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Hydrologic implications of smoldering fires in wetland landscapes

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Abstract: Smoldering fires in organic soils have negative effects on air quality and motorist safety as well as global implications from their release of large quantities of refractory C. However, the ecological implications of their occurrence are relatively unexplored despite their potential importance to the management of wetland ecosystems. We developed a conceptual model of the ecohydrologic implications of peat-consuming fires that explores the interactive effects of fire, hydrology, and C dynamics on hydrology. We modify an existing wetland hydrology model parameterized with climate, soil, and spatial data from a low-relief region in southern Florida (USA) to explore hypothesized pyrogeomorphic changes to upland water table elevation, wetland inundation (depth and hydroperiod), and groundwater exchange as a function of fire severity (area and depth of burn). Smoldering fires increase hydroperiod and storage in organic soils in burned wetlands by changing soil elevation. After fire, negative feedbacks to fire occurrence are likely because of increased hydroperiods in burned areas. However, adjacent, unburned wetland areas and uplands may experience drier conditions that increase fire frequency in distal locations. Simulation results indicate that increasing the area of soil combustion or depth of burn increases wetland hydroperiod, flooding depths, and groundwater exchange between wetlands and surrounding uplands. Additional field data characterizing fire effects on organic soil elevations and wetland bathymetry are needed, but the model supports our hypothesis about the effects of soil-consuming fires on hydrology and habitat, and these results will inform future work on the ecological role of peat-consuming fires.
Key words: Smoldering combustion, pyrogeomorphology, wetland fire, peat fire, hydrologic change, fire feedbacks

The occurrence of fire in wetlands would seem to be rare because of inundated or saturated conditions, but many wetlands ecosystems do occasionally experience fire. Wetland fire is particularly common in regions with distinct wet and dry seasons where wetlands exhibit high hydrologic variability and the seasonal onset of rains coincides with high lightning activity (Wade et al. 1980, Snyder 1991). For example, in the southeastern USA where wetlands often occur adjacent to frequently burned uplands (e.g., cypress domes in a pine flatwoods matrix; Abrahamson and Hartnett 1990), wetland fires can occur with surprising frequency—as often as every 1 to 2 decades (Snyder 1991, Ewel 1995). Even long-hydroperiod wetlands may burn once or twice per century (Mitsch and Gosselink 2007). Most often, fires that occur in wetlands (and other ecosystems) burn aboveground fuels, with effects that depend largely on vegetation composition (e.g., maintenance of cypress dominance; Duever 1984). During prolonged droughts, however, organic wetland soils may dry sufficiently to ignite and burn (de Groot 2012). Such fires, variously called ground fires, peat fires, or muck fires, are the result of smoldering combustion in organic soils and can result in changes to wetland vegetation, bathymetry, and organic matter storage (Watts and Kobziar 2013). The fires can have significant negative effects on human populations, so the tendency of fire managers to aggressively suppress and attempt to prevent them is understandable. However, the degree to which their periodic occurrence is beneficial in shaping wetland ecosystems is not fully known. Thus, the costs and benefits of smoldering fires and human efforts to avoid or suppress them can-

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not be assessed accurately without a better understanding of the ecological effects of such fires.

In contrast to flaming combustion, which typically lasts a fraction of an hour at a given location, smoldering is a flameless form of combustion that occurs for longer durations at the surface of solid fuels (Ohlemiller 1995, Hadden et al. 2013). Smoldering ground fires can continue in organic soils such as peat—soil developed from accumulated biomass (Joosten and Clarke 2002, Hurt et al. 2003)—for many days or even months in cases, such as the Kalimantan peat fires in Indonesia in 1997 (Page et al. 2002, Usup et al. 2004) and Georgia's Okefenokee Swamp (Florida Times-Union 2012). Smoldering combustion typically occurs at lower temperatures than flaming combustion (500–700°C vs 1500–1800°C; Rein et al. 2008), but persistent smoldering fire can eventually transfer more heat to surrounding soils and plants than does flaming combustion (Kreye et al. 2011). Smoldering fires can also produce significant ecological effects because of their long duration, lateral spread, and occurrence in the rooting zone where plants have few adaptations to withstand fire (Fig. 1).

Many reasons, the most obvious of which are the costs to human health and smoke-related impediments to transportation, exist to attempt to control or extinguish ground fires. Ground fires are far less modulated by diurnal weather patterns, convection, and air currents than flaming combustion, so smoke can accumulate at ground level at nighttime or during periods of low smoke dispersion and cause dangerous reductions in visibility on roadways. These accumulations can cause tragic vehicle accidents (Abdel-Aty et al. 2011, Gainesville Sun 2012). Ground fires also produce more particulate matter with average particle sizes smaller ($\leq$2.5 μm) than that of wildfires (Muraleedharan et al. 2000). This size class of particulate matter is considered particularly harmful for cardiovascular health because of the ease with which the particles pass into the body (See et al. 2007).

Figure 1. Smoldering combustion in organic soils, such as the muck in this dry Florida lake bed, can cause local changes to soil topography. The resulting elevation changes, which can be tens of centimeters to >1 m in certain circumstances, can cause changes to local hydroperiods.

The environmental effects of ground fires extend beyond immediate and direct effects for humans at local scales. Organic soils are the result of accumulation of plant biomass over many decades to centuries (or longer), and ground fires can consume much of this organic material in a matter of weeks. The enormous C stocks in organic soils can result in the release of substantial amounts of C to the atmosphere during ground fires (Page et al. 2002, Mack et al. 2011). Langmann and Heil (2004) estimated that peat fires may produce 75% higher emissions/ha than fires consuming standing vegetation alone. Efforts to quantify the potential for C sequestration on public lands as a means of mitigating anthropogenic CO_2 emissions (e.g., Depro et al. 2008, Failey and Dilling 2010) will further increase interest in soil-consuming fires among managers charged with preventing them or accounting for their effects on ecosystem C pools.

