Forest Ecology and Management xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Organic soil combustion in cypress swamps: Moisture effects and landscape implications for carbon release

Adam C. Watts

Fire Science Laboratory and School of Natural Resources and Environment, University of Florida, P.O. Box 110485, Gainesville, FL 32611-0485, USA

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Smoldering
Swamp
Peat
Cypress
Taxodium distichum
Ground fire

ABSTRACT

Swamps, peatlands, and other wetland ecosystems can store vast amounts of carbon in organically-derived peat soils. Wildfires during severe droughts can produce smoldering combustion in these soils, releasing large quantities of carbon to the atmosphere and causing dramatic changes at the local scale due to plant mortality and hydrologic effects. I studied variation in moisture content and carbon loss from smoldering combustion in soils from pondcypress (*Taxodium distichum* var. *imbricarium*) swamps in Florida USA. In a lab study, soil moisture content near the surface (upper 10 cm) did not predict vertical depth of soil combustion. Mass loss of organic carbon from soil profiles was, however, negatively related ($P < 0.01$). I also studied spatial variation in soil moisture, as a predictor of potential soil combustion, at a range of distances from edges of cypress-swamp patches. A weak, but significant ($P < 0.01$), positive relationship exists between distance from edges and upper-layer soil moisture, indicating that some inhibitive effect on smoldering may be present proceeding toward the centers of larger swamp patches. Conservative estimates of SOC content in cypress peats (approximately 41% by mass, compared to a figure of 50% sometimes used in such studies) indicate substantial potential for soil carbon loss (over 4 kg m^2) from wildfires in cypress swamps. This initial study on smoldering of cypress peats also makes recommendations for future efforts to study ground fires in these regionally important ecosystems.

1. Introduction

Extended droughts across large areas have contributed to headline-generating wildfires in recent years, including across large areas of North America (Mack et al., 2011; Leahy, 2012) and Siberian Russia (Doyle, 2010; Kramer, 2010). Severe droughts can create conditions sufficient for wildfire to spread into areas normally inundated or too wet to support combustion, which often contain soils with high organic content (De Groot, 2012). In addition to the flaming combustion associated with combustion of aboveground vegetation, ground fires can occur in which organic soils are consumed via smoldering combustion. The dynamics, controlling parameters, and consequences of ground fires are far less understood than their surface and aerial fire counterparts. Yet the ecological impacts posed by smoldering combustion to ecological processes as well as public health (Rappold et al., 2011) and safety (e.g., Abdel-Aty et al., 2011) are considerable, and may be expected to increase if ground fire activity grows in response to changing climatic conditions as predicted (IPCC, 2007). Thus an improved understanding of factors influencing smoldering combustion, as well as expanding the study of ground fires to more ecosystems in which they occur, will be important in a future marked by increased occurrence of wildfire and so-called "megafires" (National Interagency Fire Center, 2009).

In contrast to flaming combustion, which typically lasts a fraction of an hour at a given location, smoldering combustion is a flameless form of combustion that can persist for long periods (Ohlemiller, 1995). 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 Indonesia's anthropogenic Kalimantan peat fires in 1997 (Page et al., 2002; Usup et al., 2004) and the naturally ignited fire in Georgia's Okefenokee Swamp (burning in "muck" soils from 28 April 2011 until at least February 2012; Florida Times-Union, 2012). Despite typically lower temperatures for smoldering combustion compared to flaming combustion (500–700 °C versus 1500–1800 °C; Rein et al., 2008), smoldering fire persistence can eventually transfer more heat to surrounding soils and plants than flaming combustion (Kreye et al., 2011), and can produce significant ecological effects both because of the long residence time and their occurrence in the rooting zone (Rein et al., 2008), where plants have few adaptations to withstand fire. Sustained smoldering can occur in peat soils with far higher moisture content than those which would support flaming combustion in other fuel classes. Peat formed by accumulated *Sphagnum* spp., for example, may display persistent smoldering even at a moisture

E-mail address: acwatts@ufl.edu

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http://dx.doi.org/10.1016/j.foreco.2012.07.032

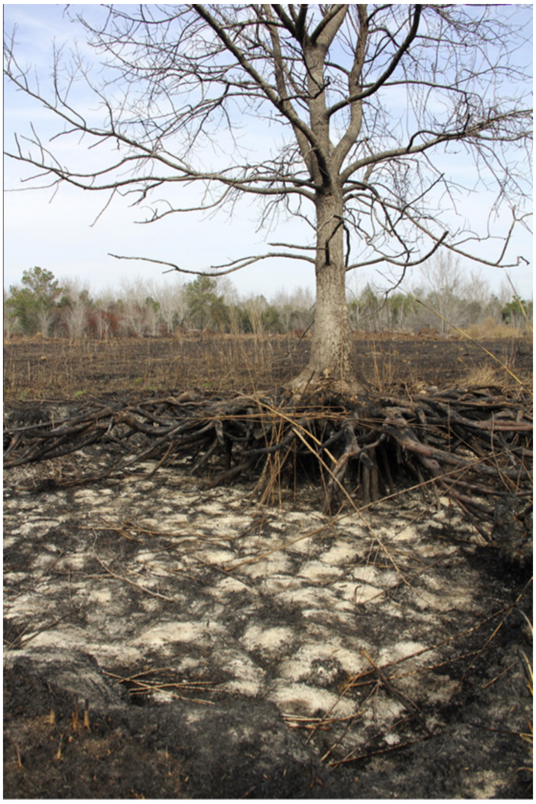

Fig. 1. Consumption of peat and other soils high in organic matter due to smoldering combustion can cause severe damage to trees by the removal of soil from the root zone. Additional effects of geomorphic change due to fire may be significant in areas of low topographic relief where these soils occur, as in this marsh in Putnam County, Florida USA.

content above 120% (Frandsen, 1997), and McMahon et al. (1980) found Florida organic soils to support smoldering at moisture levels of 135%.

