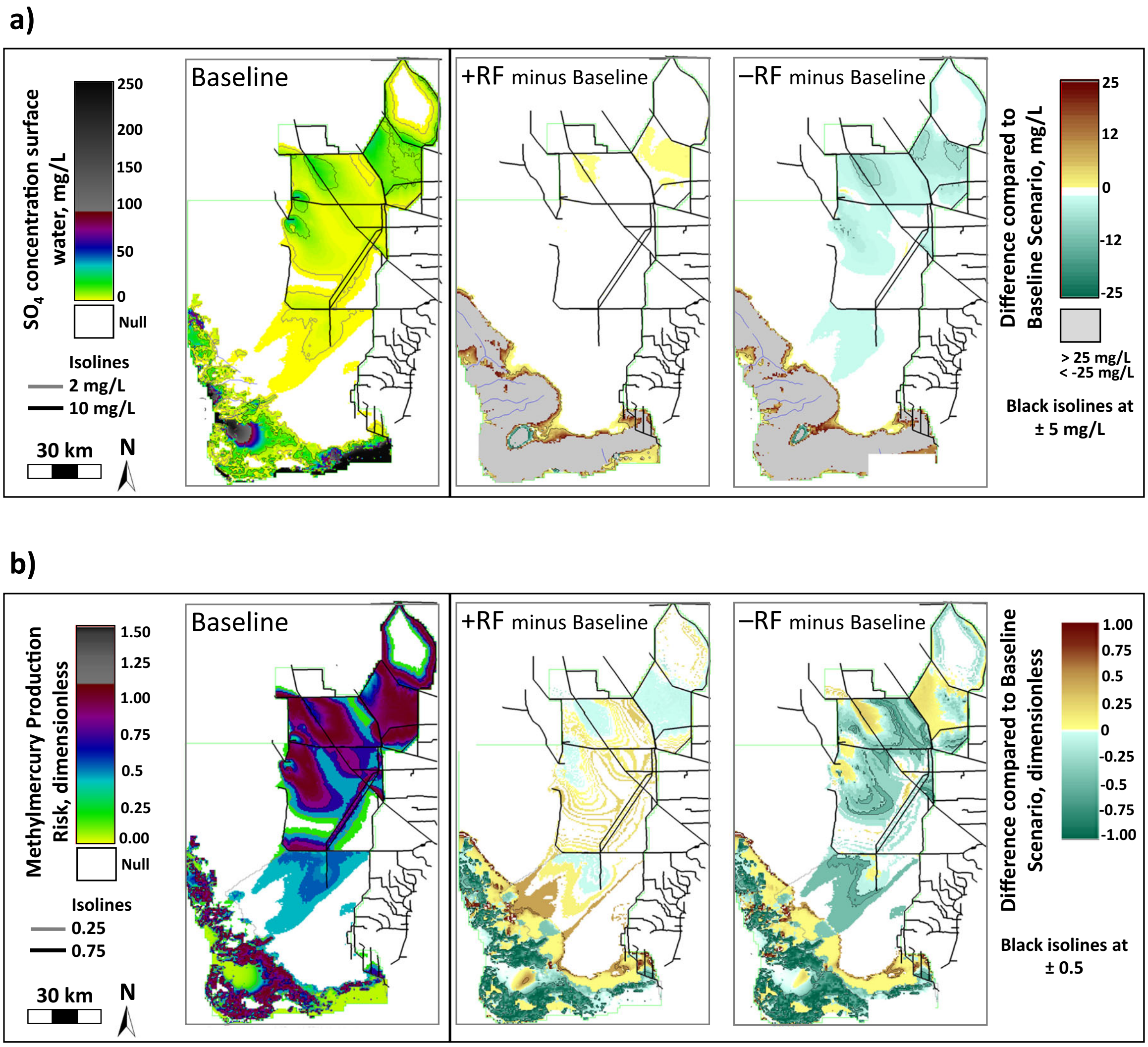

Fig. 7 Daily means for the period of simulation for **a** sulfate concentration in surface water, and **b** Methylmercury Production Risk. Simulation maps are provided for the Baseline scenario (maps on the left). Difference maps compare the +RF scenario (middle) and −RF scenario (right) to the Baseline scenario

−RF scenario

With decreased inflow from water control structures, surface water sulfate concentrations declined to a meaningful degree (>5 mg/L) in three downstream locations, corresponding to areas that had particularly high sulfate concentrations in the Baseline scenario in WCA-3A North, and WCA-2B.