Plant mortality is a direct and easily observable effect of ground fires. The combination of heating, direct consumption of roots embedded in organic soils, and organic soil loss to combustion can result in significant damage and mortality to trees (Ewel and Mitsch 1978, Hartford and Frandsen 1992, Stephens and Finney 2002, Watts et al. 2012). However, different levels of fire severity yield distinctly different effects on ecosystem organization. For example, moderate-severity fires in cypress swamps leave some pondcypress (*Taxodium distichum* var. *imbricarium* Nutt.) or bald cypress (*Taxodium distichum* var. *distichum* (L.) Rich.) alive, while killing potential competitors (Duever et al. 1986). In this system, fires of moderate severity can be a mechanism of continued dominance by cypress, whereas severe ground fires can serve as a disturbance that shifts community composition from forested ecosystems to herbaceous marshes (Gunderson 1977, Duever et al. 1986, Casey and Ewel 2006). Thus, the role of fire may be seen as negative (e.g., tree mortality, CO_2 emissions) or potentially positive (e.g., a natural disturbance influencing vegetation structure).

Consumption of organic rich soils by ground fires can lead to changes in wetland elevation and morphology (Watts and Kobziar 2013; Fig. 1). In the wetland landscapes where these soils often occur, a fire that burns thick layers of organic soil over large areas could produce hydrologic effects via changes in surface water storage capacity. Fire-induced hydrologic alterations could consequently produce changes to ecosystem structure and processes that range from wetland habitat and organic matter dynamics to future fire susceptibility. Here we present a conceptual model to develop hypotheses concerning potential influences of ground fires on hydrology, habitat, and organic matter cycling. We then apply and modify an existing wetland hydrology model specifically to simulate fire-induced geomorphic changes to hydrology in a low-relief landscape dominated by wetland features and frequent fire as a first step in exploring our conceptual model. Last, we discuss future areas of investigation to validate our model and empirically explore the feedbacks we suggest among fire, hydrology, habitat, and organic matter cycling in wetlands.

CONCEPTUAL MODEL

To begin exploring the ecological effects of soil-consuming ground fires in wetlands, we present a conceptual model of the potential interactive effects of fire, hydrology, productivity, organic matter accumulation/loss, wildlife habitat, and atmospheric CO_2 in these ecosystems (Fig. 2). This model, presented in the form of an influence diagram, helps to motivate and organize a set of hypotheses.

In areas of low topographic relief, ground fires can lower the elevation of depressional wetlands as wetland soil is consumed. This process has local and adjacent hydrologic consequences. By changing the storage volume of a wetland, soil-consuming fires may increase surface water availability (depth and duration) in the burned portion of the wetland (Fig. 2, H1). Increased surface water storage can affect adjacent hydrology by decreasing water availability in the unburned portion of the wetland or by influencing upland water table dynamics (H1; McLaughlin et al. 2014). Greater flooding depths and longer hydroperiods may mean that burned wetlands can serve for longer periods of time as sources of water for wildlife or as habitat for their prey during droughts. For example, in southern Florida, 2 federally listed endangered species (the Wood Stork *Mycteria americana* and the Florida panther *Felis concolor coryi*) are thought to depend strongly on the existence of standing water late in the region's dry season (Fleming et al. 1994, Cox et al. 2006, Benson et al. 2008). To the extent that soil-consuming ground fires maintain open water by lowering soil elevations and simplifying vegetation structure, low-frequency ground fires may provide an indirect ecological benefit.

Following from these hypothesized changes in hydrology, soil-consuming ground fires probably will affect subsequent C accretion rates and future fire risk and effects (Fig. 2). Increased hydroperiod in burned portions of a wetland will cause soils to remain inundated and anaerobic for longer durations, leading to the potential for in-

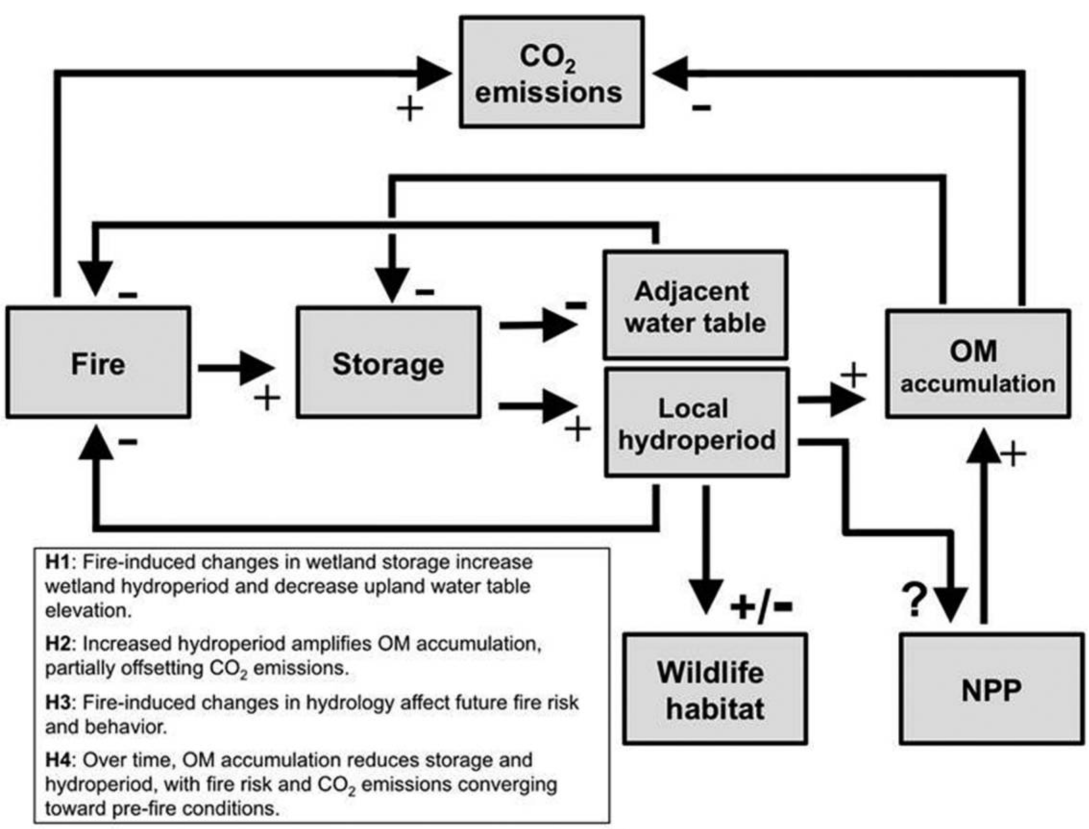

Figure 2. Influence diagram and implicit hypotheses about the relationships among fire, hydroperiod, water storage, and organic matter (OM) storage in wetlands with organic soils. Ground fires in wetlands with organic soils may have complex relationships to wetland depth and hydroperiod, net primary productivity (NPP) and OM accumulation, atmospheric emissions, and habitat for some wildlife species.