The combination of heating, direct consumption of roots embedded in organic soils, and organic soil loss to combustion (Fig. 1) can result in significant damage and mortality to trees (Hartford and Frandsen, 1992; Stephens and Finney, 2002). In landscapes with low topographic relief, soil-consuming fires also may produce significant hydrologic consequences. Where subtle changes in elevation can significantly affect hydroperiod, vegetation communities or wildlife species may experience change due to the change in soil elevation from ground fires (Cook and Ewel, 1992; Watts et al., 2012). Ground fires could change the volume of depressional isolated wetlands, with hydrologic consequences for the surrounding landscape: given a set amount of water delivered to a landscape via precipitation or overland flow, greater depressional storage volume may provide increased water availability proximate to basins, while limiting availability to higher-elevation areas of landscape.

Implications of ground fires extend beyond local scales. Peat soils represent accumulation of plant biomass over many decades to centuries or longer, as flooded or otherwise anoxic conditions have retarded their decomposition. Ground fires may release far more carbon to the atmosphere than fires that consume standing vegetation alone (Langmann and Heil, 2004). Existing efforts to quantify the potential for carbon 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 who may be charged with preventing them or accounting for their effects on ecosystem carbon pools.

Future climate change scenarios predict drought events of greater severity and frequency in many areas, including those with the potential for ground fires to occur (Running, 2006; Liu and Stanturf, 2010). Despite studies of ground fire effects and behavior in Indonesian forests (Page et al., 2002), Canadian peatlands and boreal forests (Benscoter et al., 2011), and a handful of North American ecosystems (Reardon et al., 2007), many additional peat-based ecosystems (i.e., those occurring on soils with >30 cm of peat, Page et al., 2011) exist and are susceptible to ground fires. Our understanding of fire effects in these peat systems is nearly nonexistent. One example of regionally important ecosystems with peat soils in the southeastern U.S. and portions of Mexico are swamps dominated by cypress trees (genus *Taxodium*). Cypress swamps have long hydroperiods that promote development of organic soils, but occasionally experience severe droughts that expose them to the occurrence of ground fires as frequently as every 100–150 years (Snyder, 1991). The widespread occurrence of small (<10 ha) circular-shaped cypress swamps amid upland communities with frequent fire regimes provides ample potential ignition sources, making these embedded ecosystems good models for increasing our understanding of smoldering combustion and its consequences.

Vegetation structure, soil elevation, and severity of drought-condition wildfire in cypress swamps are influenced by landscape position, edge effects, and swamp size (Watts et al., 2012). Compared to their edges or adjacent upland communities, locations toward the centers of cypress swamps are cooler, more humid, and slightly lower in elevation, with taller and larger-diameter trees (Watts, 2012). The biophysical consequences of these spatially explicit factors—higher humidity, lower temperature, and decreased insolation due to larger canopies (Kira et al., 1969)—would appear to influence soil moisture, and therefore peat fuel availability and combustion (although increased evapotranspirative losses from larger trees may counteract predicted differences). Lower elevations toward centers of domes act as physical sinks for water and nutrients, and increased hydroperiods limit decomposition due to longer periods of anoxic soil conditions. Thus while landscape and structural factors might lead to the expectation of increased soil moisture toward the centers of desiccated swamp patches, nutrient-driven productivity increased and anoxia-limited decomposition may lead to higher biomass accumulation and levels of soil organic carbon (SOC) content with increased distance from swamp edges (but see Burns, 1984 for a conflicting view). Together, these factors may oppose one another in affecting the degree to which distance from swamp edge impacts peat fuels consumption in depressional cypress ecosystems.

This study investigates SM and SOC effects on smoldering combustion in extracted samples of peat from cypress swamps, and predicts consequences to soil carbon pools and modeled local hydrologic factors. Specifically, I address the following questions and predictions:

1. What are the influences of SM, mineral, and SOC content on degree of combustion of peat found in Florida cypress swamps? I predicted a strong negative influence of SM on depth of combustion and SOC combustion, and a positive influence of SOC on depth of combustion.
2. How do SM, mineral, and SOC values change according to swamp size, edge distance, and depth? Is it possible to use predictive relationships among SM and/or SOC values and soil consumption to determine whether potential combustion could vary according to landscape position within the swamp?
3. What are the implications of soil-consuming fires for release of SOC at the landscape scale?

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2. Materials and methods

2.1. Study site

In a low-relief, carbonate platform region of southern Florida USA, Big Cypress National Preserve comprises 300,000 ha, and contains many hundreds of distinct wetland forest patches dominated by pond cypress (*Taxodium distichum* var. *imbricarium* [Nutt.]; Fig. 2a,b). These elongated strands and circular or teardrop-shaped patches (the latter technically fens) tend to be separated by higher-elevation communities of slash pine (*Pinus elliottii* var. *densa* [Little and Dorman]) flatwoods or transitional pine rocklands, or graminoid prairies dominated by muhly grass (*Muhlenbergia capillaris* [Lam]) or sawgrass (*Cladium jamaicense* [Crantz]). These flatwoods or prairie communities typically experience natural or anthropogenic prescribed fires every 2–6 years (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: with frequent inundation and occasional sheetflow occur during the wet summer months during which 70% of rainfall occurs (Duever et al., 1986), 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 allow buildup of a layer of organic matter in the form of fibric peat that can exceed 1 m in thickness over the region's calcareous soils in the centers of small depressional wetlands—called domes because of their characteristic structure, probably dictated primarily by hydrologic and edaphic factors (Kurz and Wagner, 1953) and exaggerated by mortality and topkill from fires (Watts et al., 2012)—and 2 m in thickness in larger strands or slough-swamps (Duever et al., 1986). During drought conditions, the peat accumulated within cypress swamps may dry sufficiently to support combustion (Ewel, 1995).