Methylmercury

Baseline scenario

Methylmercury production risk was greatest in the northern part of the system (Fig. 7b). The pattern of highest methylmercury production mirrored the elevated sulfate pattern except that small areas of relatively low risk occurred at the key inflow points, which exceeded 15 mg/L sulfate (a level too high for optimal methylmercury production in the ELM module). Along the northern boundary of the ENP, elevated methylmercury risk was visible in the same areas adjacent to Tamiami Trail noted for plumes of elevated sulfate concentration.

+RF scenario

A zone within 10 km of the highest water inflow points (coinciding with sulfate increase zones) points exhibited decreased methylmercury production risk. Downstream of these zones of decreased risk, plumes of increased methylmercury production risk spread out across much of WCA-3A.

−RF scenario

Methylmercury risk was substantially reduced compared to the Baseline scenario. The effect was a mirror image from the +RF scenario: significant increased risk was exhibited in the same regions that exhibited decreased methylmercury risk in the +RF scenario, i.e., within 10 km of key water inflow points. Whereas the plume of elevated risk shrank back toward the inflow points in the +RF scenario, in the –RF scenario they spread out and reached further downstream. Large areas had 50-90% risk reduction in WCA-2B, WCA-3A North and South, and central ENP.

Discussion

The highly managed remnant Everglades ecosystem has developed a hydrologic pattern of surface water distribution, depth, quality, velocity, and hydroperiod that differs greatly from the historical patterns (Light and Dineen 1994; Sklar et al. 2002). In turn, these hydrologic alterations have led to consequences for soil biogeochemistry, flora, and fauna (Sklar et al. 2005). How might climate change further alter soil process and patterning?

Our simulations offer glimpses of possible futures for the Everglades with either an increase or decrease of rainfall 10% in the face of increased warming (1.5C), and evapotranspiration (+7%), and sea level rise (0.5 m) for mid-century (Table 2). In this study we focus exclusively on the sensitivity of the freshwater remnant to climate change; a previous project focused on the coastal Everglades (Flower et al. 2017). Although these scenarios are not necessarily our predictions or projections for the future, examining such scenarios can help us visualize how the trajectories of ecosystem change may diverge depending on whether rainfall increases or decreases.

Similarly, the output from the ELM is not intended to be taken as quantitative ecological predictions in a literal sense (i.e., a given parameter will change by x amount in a particular location). In addition to limitations in the climate scenarios, each module has its own limitations, and any attempt to model a complex natural system has inherent limitations. However, they do provide an overall picture of plausible outcomes of the climate model applied under different conditions, and indications of areas of the ecosystem most impacted by these changes. By revealing vulnerabilities and strengths in the system in the absence of restoration, our results offer insights as to restoration goals that may be realistic and strategies that may benefit the system whether rainfall decreases or increases.

The drivers of soil process and patterning (water availability, surface water depth, and surface water velocity) combined to produce indicators of change in the soil, including changes in carbon storage due to muck fire risk, peat accretion, and P accumulation, changes in soil patterning. Below we highlight the key changes to these parameters, organized around five main points that emerge from simulations:

1. Increased evapotranspiration required more structural inflow from upstream sources.
2. Decreased rainfall led to a drier Everglades and high muck fire risk.
3. Increased rainfall indirectly led to increased flow-loading of pollutants.
4. Increased rainfall raised water levels in areas already too wet.
5. Increased rainfall provided little benefit over the baseline.

Increased Evapotranspiration Required more Structural Inflow from Upstream Sources

Although rainfall increased by 10% in the +RF scenario, the simultaneous increase in evapotranspiration eliminated this advantage, producing a 10% deficit in internal water supply compared to the Baseline scenario, effectively creating a drought relative to today's supply (Table 1). Water management rules increased structural inflow by 10% to compensate, with the result that the overall water availability in the +RF scenario was slightly greater than in the Baseline scenario.

Although it is not possible to drought-proof an ecosystem, nevertheless the Sixth Biennial Review of Everglades Restoration Progress expressed concern that storage capacity must increase so as to help compensate for dry years (NRC 2016). The stress of future evapotranspiration exacerbates the water deficit, even if rainfall increases. Greater storage capacity adds greater water security, and greater flexibility for managing the water supply in the face of future increases in evapotranspiration (Choi and Harvey 2017).