creased net organic matter (OM) accretion because of lower soil respiration rates (Fig. 2, H2). Moreover, increased local hydroperiod should reduce future fire risk, with concomitant effects on OM storage, whereas fire-induced changes in adjacent hydrology (e.g., reduced upland water table) may have different consequences for fire risk and behavior in surrounding areas (Fig. 2, H3). Net OM accumulation is also determined by net primary productivity (NPP), but because the effects of fire on NPP may vary (NPP may decline because of increased hydroperiod and anaerobic stress or increase in response to nutrients liberated by fire), the re-accumulation of organic soils is difficult to predict. The presence of thick layers of organic-rich soils in many fire-prone wetlands suggests the likelihood that, in the absence of fire, OM accumulation will proceed. Therefore, we hypothesize that fire-induced deeper wetland areas are ephemeral over longer (centuries long) time scales and that the burned depressions eventually fill in as new organic soils essentially replace the organic C lost during combustion (Fig. 2, H4). Correspondingly, the fire return likelihood in wetlands will initially be low after fire (because of wetter conditions) but will increase with time and OM accumulation.

Understanding and modeling the influences of ground fires on wetland habitat, landscape hydrology, ecosystem C balances, and fire return frequency can help guide management of ground fires in wetlands. Therefore, we applied and modified an existing wetland hydrology model to explore the local and adjacent hydrologic consequences of wetland fires (Fig. 2, H1) based on the wetlands of Big Cypress National Preserve, Florida, as a test landscape.

SIMULATION OF FIRE EFFECTS ON LOCAL AND ADJACENT HYDROLOGY

Test landscape

We explored the effects of ground fires on wetland water depths and hydroperiods, groundwater exchange between wetlands and uplands, and upland water table elevations in Big Cypress National Preserve (BICY; Fig. 3A). BICY is an ideal landscape for testing H1 given its high density of small wetland features, fire frequency, and distinct differences between wet- and dry-season weather and flooding dynamics. BICY, spanning ~300,000 ha, is situated on the low-relief, carbonate platform region of southern Florida and contains hundreds of distinct wetland forest patches dominated by pondcypress (Fig. 3B). These wetland features are either elongated strands or circular patches that tend to be separated by higher-elevation communities of slash pine (*Pinus elliottii* var. *densa* Little and Dorman) flatwoods, transitional pine rocklands, or graminoid prairies dominated by muhly grass (*Muhlenbergia capillaris* Lam) or sawgrass (*Cladium jamaicense* Crantz). These pine or prairie communities typically experience natural or anthropogenic prescribed fires every 2 to 6 y (Abrahamson and Hartnett 1990, Snyder et al. 1990), with the former type occurring most often during the onset of the region's rainy-season thunderstorms in the late spring. Precipitation drives regional hydrology, which follows a strongly seasonal pattern. Frequent inundation and occasional sheet flow occur during the wet summer months, during which 70% of rainfall occurs (Duever et al. 1986). The wet season is followed by a dry season and retreat of water levels below the surface in all but the lowest elevations within marshes and swamps. Long hydroperiods in wetland depressions allow buildup of a layer of organic matter in the form of fibric peat, which can be >1 m thick in the centers of small depressional wetlands called domes because of their dome-shaped canopy structure. This characteristic structure probably is dictated primarily by hydrologic and edaphic factors (Kurz and Wagner 1953) and exaggerated by mortality and topkill from fires (Watts et al. 2012). During droughts, the peat accumulated in cypress swamps may dry sufficiently to support combustion (Ewel 1995), allowing the frequent upland fires to spread into cypress domes and to ignite smoldering peat fires. These peat fires are thought to occur ~1 to 5 times/century, depending on several factors including cypress dome size and elevation (Snyder 1991).

For our simulations of fire-induced changes in wetland hydrology, we selected landscape blocks across 3 regions of BICY that represent the range of depressional size, configuration, and extent found within the preserve. Landscape blocks included areas dominated by depressional wetlands embedded in a higher-elevation matrix of pinelands, hammocks, and shrubs (Fig. 3C), areas where depressions are relatively sparse in coverage and are scattered among extensive stands of small-stature pondcypress (Fig. 3D), and areas with intermediate coverage of cypress domes among pinelands (Fig. 3E).

Simulation model

To quantify the effects of ground fire depth and areal extent on hydrology, we modified a process-based model, developed by McLaughlin et al. (2014), of wetland and upland hydrology in low-relief landscapes dominated by geographically isolated depressions. The model simulates daily wetland stage and upland water table elevation based on a set of input variables and parameters including climate (rain and potential evapotranspiration [PET]), wetland and watershed geometries, and soil characteristics (Fig. 4). Therefore, this modeling framework is well suited for the low-relief, depressional landscape of BICY and allowed us to parameterize wetland configuration and climate with data from BICY while also modifying wetland bathymetry to simulate the hydrologic effects of fire on wetland hydrology. Here, we briefly describe the original model and