Mineral soils in the region are derived from shallow Tamiami and Fort Thompson carbonate rocks of Pleistocene age. The result-

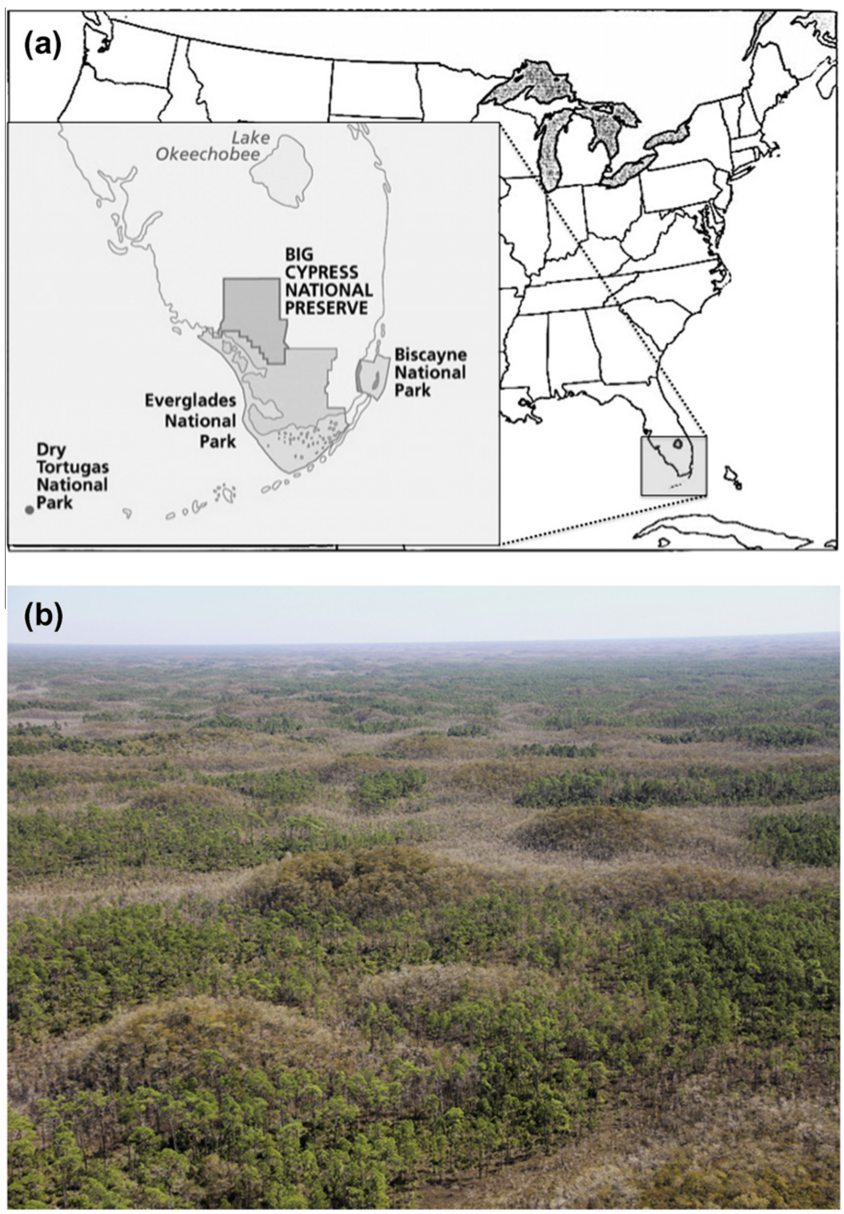

Fig. 2. (a) Big Cypress National Preserve in southern Florida comprises 300,000 ha containing a range of upland and wetland communities, including swamps of various sizes dominated by pondcypress (*Taxodium distichum* var. imbricarium). (b) In this image taken from approximately 250 m altitude, numerous cypress swamps are apparent due to their dome-like canopy shapes; the surrounding landscape is comprised of frequently-burned slash pine flatwoods. This configuration is typical of large areas of the preserve.

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ing calcareous mineral soils contain ca. 20% insoluble material (primarily quartz; A. Watts and J. Martin, *unpublished data*). In upland communities adjacent to cypress swamps these soils are very thin, often occurring only within crevices in exposed carbonate rock. Despite very shallow landscape relief (ca. 5 cm/km mean north–south bed slope), these soils occur in thicker deposits in the bowl-shaped depressions in which cypress domes occur. Over these mineral soils lies accumulated organic matter, which may occur as histic epipedon near edges of swamps or fibric peat in thicker deposits, which are still quite shallow in comparison with peats from boreal regions or some areas of the tropics (e.g., Page et al., 2011). An abrupt transition typically exists between organic and mineral horizons, yet quartz sand and carbonate particles occur in the soil profile due to bioturbation and sediment transport from surrounding uplands (although contribution from the latter is likely minor due to minimal transport velocities). These mineral inclusions in the peat profile would be expected to exert a negative influence on combustibility, as described by Frandsen (1987) and Reardon et al. (2007).

2.2. Sample collection and combustion

In May and June 2011, near the end of a historic drought and active wildfire season in the region, we collected 14 cylindrical, monolithic samples of fibric peat profiles from cypress domes within the Preserve for lab combustion experiments (Figs. 3 and 4). Samples were collected by cutting a ca. 20 cm-diameter circle into the soil profile, and inserting a waxed-cardboard tube until the encompassed profile included the extent of organic-derived soil.[1] Intact cores were then excavated with a shovel, protected in vapor-barrier containers, and transported on ice to a cold room where they were stored at 1–2 °C pending combustion. The position of each sample within a circular pondcypress dome was recorded, and the distance to the edge of the community recorded.

