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Factors affecting sustained smouldering in organic soils from pocosin and pond pine woodland wetlands*

James Reardon[A,B], *Roger Hungerford*[A] *and Kevin Ryan*[A]

[A]Rocky Mountain Research Station, Fire Sciences Laboratory, 5775 Highway 10 West, Missoula, MT 59803, USA.
[B]Corresponding author. Email: jreardon@fs.fed.us

Abstract. The smouldering combustion of peat and muck soil plays an important role in the creation and maintenance of wetland communities. This experimental study was conducted to improve our understanding of how moisture and mineral content constrain smouldering in organic soil. Laboratory burning was conducted with root mat and muck soil samples from pocosin and pond pine woodland wetlands common on the North Carolina coastal plain. The results of laboratory and prescribed burning were compared. Laboratory results showed that moisture and mineral content influenced sustained smouldering in root mat soils. Predictions based on logistic regression analysis show that root mat soils with an average mineral content of 4.5% had an estimated 50% probability of sustained smouldering at a moisture content of 93%, whereas at moisture contents above 145% the estimated probability was less than 10%. The odds that root mat soil will sustain smouldering decrease by 19.3% for each 5% increase in moisture content. Root mat soils with an average mineral content of 5.5% and a moisture content of 93% had an estimated 61% probability of sustained smouldering. The odds that root mat soil will sustain smouldering combustion increased by 155.9% with each 1% increase in mineral content. Root mat and muck soils differ in physical and chemical characteristics expected to influence smouldering behaviour. The formation of muck soil has led to increases in density, smaller soil particle size, changes in water holding characteristics and increases in waxes, resins and bituminous compounds. Muck soil smouldered at higher moisture contents than root mat soil. Muck soil at a moisture content of 201% had an estimated 50% probability of sustained smouldering, whereas at moisture contents above 260% the estimated probability was less than 10%. The odds that muck soil will sustain smouldering combustion decrease by 17.2% with each 5% increase in moisture content. Ground fire in the prescribed burns stopped its vertical spread in organic soils at moisture contents consistent with logistic regression predictions developed from our laboratory results.

Introduction

Decreased fire frequency in wetland communities on the US south-eastern coastal plain is largely the result of fire suppression, timber harvesting, and other human activities (Herman *et al*. 1991; Frost 2000). This decline has produced changes in species composition and plant community characteristics that subsequently affect fire behaviour.

Changes in plant community characteristics also influence the potential for organic soil consumption by fire. Through its interaction with hydrology, ground fire plays an important role in the creation and maintenance of wetland communities. Fire frequency changes in nutrient-limited wetland soils may affect decomposition and accumulation rates. Increases in organic soil accumulation above the average water table depth and associated plant community changes increase the likelihood of fire in these wetland communities (Christensen *et al.* 1981).

Fires that occur in wetlands, when the soil is saturated, may consume significant amounts of live and woody fuels and litter, with little organic soil consumption. These fires may result in limited hydrologic and vegetation community changes. In contrast, fires that occur in wetlands with organic soils that have dried due to evapotranspiration or drainage can result in substantial consumption of surface fuels and soil (Christensen 1981).

The interaction between fire and hydroperiod influences plant community composition by affecting species establishment, survival, reproduction, and growth. In North Carolina, pond pine woodlands and peatland Atlantic White Cedar forests are present on sites with similar organic soil thickness and hydroperiod. Pond pine woodlands are the result of relatively frequent fires, whereas the long-term persistence of Atlantic White Cedar is the result of regeneration after a catastrophic fire event that is followed by a long fire return interval (Weakley and Schafale 1991). Evergreen and deciduous Bay forests are also present on sites with organic soil thickness and hydroperiod similar to pond pine woodlands, and their presence may be the result of fire exclusion (Kologiski 1977).

The fire history of the south-eastern US coastal plain organic soils is preserved by charcoal deposition (Watts 1980; Whitehead 1981). Historically, peat fires were quite common and have played a significant role in shaping the landscape of the south-eastern coastal plain. Present day peat thickness throughout the region has been affected by past ground fire (Wells and Boyce

1953) and it has affected the depth of most histisols in North Carolina (Lilly 1981).