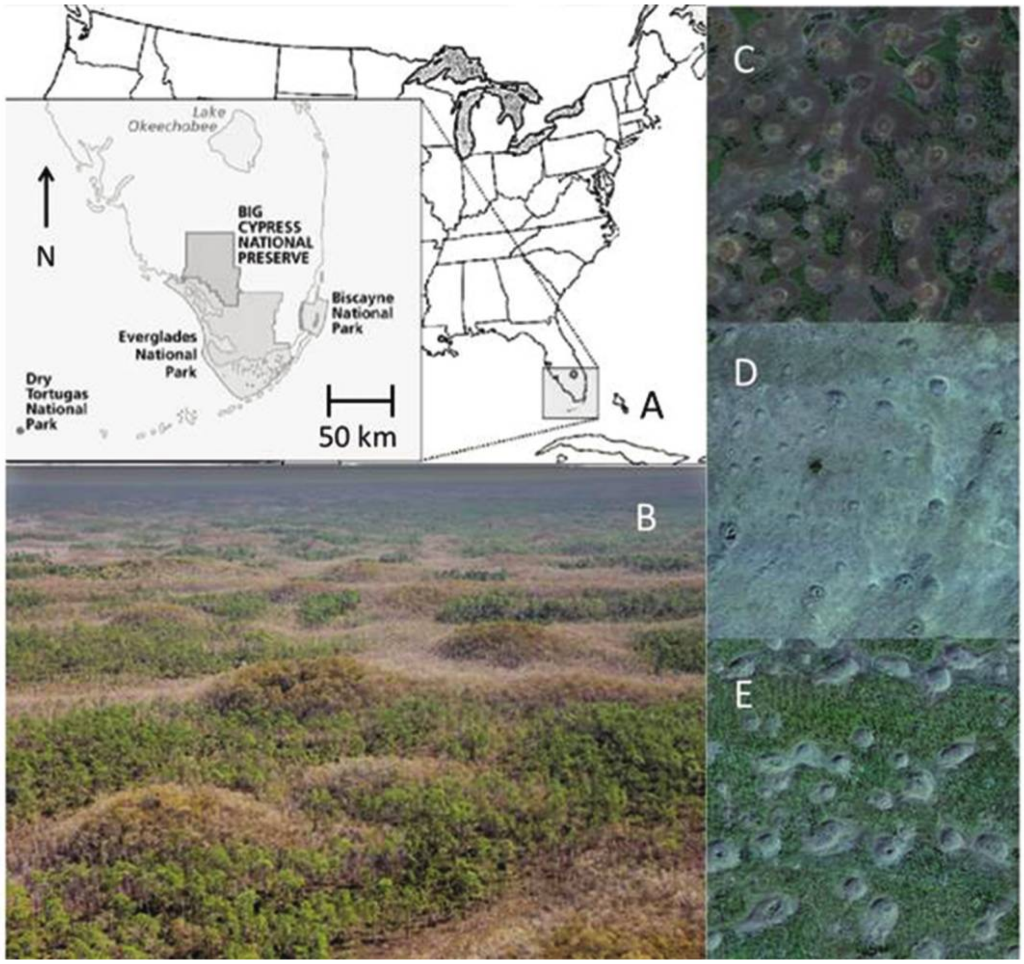

Figure 3. Map of Big Cypress National Preserve (BICY) in southern Florida, USA (A), and photographs illustrating the presence of many hundreds of small wetland patches distributed across the landscape (B) and in Deep Lake (C), Low Site (E), and Raccoon Point (F), 3 representative landscape blocks (Watts et al. 2014) used to parameterize the model of fire effects on wetland hydroperiod and water storage.

then discuss modifications and parameterization specific to the simulation of peat fire effects on local and adjacent hydrology in BICY.

McLaughlin et al. (2014) simulated the effect of varying total wetland area (%) and number of wetlands on water table dynamics in a generic landscape where all wetlands are cylindrical, have equal area, and are uniformly distributed (i.e., each wetland has the same watershed area). The model explicitly focuses on the ability of geographically isolated wetlands to buffer landscape water table dynamics through a water sink/source function that results from differences in specific yields (S_y) between upland aquifers and wetlands. S_y can be defined as the ratio of water input (rain) or output (evapotranspiration [ET]) relative to induced water-level change (Healy and Cook 2002). This parameter determines the sensitivity of water levels to atmospheric fluxes. Differences in the value of S_y between open water ($S_{y,ow}$ = 1.0) and groundwater systems ($S_{y,soil}$ = 0.1–0.35; Loheide et al. 2005) mean that upland groundwater levels respond more than wetland water tables to both precipitation and ET and that wetlands alternate between acting as sinks (groundwater inflow) and sources (outflow) of water to surrounding uplands during wet and dry cycles, respectively (McLaughlin and Cohen 2013). McLaughlin et al. (2014) used 1000-y simulations with varying wetland area and density, climate (daily rain and PET), and soil type to evaluate the degree to which this mechanism affects regional hydrology.

We parameterized this model for 3 landscape blocks in BICY (Deep Lake [DL], Low Site [LS], and Raccoon Point [RP]; Fig. 3C–E) based on the specific wetland configuration in each landscape block and used climate data collected over 22 y (1992–2014) at BICY. We restricted our focus to the wetland scale; i.e., we evaluated wetland and upland water table hydrologic regimes within 1 watershed–wetland complex for each block. We used landscape block area (22,500 m^2), total wetland area, and wetland number (Watts et al. 2014) to estimate a characteristic individual