The day prior to combustion, these peat monoliths were removed from cold storage to allow equalization to ambient lab temperature (24 °C), which was set to match within 1–2 °C of diurnal temperatures found in soils during sample collection. Monoliths were placed in aluminum trays and the waxed-cardboard sleeves removed. We assessed soil moisture by collecting subsamples from each monolith collected at three depth ranges: 0–10 cm, 11–20 cm, and 21–30 cm. The 10 cm stratifications were determined based on the preponderance of small roots to approximately this depth, and following the methods of Reardon et al. (2007). Samples were then dried to constant weight at 70 °C; subsequently, these subsamples were combusted in a muffle furnace at 500 °C for 8 h to determine loss on ignition (LOI), the relatively low combustion temperature being preferred in the instance of soil with significant calcareous mineral content, as higher temperatures could introduce error due to mineral content contributions. Change of organic carbon content based on furnace or smoldering combustion was calculated using the equation

$$\mathrm{SOC} = (0.40 \pm 0.01 * \mathrm{LOI}) + (0.0025 \pm 0.0003 * \mathrm{LOI}) \quad (1)$$

where SOC = soil organic carbon (expressed as percent), and LOI = -loss on ignition (Craft and Seneca, 1991); i.e., the loss of mass in an oven-dried soil sample subjected to complete combustion.

Vertical sides of the cylindrical monoliths were wrapped in a layer of 8 cm fiberglass insulation; in addition to supporting sides of the sample and preventing collapse during combustion, the insulation reduces convective and radiative heat loss during combustion and better simulate *in situ* conditions (Reardon et al., 2007; Benscoter et al., 2011). Wrapped samples were placed outside in a wind-sheltered location on a day when forecast conditions conformed to those typically found in their parent locations near the end of the dry season, which is the typical wildfire season (i.e., 32–34 °C, 30–40% relative humidity, calm wind). The ignition source for smoldering experiments was an electric heating element in a half-loop shape, with 500 W output (sufficient to initiate smoldering combustion in pilot experiments). The element was situated with the terminal portion embedded 4–5 cm into the soil profile (approaching the depth limit for sustained smoldering in duff, Miyanishi, 2001) along one side of the sample, and the remaining

[1] Actual diameter of samples varied according to interior dimensions of cardboard tubes, which measured 18.5–21.0 cm in diameter.

Fig. 3. Each peat monolith collected from within cypress domes for combustion was 20 cm in diameter and ranged from approximately 20 cm to 40 cm in height. This typical sample illustrates the preponderance of small roots in the upper 10 cm of the profile.

Fig. 4. Typical cypress dome interior during severe drought conditions, showing the widespread occurrence of coarse woody debris. Branches from cypress, whose wood is famously resistant to decay, become incorporated into the upper layers of peat and can serve as ignition vectors for smoldering when ignited by passing flame fronts. Thickness of litter layer near the bases of cypress trees often is somewhat thicker compared to locations a few m away, where sampling was conducted in order to minimize inclusion of large roots.

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Fig. 5. The monolith sample collected from a pondcypress (*Taxodium distichum* var. *imbricarium*) swamp after ignition by an electric heating coil.

portion angled above the sample surface (Fig. 5). This arrangement simulated both the initiation of smoldering combustion via radiative heat transfer from flaming combustion (i.e. passage of the flame front through aerial fuels), as well as propagation of the smoldering front through the soil matrix (Rein, 2009) or via embedded solid fuels and conductive heat transfer (e.g. branches, roots). Current was applied to heating elements for 5 min to simulate the approximate burnout time of small branches which may serve as combustion vectors (and based on the Benscoter et al. (2011) study in boreal sphagnum peat), after which time they were carefully removed.

2.3. Post-combustion processing and data analysis

After samples had finished burning and had cooled, they were returned to the lab where they were weighed to determine mass loss due to combustion. Volume loss was calculated by determining change in height based on five averaged measurements of the post-combustion soil surface, based on pilot experiments indicating that combustion was not uniform in depth across the entire face of the monolith. To measure height of the resulting organic matter constituting the soil surface as opposed to the top of the resulting ash layer (which may be multiple centimeters thick depending on soil mineral content but which is highly porous and friable), a force of 1.5 N over a 1 cm^2 area was applied using a weighted dowel. Measurements of SM and OC content obtained for each sample for three profile depth ranges, and pre-fire volumetric measurements of monolithic soil samples, were used in conjunction with dry bulk density measurements at corresponding depths to estimate SOC storage within each soil profile "layer." SOC loss due to smoldering combustion was calculated using sample mass loss and measurements of SM and OC from the three 10 cm-thick "layers" analyzed from each monolith sample. Regression analyses were performed using data from the monolith combustion to determine relationships, if any, between combustion depth or volume or mass loss and hypothesized predictor variables of soil moisture at various depths (Sokal and Rohlf, 1995, p. 455). Models were compared using Akaike's corrected information criterion (Burnham and Anderson, 2002; Crawley, 2007) to compare model performance.

To permit characterization of SM under typical field conditions and organic carbon content in relation to landscape position and profile depth, a second set of 134 samples were collected from 34 cypress domes. Samples were collected at a variety of distances from community edges and at four depths (0–5 cm, 6–10 cm, 11–15 cm, and 16–20 cm) at each location. To reduce possible diurnal effects on soil moisture, all samples were collected during a 3-h period (1200–1500) on two subsequent days during which temperature and humidity profiles were nearly equal, and precipitation had not occurred for at least one month prior to sampling. Upon collection, samples were placed in vapor-barrier bags and transported on ice to a laboratory where they were analyzed for field moisture content (i.e., weighed, then oven-dried at 70 °C to constant weight and weighed again). These samples were then burned in a muffle furnace at 500 °C for 8 h to determine organic matter loss. Change of organic carbon content was calculated using Eq. (1). To determine whether soil moisture values or SOC content varied according to position with respect to patch edge (i.e., edge, center, or halfway between the two), landscape position was used as the basis for comparisons of these variables at each of the four depths sampled. Due to the presence of unequal sample sizes (e.g., some locations at edges were not sampled to 20 cm depth due to a lack of soil), Dunnett (1980) modified Tukey–Kramer multiple pairwise comparison tests were used; these tests account for unequal variance and sample size. Implementation of this procedure was facilitated by the DTK package in program R (R Development Core Team, 2005). Next, regression analyses were performed to determine the degree to which edge distance and profile depth predicted soil moisture or organic carbon content. Models developed from the combustion experiment were used to estimate the potential for carbon release and soil surface height changes given the snapshot of soil moisture values obtained from these samples.