Decreased Rainfall Led to a Drier Everglades and High Muck Fire Risk

The water scarcity in the –RF scenario was substantial: there was no surplus (rainfall is fully canceled out by evapotranspiration) and rather than compensate for this, structural inflow decreased by 36% due to lack of supply upstream (Table 1). Lack of upstream water supply under this scenario was directly visible in the simulations of the surface elevation of Lake Okeechobee by Havens and Steinman (2015). In the same decreased rainfall scenario that we used, they simulated the surface of this shallow lake as dropping by more than 2 meters compared to the Baseline scenario, and extreme low elevation persisted in the lake for multiple years (Havens and Steinman 2015). Both Orem et al. (2015) and Nungesser et al. (2015) surmised that large portions of Everglades soil would undergo extended dry-down under this scenario.

Our –RF scenario simulations offered visualization of how this lack of water supply may cause decreased surface water depth across much of the landscape (Fig. 2). The modern compartmentalization, canalization, drainage, and subsequent interruption of historical laminar flow has transformed the northern Everglades into a series of levee-surrounded basins like stepped pools with some areas chronically too dry and others too wet (SERES 2011). The geometry of a flat water surface above a gradually southward-sloping ground surface results in a wedge shape of shallower surface water in the northern parts of each sub-basin and deeper water where it is impounded along southern boundaries (Harvey et al. 2009). The depth distributions in WCA-3A exemplify the consequences of the extremes in surface water depth distributions: WCA-3A North is over-drained and suffers too dry conditions, central WCA-3A has generally beneficial hydrology (e.g., median water level of ~30 cm), and southern WCA-3A is too wet due to levee impoundments (Watts et al. 2010). In the case of WCA-3A South and WCA-3B, the water also deepens toward the east due to topographic gradients and the eastern boundary levees.

Our ELM surface water depth pattern is higher resolution, but similar to that produced using SFWMM for the same climate scenarios by Obeysekera et al. (2015), and Nungesser et al. (2015). Projections of mean annual surface water depth must be interpreted in context of seasonal variations; most areas will have higher depths in the wet season and lower depths in the dry season. Further, interannual variability will result in particularly deep water in wet years, and particularly low surface water depths during drought years. Areas with low mean annual depths are more likely to dry out in the dry season. In this way, the spatial distribution of surface water depths serves as a short-hand indicator of a large suite of hydrologic factors such as hydroperiod and soil moisture, which in turn drive the biogeochemical processes which are the focus of this project.

Under the –RF scenario there was significant expansion of the areas subjected to the range of annual mean surface water depths of <30 cm (Fig. 2), that characterize current conditions defined as chronically "too dry." These areas, typically in the northern end of sub-basins, have experienced significant soil losses in the last 50 years (Osborne et al. 2011; Scheidt and Kalla 2007). Currently, WCA-3A North has surface water depths of ≤30 cm in the Baseline scenario, and has long suffered from soil subsidence, fires, and other impacts (Orem et al. 2015). Even more concerning, areas with mean annual surface water depth <10 cm above ground surface were rare in the Baseline scenario but became much more widespread in the –RF scenario. Further, Shark River Slough narrowed significantly, as predicted by Orem et al. (2015).

Our study provides the first numerical modeling of future muck fire risk in the Everglades under climate change. Nungesser et al. (2015) envisioned that under the –RF scenario, higher frequency droughts would lead to more frequent and larger magnitude muck fires, as well as vegetative fires that do not include the soil. Our time series of the –RF scenario offers a glimpse of how muck fire risk might unfold over a period of decades with less rainfall (Fig. 5). In the over-drained WCA-3A North, Indicator Region 2 exhibited elevated muck fire risk half of the time, with some years incurring 300 straight days of muck fire risk, and years of high muck fire risk were commonly clustered together. Clusters of dry years are particularly concerning. In the 1920s and 1950s, clusters of dry years led to extensive multi-year peat fires that burned areas up to 300 km^2, with smoldering continuing even through the wet seasons, and resulting in 7–30 cm of peat depth reduction (Bender 1943; Cornwell and Hutchinson 1974).

Our simulations show that muck fire risk may not be limited to the too dry areas, a concern not raised in prior work. Even the too wet area (Indicator Region 3) underwent more than fourfold increase in muck fire risk, up to 19% from 4% in the Baseline for the period of simulation, bringing it close to the 20% risk in the Baseline scenario in the too dry Indicator Region 2 (Fig. 5). Thus, under the –RF scenario, areas that are currently too wet may in some cases face muck fire risk similar to today's too dry areas. The ELM peat accretion module does not account for soil loss from muck fire; the increases above 0.25 mm/year for peat accretion in the –RF scenario compared to the Baseline scenario occur in areas that had been too deep (>1 m) in the Baseline scenario, and were relieved of that excess depth in the –RF scenario (Fig. 4).