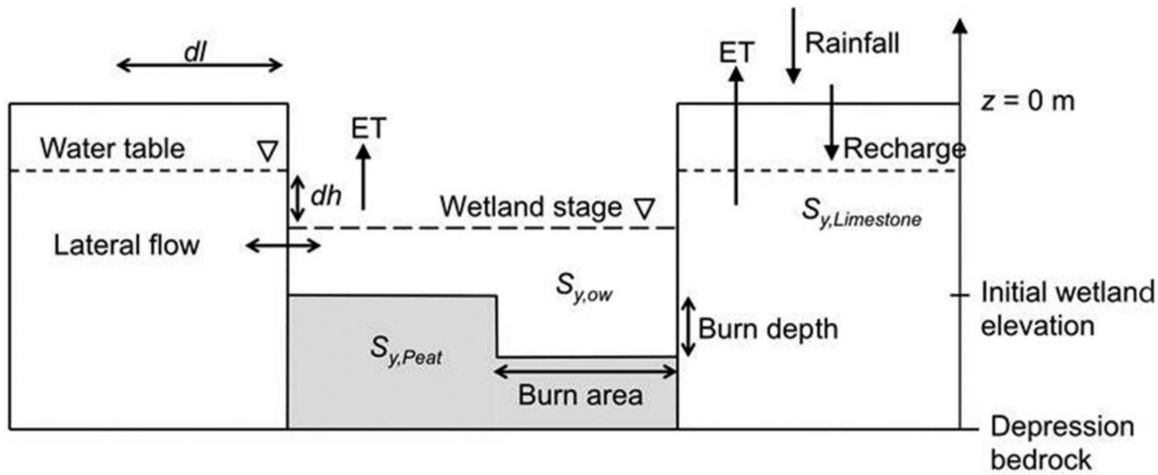

Figure 4. Cross section of simulated wetland and upland complex illustrating relevant parameters used in the model of fire effects on wetland hydroperiod and water storage. Burn depth and burn area are simulated at varying combinations of ranges (0–50 cm and 0–50%, respectively) and together determine the change in wetland storage and specific yield (S_y). $S_{y,ow}$ = specific yield for open water, $S_{y,Peat}$ = specific yield for peat, $S_{y,Limestone}$ = specific yield for limestone, ET = evapotranspiration, dh/dl = lateral groundwater flow from hydraulic gradient, z = elevation of the upland surface. Modified from McLaughlin et al. (2014).

wetland area and its surrounding watershed area for each block (Table 1). We used high and low modes from bimodal distributions of surface elevations in each block (Watts et al. 2014) to calculate representative mean wetland elevations (relative to upland surface, arbitrarily set to z = 0 m) for each block. Other parameters (saturated hydraulic conductivity [K_{sat}] of limestone and S_y values for limestone aquifer and wetland peat soil) were constant across simulated landscape blocks and were from various sources (Table 1). We obtained daily rainfall and PET rates in BICY for 1992–2014 from the South Florida Water Management District's online database, DBHYDRO (http://my.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu; station BIG CY SIR). We filled gaps caused by missing PET values with values from the nearby S78W station retrieved from the same database.

Two model modifications were required to represent BICY and to vary burn depth and areal extent. The original model included an upland vadose zone compartment that acted to reduce both water table recharge from rain events (resulting from soil moisture storage) and ET flux from the water table (from vadose-zone water use). However, uplands in BICY have thin soils (often <30 cm; Watts et al. 2014) that overlie highly permeable limestone, so vadose storage of infiltrating rainfall and vadose-zone contribution to ET are limited. Therefore, we removed this modeling component and set recharge equal to precipitation (i.e., all rainfall is delivered to the water table; Fig. 4). Removing the vadose-zone component also required a revised approach to simulating ET as a function of PET and water table depth. Following Shah et al. (2007), we modeled ET as an exponential decline based on water depth:

$$\frac{\mathrm{ET}}{\mathrm{PET}} = \begin{cases} 1 \text{ for } d \le d' \\ e^{-b(d-d')} \text{ for } d > d' \end{cases} \qquad \text{(Eq. 1)}$$

Table 1. Values for hydrologic parameters (saturated hydraulic conductivity [K_{sat}], specific yield [S_y]) for limestone and wetland peat soils and wetland configuration at each simulated landscape block in Big Cypress National Preserve. RP = Raccoon Point, LS = Low Site, DL = Deep Lake.

Parameter	RP	LS	DL	Source
Limestone K_{sat} (m/d)	275	275	275	Wacker et al. 2014
Limestone S_y	0.15	0.15	0.15	Bolster et al. 2001
Peat S_y	0.2	0.2	0.2	Sumner 2007
Area of landscape block (ha)	225	225	225	Watts et al. 2014
Number of wetlands	59	46	64	Watts et al. 2014
Total wetland area (%)	35	11	28	Watts et al. 2014
Mean wetland area (ha)	3.81	0.54	3.52	Watts et al. 2014
Mean wetland elevation (m)	−0.30	−0.15	−0.30	Watts et al. 2014

where d is water table depth, d' is transition depth (i.e., where ET/PET begins to decline from 1), and b is a decay coefficient. Values for d' and b were not available for limestone, so we used values published by Shah et al. (2007) for coarse sand soils (which have low capillary forces similar to limestone) and grasses (to simulate shallow rooting characteristic of BICY uplands).

The 2nd model modification consisted of refinements to allow simulation of different elevations within a wetland. The original model treated wetlands as cylinders with equal bottom elevation, whereas our goal was to simulate changes in wetland elevations resulting from varying depths and areal extents of burns (i.e., different elevations within wetlands). We retained the simplified geometric approach but allowed the wetland cylinder to have 2 different elevations, where the unburned area is at the initial wetland elevation (Table 1) and the elevation of the burned area is equal to initial elevation minus burn depth (Fig. 4). Having 2 different wetland elevations results in periods when only a portion of the wetland area is flooded, which required adjustments to the calculation of wetland S_y. In the model by McLaughlin et al. (2014), wetland S_y was set to $S_{y,ow}$ (i.e., 1) for flooded conditions and $S_{y,soil}$ for nonflooded conditions. However, under conditions of partial wetland flooding, wetland S_y is a composite determined by $S_{y,ow}$ of flooded areas and $S_{y,soil}$ of exposed wetland soils. Following McLaughlin and Cohen (2014), we assumed rapid water-level equilibration between flooded and exposed wetland areas and calculated a wetland S_y:

$$\text{Wetland } S_y = S_{y,ow} \times \left(\frac{A_I}{A_T}\right) + S_{y,soil} \times \frac{(A_T - A_I)}{A_T} \quad \text{(Eq. 2)}$$

where A_I is the inundated area and A_T is the total wetland area. Note that Eq. 2 results in Wetland $S_y = S_{y,ow}$ (1.0) when both burned and unburned areas are flooded (i.e., $A_I = A_T$) and yields a composite value when only the burned area is inundated.