Ground fires are also responsible for the formation and maintenance of shallow peat-based marshes and lakes (Herman *et al.* 1991) and the origin of lakes adjacent to the peat deposits in the Croatan National Forest (Christensen *et al.* 1988).

In wetland communities, the degree of organic soil consumption is an important predictor of fire effects. The wide range of wetland community response to fire reflects variability in fire behaviour. High aboveground temperatures of relatively short duration are associated with flaming combustion, whereas lower temperatures of longer duration are associated with the smouldering combustion of organic soils. The long duration of smouldering combustion make ground fire a serious concern in prescribed fire and wildfire management of these wetlands.

Smouldering is a flameless form of combustion characterised by low temperatures of long duration (Ohlemiller 1995). To investigate structure and product safety, studies of smouldering processes have been conducted using cellulose and polyurethane foam materials (McCarter 1978; Ohlemiller *et al.* 1979; Ohlemiller 1995). These studies have established that, although the initiation of smouldering is dependent on fuel properties and reaction kinetics, the continued propagation of smouldering is controlled primarily by oxygen flow to the smouldering front. The smouldering rate of these materials under similar air flow conditions is comparable despite variation in the chemical nature of these fuels (Ohlemiller 1995). Smouldering tendency differences in cotton fabric and wood fibre were linked with water soluble and non-water soluble inorganic impurities (McCarter 1978). Although these studies have improved understanding of smouldering processes in organic materials, they have not considered duff or organic soils that are heterogeneous mixtures of organic and mineral components and moisture.

Several smouldering combustion studies have been conducted using commercial peat moss as a substitute for duff and organic soil materials (Frandsen 1987; Hartford 1989; Peter 1992; Hawkes 1993). These studies have identified the major factors influencing energy output and consumption in mixtures of organic and non-organic materials. The total heat produced (per unit mass) and the rate of consumption of the surrogate material is dependent on organic mass and moisture content (Frandsen 1987). Laboratory estimates of peat moss consumption rates of 1.5–3 cm h^{-1} were comparable with rates reported by Wein (1981).

Studies of smouldering limits conducted using peat moss showed that sustained smouldering was influenced by both moisture and mineral content (Frandsen 1987; Hartford 1989). These results were representative of the expected limits of other cellulose materials under diffusion-driven smouldering (Ohlemiller 1995). In addition, smouldering moisture limits are also sensitive to radiant energy from the flaming combustion zone. Increased radiant energy increases the moisture content at which smouldering is likely to be sustained (Hawkes 1993).

Other experimental studies of ignition or sustained combustion limits have been conducted using organic soils from a wide range of wetlands, and forest floor/duff from non-wetland sites (Hungerford *et al.* 1995; Frandsen 1997). The results supported the conclusions of previous studies conducted using peat moss. The likelihood of ignition or sustained combustion decreased with increasing moisture content and was dependent on the organic bulk density and the mineral content.

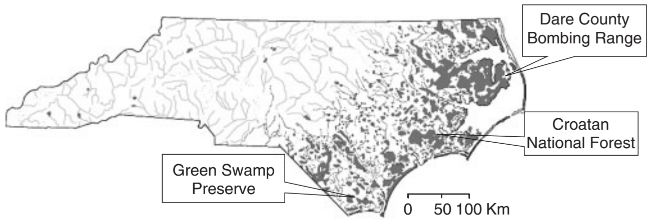

Fig. 1. Widespread distribution of wetlands and the location of sample sites on the coastal plain of North Carolina. (Adapted from Dahl 1991.)

The current study was conducted to improve our understanding of organic soil smouldering combustion limits, in particular the relation between mineral and moisture content. Laboratory burning was conducted with organic soil from sample sites on the North Carolina outer coastal plain. The laboratory results are compared to results from prescribed burns conducted by the Nature Conservancy and the North Carolina Department of Forest Resources in the Green Swamp Preserve in Brunswick County, North Carolina.