2.4. Landscape extrapolations

Finally, a third set of volumetric core samples ($N = 21$) collected from a subsample of cypress domes were sectioned at 5 cm increments to determine bulk density and porosity for subsequent estimation of soil physical properties. To estimate potential implications for carbon storage and emissions, soil physical properties and relationships between combustion and variables measured in these experiments were extrapolated to the Big Cypress landscape. For this purpose, individual measurements were made of spatial attributes for three separate landscape blocks representative of community mosaics where fire-dependent upland ecosystems are juxtaposed with depressional wetland patches underlain by thick peat soil. Each block measured 1.5 × 1.5 km (225 ha), containing a total of 165 distinct patches (Fig. 6). Heads-up classification (Wolf and Dewitt, 2000) of 2.5 m resolution images from SPOT (Satellite Pour l'Observation de la Terre) was used for remote measurements of the sizes of individual domes based on community edges. Ground-truth testing using Wide Area Augmentation System (WAAS) enabled GPS in this area (Watts et al., 2012) indicated high degree of accuracy (90–95%) of this method in both measurement of the area of landform depressions and in the co-occurence of easily-discernable community boundaries with organic soils of ca. >5 cm thickness. SOC on a per-m^2 basis for Big Cypress peat, based on monolith and volumetric samples, was used to estimate SOC at the landscape scale using remote measurements of dome area as proxy for the approximate boundaries of shallow peat soils. C release from smoldering was scaled to the landscape using these values and emissions modeled using results obtained from

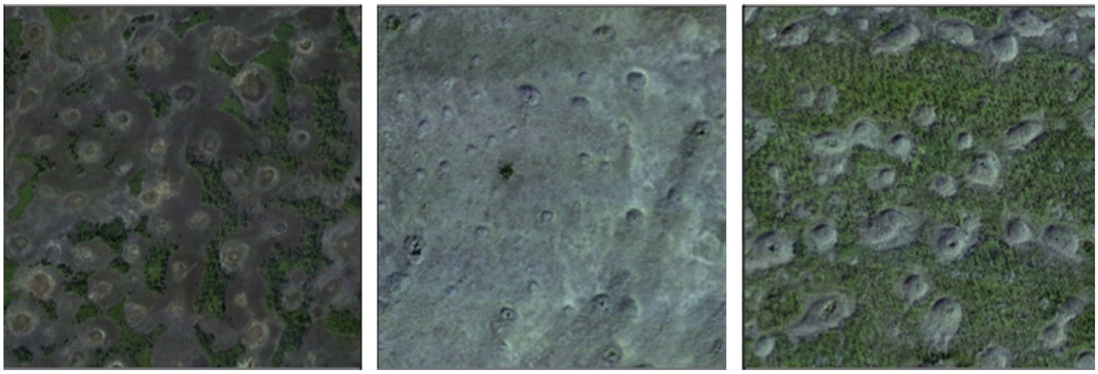

Fig. 6. Three square, 225 ha blocks representative of landscape configurations within Big Cypress National Preserve were selected for landscape-scale extrapolations of SOC release from smoldering fires. SPOT imagery viewed with Google Earth (Google, Inc., Mountain View, California, USA). From left to right: "Deep Lake" sampling block (26° 4′, 81° 14′; "DL" in Table 2), "Low Site" block (25° 55′, 80° 58′; "LS"), "Raccoon Point" block (26° 0′, 80° 56′, "RP").

smoldering experiments and mean SM values at upper and middle soil layers found among the from the 134 field-moisture samples.

3. Results

3.1. Monolith sample combustion

The 14 monolith soil samples ranged from 20–39.5 cm in pre-fire height. Subsample analysis indicated highly variable field soil moisture values, from a minimum of 36.4% in the upper 10 cm to a maximum of 268% at a depth of 11–20 cm in one sample. Pearson's correlation test performed on SM values observed at 0–10 cm depths and 11–20 cm depths found little relationship between the two (0.158), although SM at 11–20 cm was highly correlated (0.760) with SM at depths of 21–30 cm. Calculated SOC content as a percentage of profile-layer mass ranged from 4.75% to 36.25% (Table 1).

Smoldering combustion, initiated by the electric heating element, generally proceeded simultaneously outward from the element as well as downward, although these observations were not quantified by measurements. None of the predictor variables (soil moisture, SOC content, or mineral content), regardless of depth at which they were measured, were statistically significant predictors of soil consumption as measured by change in soil-surface height. When soil consumption due to smoldering was measured by SOC loss normalized to area, the best-fit regression model indicated significant negative relationships between soil moisture and consumption ($P < 0.01$). Addition of the soil moisture at depths of 11–20 cm, while not itself a parameter with significant predictive power, provided the best-fit model (Fig. 7):

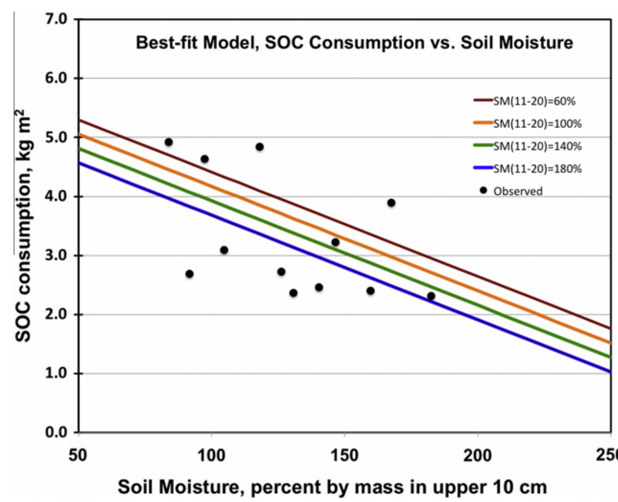

Fig. 7. Best-fit general linear model predicting carbon emissions from cypress peat soils (in kg m^2), incorporating soil moisture at 0–10 cm and 11–20 cm; predictions are shown for four realistic values of soil moisture in the 11–20 cm soil layer. Observations from the 14 monoliths from the study also are shown (in blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$SOC^* = -9.66 \cdot SM_{0-10} - 5.75 \cdot SM_{11-20} + 9897.8 \quad (2)$$

where SOC* represents SOC consumed, expressed as kg m^{-2}, and SM_{0-10} and SM_{11-20} are soil moisture values observed at depths of 0–10 cm and 11–20 cm, respectively.