Model modifications allowed us to simulate different combinations of burn depth and burn extent (i.e., percentage of wetland area that burns). Organic soil depths in BICY can be >1 m in depth, but we restricted simulated burn depth to 0 to 50 cm based on laboratory measurements of burn depth at varying moisture levels and a set of 134 samples collected from 34 cypress domes near the end of the 2011 dry season (Watts 2013). Simulations of burn extent were limited to a maximum of 50% of wetland, but greater areal extents are possible (e.g., the 2009 Deep Fire; Watts et al. 2012). Changes in wetland bathymetry from varying combinations of burn depth and extent resulted in different water storage potentials and wetland S_y, with potential influences to wetland and adjacent water table hydrology. We evaluated the effect of burns on wetland hydroperiod (HP = % time flooded), water depths in shallow (unburned portion) and deep (burned) wetland areas (Fig. 4), and water table elevations.

RESULTS

We used the modified model, parameters in Table 1, and daily rainfall and PET rates measured at BICY from 1992–2014 to simulate different combinations of burn depths (0–50 cm) and areal extents (0–50%) and evaluated resulting changes in the 22-y hydrologic regime of the characteristic wetland and its surrounding uplands in each of the 3 landscape blocks. In the following, the "unburned" case refers to the base case with no burn and, therefore, only 1 water-depth time series. "Burned" scenarios have 2 distinct elevations (Fig. 4), resulting in 2 water-depth time series: one for the burned portion (deep zones) and one for the unburned portion of the burned wetlands (shallow zones).

Simulated hydrology in all sites was characterized by strong seasonal water-level variation, with annual wetland inundation and drawdown (shown for the most extreme burn scenario [50 cm depth, 50% areal extent] at site RP in Fig. 5). This burn scenario is likely to be rare in BICY, but this simulation is useful for demonstrating the trends in hydrologic modifications. Simulated water depths and HPs in the unburned scenario (mean wetland water depth = −0.04 m relative to DBHYDRO data; HP = 51%) compared well with observed hydrology in BICY cypress domes (Everglades Depth Estimation Network; Telis 2006, ACW, unpublished data), but we note that observed data were from a shorter period (~1.5 y) of record than the simulation. Figure 5 also demonstrates the relatively small effect of fire when comparing water depths in the unburned scenario with those in the shallow (i.e., unburned) portion of burned wetlands. In this example, mean shallow-zone water depth in the burned case (50% extent, 0.5 m depth) was only 2.3 cm *lower* than in the unburned case, although daily depth differences of up to 50 cm between the 2 scenarios were observed for short periods. Deep-zone water-depth time series (not shown) were parallel to shallow-zone depths in the burned case but were offset by burn depth. For example, deep-zone water depths for the scenario depicted in Fig. 5 are 0.5 m greater than shallow-zone depths, yielding a mean deep-zone water depth *increase* of 47.7 cm in the burned wetland relative to the unburned case.

Beyond the extreme burn scenario outlined in Fig. 5, the effects of varying burn depth and extent on wetland hydrology across all sites follow a similar pattern and are summarized for site RP in Fig. 6A–F. As expected, greater burn depths and larger burn extents yield decreased mean water depths (Fig. 6A) and HPs (Fig. 6B) in the shallow zone because of increased overall storage in the system. In contrast, mean deep-zone water depths (Fig. 6C) and

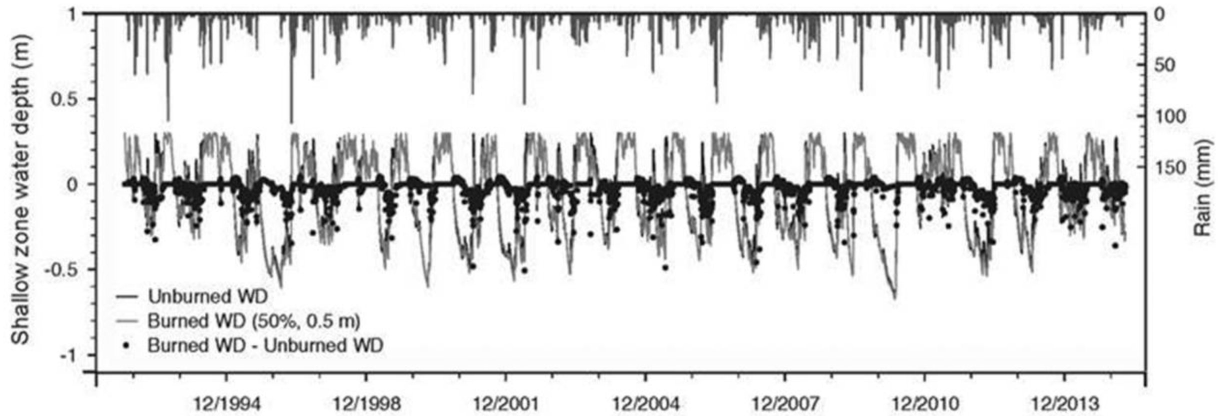

Figure 5. Simulated daily water depths (WD) in the shallow zones of unburned and burned wetlands based on daily climate data (1994–2013) from Big Cypress National Preserve. The most extreme burn scenario (burn depth = 0.5 m, burn extent = 50%) is depicted here to highlight trends and differences in fire effects between burned and unburned scenarios. Black dots denote daily differences in depths between the 2 scenarios.

HPs (Fig. 6D) all increased because of the lowered bottom elevation after fire. Notably, these increases are an order of magnitude higher than the decreases simulated in shallow zones. To understand the system-level effect of this combined deep-zone wetting and shallow-zone drying, we also calculated a composite HP as the area-weighted average HP (Fig. 6E). This composite HP illustrates the overwhelming effect of increased water depths and HPs in the burned portion of the system relative to decreased depths and HPs in the unburned portion. In short, the largest changes in wetland hydrology were still seen in the most extreme burn scenarios. Last, the total volume of groundwater exchange between the wetland and the upland (Fig. 6F) was greatest in the most extreme burn scenarios and lowest for the unburned case because longer hydroperiods and deeper water supported more frequent and greater magnitude of exchange.