Study sites

Vegetation

The outer coastal plain of North Carolina is characterised by low relief and extensive forest and scrub-shrub wetlands. Pocosin and pond pine woodland wetland communities were selected for study because they are associated with deep organic soils. Low pocosin sample sites were selected on the Dare County Bombing Range (DCBR) and the Croatan National Forest. High pocosin sample sites were selected on the DCBR and the Green Swamp Preserve in Brunswick County, NC. Pond pine woodland sites were selected on the DCBR (Fig. 1).

The vegetation on the low pocosin sample site is dominated by low stature shrubs, such as zenobia (*Zenobia pulverulenta*), gallberry (*Ilex glabra*), and fetterbush (*Lyonia lucida*). Shrub height was less than 1.5 m and there was a low density of stunted pond pine (*Pinus serotina*). The productivity of this community is limited by low nutrient availability and long hydroperiod.

The vegetation of the high pocosin sample site is dominated by a taller more continuous shrub layer of gallberry and fetterbush, ranging in height from 1.5 to 3 m. In comparison with the low pocosin site, pond pines are more abundant and taller. Productivity of this community is also limited by the low nutrient status of the soils, but is greater than the low pocosin community primarily due to a shorter annual hydroperiod.

The structure of the pond pine woodland community is composed of an overstorey, midstorey and understorey. The overstorey is dominated by a closed or nearly-closed canopy of pond pine. The midstorey is composed of red bay (*Persia borbonia*) and loblolly bay (*Gordonia lasianthus*). The understorey is a discontinuous shrub layer, less than 3 m in height, that is dominated by gallberry and highbush blueberry (*Vaccinium corymbosum*). The productivity of this community is greater than either the high or low pocosin due to thinner organic soil layer and shorter hydroperiod. Soils of these sites are classified as medisaprist and histic humaquept, which is a mineral soil with a thick organic surface horizon. More descriptive detail of these communities can be found in Weakley and Schafale (1991). Photographs and fuel loadings of similar sites can be found in Ottmar and Vihnanek (2000).

Soils

The ground surface topography of the pocosin and pond pine woodland vegetation types is highly variable and is commonly described as hummock-and-depression microtopography. Hummocks are higher in elevation and are usually associated with tree and shrub species, whereas depressions are associated with an absence of woody vegetation. Individual hummock area is variable, but 0.5–0.9 m elevation changes are common in the transition from depression to hummock areas over distances of 1–3 m.

The soils present on the study sites are very poorly drained and formed in organic material over marine sediments. They have been classified as medisaprist, which are histisols comprised of highly decomposed organic material (Tant 1992). These soils are characterised by three major organic soil horizons of concern in fire management.

The surface organic horizon (Oe) of a typical soil is composed of needle, leaf and twig litter of intermediate (hemic) decomposition. This horizon is typically 0 to 10 cm thick, but its thickness is dependent on microtopograhic position. An intermediate horizon (Oa1) comprises highly decomposed material of granular structure. The thickness of this horizon is typically 0 to 30 cm, but thickness is dependent on microtopographic position. The lower horizon (Oa2) is made of highly decomposed organic material of massive structure. The thickness of this horizon is typically 25–127 cm (Tant 1992).

The vertical structure of the hummocks and depressions can be stratified into layers with different physical and chemical characteristics that affect smouldering combustion processes. The root mat is composed of the upper horizons of the soil profile. It is composed of both the intermediately decomposed litter layer (Oe) and the highly decomposed granular sapric soil of the Oa1 horizon. The average thickness is between 30 and 45 cm and is related to microtopographic position. It is thickest beneath the hummocks, and thinnest beneath depressions.

Under the root mat layer is the muck layer. It comprises highly decomposed Oa2 muck (sapric) soil horizon of variable thickness. In North Carolina the average thickness of the peat is 1.4 m, with depths ranging from 0.3 to 4.6 m (Ingram 1987).