Our simulations also provided the first visualization and semi-quantitative indications of how decreased rainfall may affect surface water flow velocity, and thus landscape patterning. Under the –RF scenario, surface water flowed more slowly. Due to the shallowing of surface water, the –RF scenario produced substantial slow-downs in the too dry part of WCA-3A North, and the too wet WCA-2A, and most dramatically in Shark River Slough (more than 0.1 cm/s slower than the Baseline scenario) (Fig. 3). Surface water flow of >1 cm s^{-1} is believed to be necessary to maintain the characteristic patterning of the so-called "ridge and slough landscape" of the Everglades (Larsen et al. 2011). This is consistent with the suggestion of Nungesser et al. (2015) that the –RF scenario could convert the Everglades to an unpatterned landscape, as tree islands and ridge and slough patterns continue to degrade.

Taken together, our –RF scenario simulations portray an Everglades with internal P loading evident in elevated pore water P concentrations (Fig. 6b), much slower surface water flows (Fig. 3), and high rates of soil loss due to both highly elevated fire risk (Fig. 5) and shallow mean annual surface water depths (Fig. 2). These modeling results provide spatial and temporal support for the suggestions of Nungesser et al. (2015) that under the –RF scenario soil loss would be so severe that large areas would exhibit exposed bedrock, and habitats could succeed from peatland to mesic or xeric uplands, with associated shifts in plant and animal communities, including proliferation of invasive exotic species.

It seems unlikely that restoration would be able to prevent long-term losses associated with the –RF scenario. However, the changes will not occur overnight, and may perhaps be delayed by progress on increased upstream water storage. In addition to increased water usage efficiency, greater upstream storage capacity has the potential to provide greater flexibility to compensate for dry years by providing extra inflow. If impacts such as elevated muck fire risk occur rapidly, this prospect raises the risk for the species currently relying on the Everglades. Rapid elevation of muck fire risk also raises the risk for the large urban and agricultural areas currently relying on the Everglades' ecosystem services such as protection from saltwater intrusion and storm damage. Any slowing or delayed onset of climate-related decline would provide a critical window of opportunity to adapt to the inevitable losses.

Increased Rainfall Indirectly Led to Increased Flow-Loading of Pollutants

Flow-loading of P and sulfate is a current problem in the Everglades which restoration seeks to mitigate, and which climate change could worsen in the absence of restoration. Key structural inflows into the WCAs discharge water from upstream sources, and a pattern of flow-loading has become prominent in the northern part of the system in particular (Sklar et al. 2005). In the Everglades ecosystem, P is the limiting nutrient in bacterial, algal, and macrophyte productivity in most of the landscape (Sklar et al. 2005). Impacts from eutrophication tend to be greatest along the boundary canals and at inflow structures, with nutrient attenuation from inflow structures toward the interior marshes. To minimize flow-loading of P, water from upstream sources first passes through Stormwater Treatment Areas to reduce P concentrations before the water enters the EPA (Sklar et al. 2005).

Like P, sulfate concentrations in surface waters and soils are higher in the northern part of the system, particularly adjacent to canals and structural inflow points (Orem et al. 2011), and consequently sulfate concentrations decrease southward. As much as one-third of the Everglades is affected by sulfate contamination, with sulfate concentrations up to 100 times higher than historical levels in heavily affected areas (Orem 2004). The stimulation of sulfate-reducing bacteria is considered to be an important driver of methylmercury production in the Everglades, (Orem 2004). The ELM Methylmercury Production Risk module takes into account that the relationship between sulfur and methylmercury production is non-linear, due to inhibition of mercury methylation as sulfide levels increase (Gabriel et al. 2014; Gilmour et al. 2012).

The Baseline scenario reproduced the current pattern wherein signs of P- and sulfate-loading are concentrated at key water inflow points (Figs 6 and 7). Because the increased rainfall scenario allowed for more water availability for meeting downstream water delivery targets, the existing water management rules embedded in the hydrologic model increased structural inflow. Even without increasing the concentrations of chemical constituents in the water, mass balance dictates that an increase in volume increases the amount of chemical constituents entering the system. Orem et al. (2015) anticipated that the +RF scenario would exacerbate the loading of these influential chemical constituents to the Everglades.