Table 1
Soil moisture values and estimated organic carbon content for three portions of soil profiles, and overall combustion depth and normalized organic carbon loss for the 14 monolith soil samples.

Soil profile depth	SM (%)	SOC (%)	Mineral content (%)	Combustion depth (cm)	SOC loss (g cm^{-1})
0–10 cm	131.2 (51.4)	29.8 (6.7)	22.7 (9.8)		
11–20 cm	134.9 (58.1)	19.7 (7.7)	51.2 (19.1)		
21–30 cm	96.2 (36.3)	13.1 (8.6)	67.4 (21.3)		
Overall				8.9 (5.2)	0.785 (0.092)

Notes: SM: soil moisture content, % mass; SOC: soil organic carbon content, % mass; OC Loss cm^{-1}: calculated loss of SOC due to combustion, normalized to a cm^{-1} basis. values reported are means, with standard deviations in parentheses.

3.2. Landscape position, soil properties, and landscape extrapolations

A total of 134 samples from 34 cypress domes were collected to establish relationships between soil moisture and SOC. Soil moisture and SOC values displayed high variance, and groups of samples from a given depth did not differ significantly in moisture or OC content depending on where along the radial dome transect they were collected. Regression modeling indicated a significant predictive relationship between a given sample's distance from the dome edge (i.e., toward the dome's center) and soil moisture values found in the upper 10 cm of soil ($P < 0.01$; Fig. 8).

Values of soil moisture down the soil profile found from these samples in the upper 10 cm of soil (mean 105.8%, s.d. 60.8) and in the layer at 11–20 cm deep (mean 82.2%, s.d. 50.4), and the best-fit model of SOC consumption based on monolith combustion, allowed estimations of potential SOC loss under scenarios of

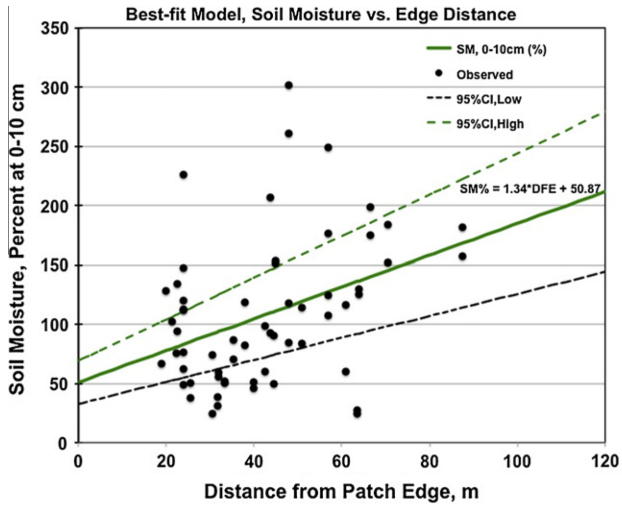

Fig. 8. Best-fit generalized linear model (in green) of 134 samples from 34 domes describes soil moisture in upper 10 cm of soil (the best predictor of SOC release from smoldering) as a function of distance from patch edge (i.e., moving toward patch center). Upper and lower 95% confidence bands shown in dashed green and black, respectively. In the model equation, SM% = percent soil moisture; DFE = distance from edge, in meters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Estimated area of peat soils in three 225 ha landscape blocks, based on ground-truthed remote measurements of individual community patches. Potential consumption of SOC due to smoldering combustion in peat soils is calculated for each landscape block given mean soil moisture values observed at 0–10 cm and 11–20 cm depths from 134 samples, using soil monolith combustion model (Eq. (2)).

Landscape Block	Number of cypress domes	Mean (s.d.) dome size, ha	Depression area, ha (%)	Mean estimated SOC consumption Mg
DL	60	0.47 (0.31)	28.11 (12.5)	1175.0
LS	45	0.25 (0.35)	11.02 (4.9)	460.6
RP	60	0.58 (0.42)	34.89 (15.5)	1458.4

Notes: "Depression area" is measured area of depressions estimated to contain combustible, shallow peat soils within each landscape block; area is expressed as estimated area in ha and percent of the total 225-ha area of landscape blocks.

observed soil moisture values across the landscape (Table 2). Given the range of observed soil moisture conditions, and variance in estimations introduced by varying peat depth and moisture by landscape position modeled peat SOC combustion are predicted between 2.78 and 5.55 kg m^2 (with a value of 4.18 kg m^2 based on sample means) in the peat soils of cypress domes. Based on the landscape area comprised of peat soils, widespread fires that ignited soils under these conditions of soil moisture could release large quantities of SOC during smoldering combustion.