Shallow- and deep-zone mean water depths and HPs (Fig. 6A–D) were all affected much more strongly by burn depth than burn extent, with only small changes in these metrics across different burn extents at the same burn depth. This pattern is the result of large changes in water depths resulting from modified bottom bathymetry relative to small changes in surface water elevations, which are caused by differences in overall storage between scenarios. In contrast, both burn depth and extent are important for composite HP (Fig. 6E), with the effect of burn extent increasing at greater burn depths. Groundwater exchange (Fig. 6F) shows slightly more sensitivity to burn extent than do shallow- and deep-zone depths and HPs but is also largely dominated by burn depth.

The direction and magnitude of fire effects on hydrologic metrics were similar across the 3 sites (shown in Fig. 7 as differences in hydrologic metrics between unburned and the extreme burn scenario simulated in Fig. 5 [burn depth = 0.5 m, burn extent = 50%]). For all sites, shallow-zone water depths and HPs decreased with fire, whereas deep-zone depths and HPs, composite HPs, and mean groundwater exchange all increased. Despite similar fire-induced changes in hydrologic metrics across sites, Fig. 7 suggests a systematic effect of wetland configuration. Sites in Fig. 7 are organized by increasing wetland area, with RP having the largest area. Burn effects in shallow zones (i.e., decreases in water depth and HP) and on groundwater exchange increased with increasing wetland area, whereas effects in deep zones (increases in water depths and HPs) and on composite HP decreased with increasing wetland area.

Last, fire-induced changes in wetland S_y and water storage affected groundwater exchange between uplands and wetlands, but the resulting influences to upland water table dynamics were marginal to negligible (data not shown). In all cases, mean water table elevation decreased with burn, but maximum changes were ~3 cm (<10% relative change). The influence to water table standard deviation (i.e., indication of buffering from wetland storage) was less systematic across simulations and even smaller (<2 cm).

DISCUSSION AND FUTURE DIRECTIONS

Our simulation results highlight the potential for interactive and complex effects of burn extent and depth on local and adjacent hydrology. Increased water depths and hydroperiods in burned wetland areas (Fig. 6C, D) can provide deepwater refugia, particularly during drought conditions. Following our conceptual model, these deeper, burned areas may have lower fire vulnerability but with higher OM accumulation rates compared with prefire conditions. However, fire also decreased water depths and HPs in adjacent unburned wetland areas (Fig. 6A, B), with the potential to drive the opposite effects on fire return likelihood and OM accumulation in these shallow-water habitats, although sim-

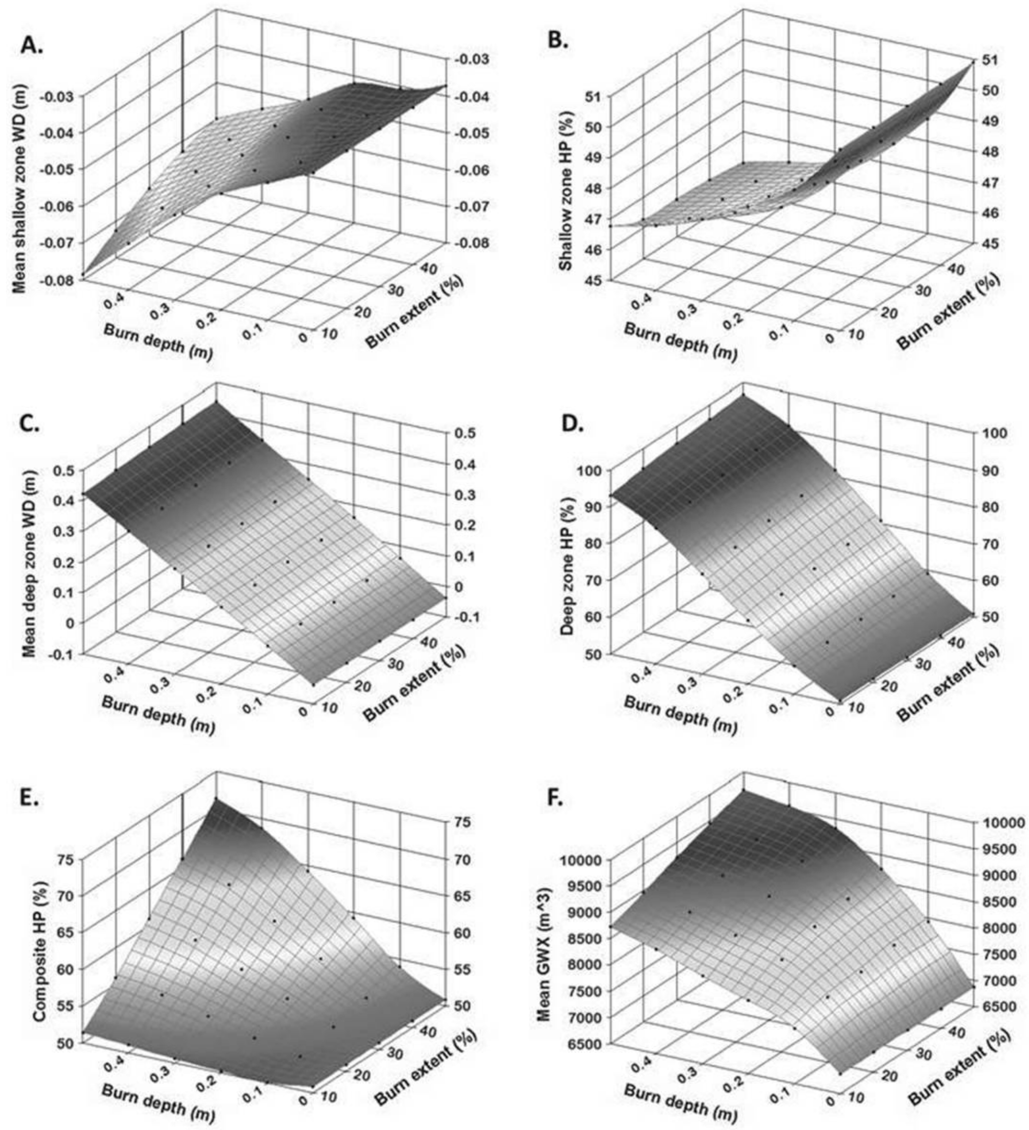

Figure 6. The combined effect of burn depth and extent on mean water depth (WD) (A) and hydroperiod (HP) (B) in the shallow zone, WD (C) and HP (D) in the deep zone, composite HP (E), and mean groundwater exchange (GWX) (F) between wetland and surrounding uplands.