Our simulations offer the first glimpse of landscape-scale changes in eutrophication of the Everglades under climate change. The effects of flow-loaded P are seen in the +RF scenario mainly in the soil P accumulation rate (Fig. 6a), and in accelerated vertical soil accumulation in two small areas near inflow points (northern WCA-2A and western WCA-3A South; Fig. 4). The rapid removal of P from the water column means that the soil more accurately signals P eutrophication than surface waters (Gaiser 2009). Field observations indicate that soil P enrichment accelerates organic matter production and processing in the Everglades (Craft and Richardson 1993). High P loads from upstream sources have already damaged parts of the Everglades by increasing primary productivity and exacerbating cattail encroachment (McCormick et al. 2002; Sklar et al. 2005).

This study provides the first simulations of methylmercury production risk responses to future climate change. Although flow-loaded sulfate declined in the –RF scenario (Fig. 7a), this may be offset by short pulses of microbial sulfate reduction and mercury methylation caused by cycles of soil oxidation and rewetting (Orem et al. 2015), consistent with field observations (Orem et al. 2011). The +RF scenario exhibited a possible trend toward greater areal coverage of high methylmercury production risk (Fig. 7b). Orem et al. (2015) warned of methylmercury production risk increasing with increased rainfall in part because wet deposition is the main source of inorganic mercury to the system. In addition, warming is likely to increase overall microbial activity, including microbial sulfate reduction rates, and by extension rates of mercury methylation (Orem et al. 2015).

It has long been recognized that the success of Everglades restoration requires reducing the load of nutrients, particularly P, that enter the ecosystem from agricultural and urban areas (Sklar et al. 2005). Further, it is understood that this will likely entail trade-offs to meet targets and needs for both water quantity and water quality (Sklar et al. 2005). Best Management Practices and restoration activities, such as enhancement of Stormwater Treatment Area management and operation, have already made notable progress in reducing P concentrations to target concentrations, and continued progress is expected (NRC 2016).

Increased Rainfall Raised Water Levels in Areas Already too Wet

More rainfall would be beneficial, given that the ecosystem suffers from too little water supply. However, high rainfall poses challenges. Areas with chronic high water levels have been associated with the loss of tree islands (Sklar and van der Valk 2002) and deterioration of the characteristic ridge and slough landscape patterning (SCT 2003).

The Baseline scenario exhibited the deepest surface water where water is impounded along the southern parts of sub-basins of the WCAs (Fig. 2), with surface water depths exceeding 1 m in large areas of WCA-2B and WCA-3A South. In the too wet WCA-3A South, the Baseline scenario exhibited particularly slow soil accretion (<0.25 mm/year), indicating lack of vegetation turn-over in the face of stressed or drowned emergent vegetation within the ELM. Today, peat accretion still occurs in these too wet areas most years (Orem et al. 2015; Watts et al. 2012). However, areas that have surface water depths that are already excessive enough to inhibit vegetation (Watts et al. 2012) may worsen and expand, along with open water.

The two places of significantly increased surface water depths (>5 cm) in the +RF scenario were in areas with chronic high water levels, WCA-3A South and WCA-2B (Fig. 2). Current water management rules are devised to remove excess water when rainfall is heavy, and without these rules the +RF scenario would most likely have exhibited even higher surface water depths in these too wet areas. However, in the absence of restoration, water management options and existing infrastructure have limited ability to mitigate against high water levels (NRC 2016). In 2016, record winter rainfall caused high water levels in the WCAs (NRC 2016).

Restoration aims to make it possible to significantly increase flow volume without incurring excess water depths. Operational practices at hydraulic structures can be adjusted to increase water surface slope through pulsed inflow, which can increase flow volume and velocity without proportionate increases in surface water depth (Harvey et al. 2009). Further, restoration activities to decompartmentalize and reduce impoundment in the WCAs will also help alleviate extremes of water depth, rehydrating the too dry areas while relieving the backwater effect adjacent to levees. Greater upstream storage capacity could be designed to offer more flexibility in water management in the face of high rainfall events.

Increased rainfall provided little benefit over the baseline

Our simulations diverged from previous work when it came to how beneficial increased rainfall would be, in the absence of restoration. The scenario of 10% increase in rainfall is widely characterized as the “best case scenario” for Everglades resilience in the decades to come (Nungesser et al. 2015). Orem et al. (2015) projected two major benefits in the +RF scenario: (1) areas that are too dry today would experience enhanced peat accretion, and (2) ridge and slough landscape patterning would be enhanced due to faster surface water flow. However, the +RF scenario provided little benefit in our simulations. Other than a modest decrease (4%) in muck fire risk in one of our Indicator Regions (Fig. 5), the +RF scenario exhibited little change over the Baseline in terms of surface water depth, flow velocity, and vertical soil accumulation rate (Figs 2–4).