4. Discussion

Although expectations of this study were that smoldering consumption in peat soil could be represented by height change and predicted by soil moisture or inorganic mineral content (Frandsen, 1987, 1997), this study could not establish a relationship between these predictor variables and depth of burn. This finding may have been due to variations in physical properties such as bulk density and porosity among upper layers of soil samples, which can affect smoldering due to impacts on heat transfer and air flow. These variables were not measured in the monoliths collected for combustion, and future studies should attempt to incorporate them to determine their relative influence on peat smoldering. While an effort was made to collect samples that did not contain large roots or embedded coarse woody fuels (i.e., larger than approximately 25 mm diameter), their undetected presence in samples could have contributed to the formation of combustion vectors and (once consumed) air pipes (Rein et al., 2008) causing variation in combustion depth. Additionally, mineral content for 21–30 cm layers was near the limit for sustained smoldering combustion in organic soils, particularly given the moisture values observed. The combination of mineral and moisture content for the 11–20 cm layers also was near this lower limit (J. Reardon, personal communication); under these marginal conditions it may be that the measured changes in soil surface incorporated sufficient uncombusted mineral ash that depth of burn measurements were decoupled from organic matter combustion. Findings from this study do refine our understanding of the moisture levels at which cypress peat will experience smoldering combustion, however: five samples underwent sustained smoldering at moisture levels above 150%. The wettest sample displayed 9 cm of combustion depth despite a moisture content of 250%. It is worth noting that observed SM values in the upper layer of soil samples bore little correlation to those at lower depths: factors such as plant rooting depths and evaporation are likely to be among the explanations for this unexpected observation.

Soil organic carbon released due to smoldering combustion was predicted by soil moisture content in the upper 10 cm of soil samples, with SM at depths of 11–20 cm improving regression model performance without itself being a significant predictor. This finding may have been due to the majority of samples experiencing consumption only of the upper 10 cm of soil (and an additional two samples with combustion depths of 11–12 cm, where moisture levels may have resembled those in the upper layer). SOC content could provide an alternative means of assessing combustion in soils where variations in soil physical properties cause problems for estimating soil height change *in situ*. Additionally, estimating combustion effects more explicitly in terms of SOC loss may help to reduce some of the uncertainties related to scaling issues that result from landscape-wide studies of smoldering. For example, rather than assuming a homogeneous depth of burn across a large burned area in order to estimate C emissions (e.g., Page et al., 2002) and then deriving C emissions from those parameters, known or inferred pre-fire soil data—even estimates available from remote-sensing assets, such as drought index, or SM estimates based on weather information—could assist in refining assessments of the carbon impact of large peat fires. Combining spatially-explicit estimates of important determinants of combustion such as SM and SOC with values for mineral content and peat texture, of they are known, would be a particularly valuable improvement over previous scaling attempts.

Soil moisture values in the upper 10 cm of soil profiles, a significant predictor of SOC release, increased with increasing distance from the edge of a wetland forest patch toward its center. This landscape position trend was weak, however, with no significant difference found based on whether a given sample originated in the center of a cypress dome, at its edge, or midway between. Therefore a weak edge distance effect may present some problems for scaling up C emissions from smoldering combustion across the landscape, where the center portions of larger patch sizes may mitigate the effects of drought (the extent to which this effect may depend on soil elevation is unclear). However; the snapshot of soil moisture values observed in this study may permit a first-order approximation of the potential for C release from smoldering combustion in the cypress peat soils of the study area's patchy landscape. On a given day when moisture conditions display similar means to those observed among the set of 134 field-moisture samples, C release potential from smoldering combustion of soils alone is modeled at a normalized 4.18 kg m^{-2} in cypress domes.[2]

This estimate is not without errors associated with landscape scaling of laboratory measurements, particularly due to the heterogeneous nature of fire events (and especially ground fires). However, this figure may be conservative in its estimation for a number reasons: first, samples were collected as far as practical from trees, in order to avoid problems of sample collection caused by the presence of large roots close to trees. Because litter and duff often collect in greater amounts close to the bases of trees, it is likely that samples collected from these locations would possess greater depths of low-mineral peat; including such estimates in an analysis would probably increase estimates of combustion potential at larger spatial scales. Also, Rein et al. (2008) describe areas closer to trees as likely to experience higher levels of soil consumption, due to the withdrawal of water by roots (and see Fig. 1). Also, soil samples for landscape-level SM estimations were collected in late April, and the study area remained under a drought for nearly two more months. The potential for soil consumption would be considerably higher as the dry season approached its end; indeed, the 2011 Jarhead Fire (14,000 ha) entered every cypress dome within the fire perimeter, in some cases consuming >1 m of accumulated peat. The widespread presence of coarse woody debris (Fig. 4), which can serve as ignition vectors, was not considered in this study. When these fuels are ignited by passing flame fronts and transition to smoldering, they can promote the initiation of smoldering. Then, as they are reduced to ash (often relatively quickly compared to surrounding peat), the channels they leave behind can become air conduits to support continued smoldering. While the ignition method (conductive heat transfer for an extended period) provided some simulation of this phenomenon, the contribution of these transitional fuels to smoldering and its maintenance should be considered in future studies. Finally, the conversion rate used in this study for calculating SOC for cypress peat soils (approximately 41%) is somewhat conservative compared to estimates of carbon concentration for various peat soils in studies surveyed by Page et al. (2011), which frequently exceed 50%.

Additional sources of uncertainty in this study include the inability of laboratory methods to replicate certain behaviors observed in smoldering of organic soils and peats. The progression of smoldering downward, sometimes leaving a thin upper layer of soil completely unconsumed, has not been reproduced in laboratory studies (G., Rein, personal communication). Likewise, the highly variable nature of combustion depths observed in many instances remain to be quantified in a spatially explicit manner. Because of the vast amount of carbon contained in these fuels, improving scaled estimates of combustion of organic soils and peats through the use of such estimates would reduce uncertainties associated with extrapolating to the extent of large burned areas. Also, the fate of combustion products is unaccounted for in this and most other studies of organic soil smoldering. While the majority of carbon from smoldering peat is converted to atmospheric CO_2 and CO, some emissions have been reported to reside in soils following combustion (e.g., Massman et al., 2010), while other organic carbon species may be formed and precipitated into unburned soil particles. An improved understanding of the partitioning of combustion products of organic soils would be a valuable addition to future estimates of atmospheric emissions from smoldering fires.