ulated hydrologic changes were an order of magnitude lower in unburned vs burned portions of the wetland. Across a wetland, the composite (i.e., area weighted) HP increased across all burn scenarios (Fig. 6E). Thus, some trade-offs in shallow- and deepwater habitat may occur after a fire, but the primary ecosystem services ascribed to wetland inundation generally increased with increasing burn depth and areal extent.

Our simulations suggested that burning (and subsequent changes in water storage and wetland S_y) had a minimal effect on water table dynamics. This result is in contrast to results by McLaughlin et al. (2014), who specifically focused on the role of geographically isolated wetlands in buffering water table dynamics and found substantial decreases in water table variability with increasing wetland area and number. In contrast, we simulated different wetland bathymetries and compared effects in systems with a given wetland area, explaining the small relative changes in mean and standard deviation of water table elevation. However, we found that increased burn depth and extent substantially increased groundwater exchange volumes (Fig. 6F), with implications for solute exchange between aquifer and wetlands and associated biogeochemical processes. In addition, our model treats wetlands as cylinders surrounded by flat uplands with a spatially uniform water table elevation, limiting evaluation of potential drying effects and associated fire vulnerability in wetland–upland ecotones. Empirical observations of the

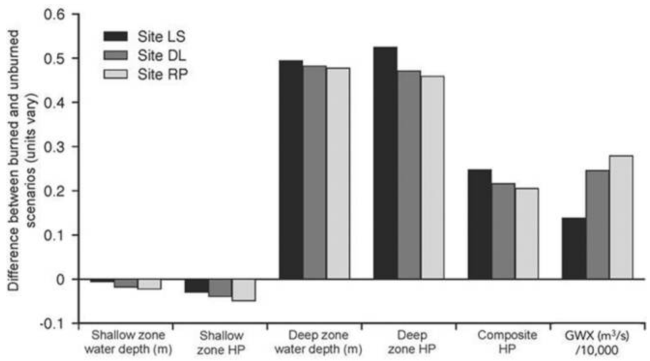

Figure 7. Difference in hydrologic metrics between unburned and burned scenarios for the 3 study sites (RP = Raccoon Point, DL = Deep Lake, and LS = Low Site). The most extreme burn scenario (burn depth = 0.5 m, burn extent = 50%) is shown to highlight trends in fire effects between burned and unburned scenarios. HP = hydroperiod, GWX = groundwater exchange.

hydrologic aspects of wetland fire effects on subsequent fire regimes of surrounding uplands are needed.

A shortcoming of our study that should be considered when interpreting simulation results is a general lack of extensive measurements of organic soil elevation change following fire, which is a common problem in studies of smoldering combustion because reliable prefire soil elevation data often are unavailable. The methods we used to predict potential values for soil elevation change resulting from fires during moderate to severe droughts correspond to ranges of values often observed in peat fires. Combining detailed measurements of the extent of combustion in 3 dimensions (areal extent and depth) would enable better parameterization and testing of our model's predictions.

Our attempts to simulate pyrogeomorphic effects on fire-prone landscapes with organic soil wetlands suggest an important role of fire in influencing hydrologic properties, such as wetland depth and hydroperiod. Previous investigators have acknowledged the role of fire in controlling wetland vegetation dynamics (e.g., Ewel and Mitsch 1978, Duever et al. 1986), but fire controls on wetland hydrology have not been well investigated. The influence of fire and effects on hydrology suggested by our results warrant further investigation on fire–hydrology interactions across a range of landscapes where fire and wetlands coexist.

This work is a first step in conceptualizing the various feedbacks among fire, wetland bathymetry and hydrology, and OM cycling and begins the exploration of these feedbacks with simulations of fire-induced changes in local and adjacent hydrology. Our conceptual model predicts hydrologic effects on habitat, fire vulnerability, and OM cycling. Future research should be focused on validating the changes in hydrology, developing realistic burn extents and depths, and empirically documenting the resulting changes in vegetative composition, NPP, and OM accumulation after fire. Measurements of peat depth in a variety of wetland types can be used to provide a range of minimum and maximum potential burn depths for peat fires. Soil samples analyzed for properties that influence smoldering potential (moisture content, mineral content, and bulk density) (Reardon et al. 2007) can be used with published models linking soil physical properties and depth of burn (Benscoter et al. 2011, Watts 2013) to generate burn-depth probabilities. Monitoring of wetlands and adjacent areas across a range of existing wetland bathymetries can provide the data needed to evaluate the hydrologic regime of these systems and confirm or modify our conclusions on the hydrologic implications of postfire bathymetric changes. Comparing groundwater exchanges and associated influences to upland groundwater levels across different bathymetries will allow us to model relationships between burn depth and adjacent hydrology. Last, the influence of hydroperiod on organic soil accretion can be quantified by measuring the balance between net ecosystem productivity and soil accretion by assessing above- and belowground biomass at different wetland depths and comparing these inputs with indicators of soil respiration (lignin content, C : N ratio, lignocellulose index). Although addressing these questions will require considerable time and investment, our work helps to highlight the potential consequences of soil-consuming fires and the importance of translating these and empirical findings into meaningful advice for natural resource managers.

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