Further, the +RF scenario suggests that a marginal increase in water supply due to current (non-restoration) water management rules and infrastructure (Table 2) is not enough to re-hydrate too-dry regions. The additional structural inflow in the +RF scenario did not significantly increase annual average surface water depths in the areas that exhibited shallow surface water in the Baseline scenario (Fig. 2). Overly drained areas at the north end of sub-basins, like WCA-3A North, gained little or no surface water depth in the +RF scenario (Fig. 2). Muck fire risk remained high during dry years in WCA-3A North in the +RF scenario (Fig. 5).

Limitations

Our simulations should be viewed as broad brush strokes of plausible outcomes, rather than predictions of absolute magnitudes. The scenarios mainly serve to evaluate the sensitivity of the system to increases or decreases of rainfall in the face of higher temperatures and evapotranspiration. The range of possible precipitation change by mid-century is larger than the ±10% we used to examine system sensitivity to precipitation change, so climate change effects on the Everglades may be more consequential than our simulations suggest. The climate scenarios involve simple offsets from current patterns, and as such many important climate components are not represented, including changes in seasonal timing and distribution of rainfall, storm frequency and intensity, as well as flood and drought frequency, intensity, and duration. Extreme events are likely to become more common under future climatic conditions (Melillo 2014; Raghavendra et al. 2019; Wuebbles et al. 2014). These possible changes would be expected to be consequential, but are currently highly uncertain. As climate projections for south Florida improve (Kirtman et al. 2017), new climate scenarios may be developed.

The ELM also has limitations. For instance, there is currently insufficient data to constrain the soil decomposition rate, which in turn affects both the soil accretion rate and P dynamics (Fitz and Trimble 2006). However, the aim of the ELM is not to make quantitative predictions for a future date, but rather to indicate the direction and relative magnitude of change. Future work can reduce uncertainties, add detail to landscape-scale modeling of climate effects, and add new modules for better characterization of ecological dynamics using the ELM.

Future scenarios modeling should incorporate alternative restoration strategies with different climate outcomes. Whereas the scenarios all assume current water management, and do not include any restoration strategies, we note that restoration planning calls for changes in water management timing, magnitudes, and spatial distributions, which may better reflect the needs of the system under climate change.

Conclusions

As adaptive restoration planning pivots from recapturing the past to building resiliency to future climate change, our simulations provide visualizations and semi-quantitative analysis of how changes in macroclimate can potentially drive ecosystem vulnerability and resilience in the coming decades in the Everglades.

The increased rainfall scenario fell short of the previously anticipated benefits. Because of the simultaneous warming, the increase in direct precipitation was approximately offset by the increase in direct evapotranspiration, but water management decisions embedded in the model resulted in greater inflow volume from water control structures to the WCAs. This approximately balanced water quantity compared to the Baseline scenario, leaving muck fire risk largely unchanged, but increasing flow-loading of P and sulfate, as reflected in accelerated soil eutrophication and an expansion of the areal extent of high methylmercury production risk. These impacts underscore the need for restoration to continue improving the quality of the water entering the system through water control structures, while increasing total water availability sufficiently to alleviate muck fire risk. In the increased rainfall scenario, continued extremes in water depth persisted. This is an indication that under climate change, activities that will mitigate against water depth extremes will be even more necessary than today.

The decreased rainfall scenario led to increased area of drier marsh habitats and substantially increased muck fire risk in currently over-drained marshes, indicating significant risk of major ecosystem degradation in large swaths of the Everglades. Mitigation of this threat in the coming decades may require measures that increase water availability on dry years, e.g. upstream water storage earmarked for the Everglades. Although problems associated with flow-loading exhibit drastic reductions under this scenario, the muck fire risk index makes it clear that these problems must be solved through water quality improvements upstream, and not at the expense of water volume.

Although some adjustments may be necessary, the main components of restoration as originally envisioned should enhance ecosystem resilience by alleviating too-dry and too-wet areas, mitigating flow-loading of P and sulfate, and soil loss from dry-downs and muck fire. Our simulations show that restoration activities become all the more urgent in the face of climate change. Although the long-term fate of the Everglades remains unclear, every healthy decade provides a unique resource for biodiversity and much-needed ecosystem services to human populations in south Florida.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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