The approach described herein for estimating SOC loss from smoldering arrives at mean consumption of 4.2 kg m^{-2} in cypress swamps based on conservative estimates of peat depths away from the bases of trees; also carbon concentration estimates are at the low end of values used for peats, while values for soil moisture used in estimating potential combustion are probably higher than those found nearer the end of the region's dry season. Even with these conservative parameters, the consumption of SOC from smoldering in cypress peats in this study is estimated to be considerably higher than the 3.2 kg m^{-2} consumption estimated in boreal organic soils such as Canadian *Sphagnum* peat (B. Benscoter, personal communication).

5. Conclusion

Globally, organic soils and peats may store as much as 6.1×10^{17} g of terrestrial C, representing between one-fifth and one-third of the planet's terrestrial organic carbon (Gorham, 1994; Page et al., 2011). This is approximately the same mass of C as that contained in Earth's atmosphere, despite peatlands occupying only 3% of its surface. Effects of fires in these ecosystems are of concern due to their potential for enormous carbon release to the atmosphere: Kasischke et al. (2005) estimated annual C emissions from boreal forest and peat soils to be $1.1–2.1 \times 10^{12}$ g, for example. The contribution from smoldering combustion of organic soils to global releases of terrestrial carbon to the atmosphere may increase under scenarios of warming and drying climatic conditions (Gorham, 1991; IPCC, 2007). The implications for contributions of peat fires to the global carbon cycle and global warming scenarios are even more striking when one considers that smoldering combustion in peats may consume carbon that has accumulated over a period of hundreds to thousands of years, in comparison to carbon release during flaming combustion of fuels that have accumulated in aboveground biomass much more recently (i.e. years to decades, generally).

The role of soil moisture in determining the release of C from smoldering in cypress peat soils is of particular importance in regard to the global impact of ground fires. Even ground fires that are small in area have the potential for large carbon emissions, especially in some larger cypress swamps where peat deposits may reach 3 m. Seasonally variable hydrology found in the range of many cypress swamps and tropical peatlands places large quantities of soils at the threshold of availability for smoldering combustion during dry seasons and droughts. Because drought conditions also are a driver of large fires (Slocum et al., 2010), emissions from smoldering combustion in deep organic soils may display a geometric response to drought severity as fire size and spread through deeper layers of the soil profile. Increasing the challenges to managers tasked with dealing with such fires are the large volumes of water required to change soil moisture values at intermediate depths (e.g., beyond 20 cm and increasing moisture to >250%), which makes the effects of droughts on the potential for smoldering combustion long-lasting and resilient to precipitation.

While smoldering fires in organic soils usually do not pose the immediate danger to life or property characteristic of some so-called "mega-fire" events such as the 2009 Black Saturday fires in Australia (Adams and Attiwill, 2011), their effects are chronic at local and global scales. Impacts to human health and safety, and the possibility that ground fires may contribute measurably to and interact with global climate change, make these events worthy of increased research to improve our understanding of their

[2] The region's calcareous mineral soils also contain vast quantities of inorganic C. During combustion above approximately 900 °C the mineral structure of calcite and aragonite of carbonate minerals begins to break down, releasing inorganic C (Heiri et al., 2001); however, during the lower temperatures associated with smoldering combustion, mineral C is likely to be retained and liberation of mineral C should be minimal.

Please cite this article in press as: Watts, A.C. Organic soil combustion in cypress swamps: Moisture effects and landscape implications for carbon release. Forest Ecol. Manage. (2012), http://dx.doi.org/10.1016/j.foreco.2012.07.032

effects and management. Attention from the public and policymakers on "mega-fire" phenomena of recent years should likewise be drawn not only to dramatic wildfire events, but also directed at future scenarios of smoldering mega-fires which can involve ancient carbon and climatic effects.

In the future, improved sampling methods allowing for the continuous monitoring of soil-moisture content in relation to atmospheric and hydrologic conditions may improve our ability to observe changes in the potential for smoldering combustion in peat soils such as those found in cypress swamps. Additionally, accounting for the generation of pyrolyzed carbon (also known as "bio-char") may increase our knowledge of the ecological impacts and carbon-dynamics implications of smoldering fires, since pyrolyzed C may alter soil chemical properties (e.g., by increasing cation-exchange capacity, Liang et al., 2006) and reduce turnover times due to its recalcitrance (Certini, 2005). Methodological improvements to capture the spatial variability in smoldering combustion, which can vary widely across even small areas, will improve estimates of emissions as well as understanding of the ecological effects from smoldering fires. While many of these effects are commonly understood to be deleterious, in some cases peat-consuming fires may be beneficial for management objectives. One example of the latter is the lowering of accumulated soil heights during drought-condition ground fires to form deep pockets which can serve as refugia for wildlife or their aquatic prey during future dry periods. In southern Florida, these dry-season refugia may be important for wood storks (*Mycteria americana*) and the Florida panther (*Felis concolor coryi*), both of qhich are endangered (Cox et al., 2006; Fleming et al., 1994). Such an understanding of the ecological role of ground fires is needed as society determines whether certain potential ecological benefits are outweighed by the considerable negative human and environmental impacts of these slow-motion megafires.

Acknowledgments

This study was aided considerably by capable field and laboratory assistance from A. Kattan and M. Streiffel, and facility contributions by University of Florida's Fire Science Lab and Wetland Biogeochemistry Lab. J. Martin of the University of Florida Department of Geology kindly performed X-ray diffraction on mineral soil samples and provided data referenced herein. J. Reardon kindly provided advice on sample collection, combustion experiments, and comments on the results presented herein, and I am grateful to L. Kobziar, T. Martin, M. Cohen, G. Rein, and an anonymous reviewer for helpful comments on the manuscript. Funding for this project was provided by the US National Park Service Fire Ecology Program, and the Graduate Research Innovation Award administered by the US Joint Fire Science Program and Association for Fire Ecology. This study was conducted pursuant to NPS Research Permit BICY-2011-SCI-0006, and the cooperation of Big Cypress National Preserve staff J. Nobles, J. Turnbo and S. Schulze is appreciated.

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