Sample collection and experimental methods

The smouldering combustion limits of root mat and muck soils were determined from laboratory burning. Moisture content, mineral content, density, and fuel depth are among the variables that have been identified as important in smouldering combustion. There are significant interrelationships between these factors. Soil volume and density are dependent on moisture content because organic soils shrink and swell with moisture. Boelter (1964) and Ingram (1987) have reported significant correlations between bulk density and moisture content in organic soils. Undisturbed medisaprist soils from North Carolina lost from 64 to 81% of their soil volume in response to drying (Badr and Skaggs 1978).

Because organic soil horizons are a mixture of organic and mineral components, bulk density is sensitive to mineral content. The true bulk density of soils is a function of the mineral and organic components (Adams 1973). Due to the interrelationship of these variables, the factors included in the analysis of root mat soil were site, moisture content, and mineral content.

Previous work by Hungerford *et al*. (1996) with organic muck soils from Dare County and the Croatan National Forest showed low mineral content and limited variability. Estimates of smouldering potential conducted on muck soils from these sites found mineral content was not a significant factor influencing smouldering (Frandsen 1997). Only moisture content was included in the analysis of muck soils because of the low mineral content, limited variability, and lack of significance found in these previous studies.

Initial work by Frandsen (1987) and Hartford (1989) was conducted using the ratios of moisture and mineral weight to the organic sample weight. Later work by Hungerford *et al*. (1995) and Frandsen (1997) was conducted using gravimetric moisture content and mineral content based on total oven dry sample weight. This analysis was conducted using gravimetric moisture and mineral content calculated on a total oven dry weight basis. To determine the mineral content, the oven-dried samples were placed in a muffle furnace at 500°C for 24 h. Mineral content was calculated as the ratio of mineral (ash) content to total oven-dry soil weight.

Root mat soil samples

Root mat samples were cut from the soil surface with a minimum of disturbance to the soil structure. Samples were collected from the upper soil profile in each of the pond pine woodland, high pocosin, and low pocosin vegetation types. Owing to a high concentration of live roots, the sampling technique was ineffective on the Dare County high pocosin site, and sampling was limited. Additional high pocosin samples were collected from the Green Swamp Preserve. Samples were taken from both upper and lower layers in the low pocosin site. Frandsen (1997) was unable to collect cubical ($10 \times 10 \times 5$ cm) undisturbed soil samples on similar sites because these soils were sensitive to disturbance. Laboratory burning in that study was conducted with loose soil. The sample thickness in the present study was increased to 10 cm to maintain soil structure.

The upper layer samples were 0–10 cm deep and were composed of leaves, twigs, needles, partially decomposed litter, fine to medium roots, and fibrous peat. The lower layer samples from the 10–20 cm depths of the low pocosin site had less fine and live roots and had a greater proportion of highly decomposed peat.

Laboratory burning of the root mat samples simulated common field conditions during which an ignition source establishes a ground fire in the root mat and then continues smouldering into adjacent root mat soil. The root mat moisture treatment range of 25 to 175% used in the present study was based on previous studies with similar soils (Hungerford *et al*. 1995; Frandsen 1997). A 0–100% chance of sustaining combustion was expected in this moisture content range.

Mineral content and starting moisture content were determined for each root mat sample. Samples were then prepared to a standard size ($10 \times 10 \times 10$ cm) and water was added to bring them to the assigned treatment moisture contents. Treated samples were placed in sealed plastic bags and equilibrated at 20 to 21°C for minimum of 5 days before burning.

Burning was conducted in an open-topped box constructed of ceramic insulation material that restricted heat loss from the smouldering soil. Each root mat sample was exposed to a standardised ignition source that consisted of 10 g of dried peat moss. The peat moss was placed in contact with a lateral sample edge and ignited using an electric heating element. The electric power to the heating element was discontinued when the ignition material sustained smouldering. After contact with the smouldering ignition material, smouldering combustion of the sample was either sustained or failed. Sample response was recorded as either burned, which was characterised by significant or total consumption, or unburned, which was characterised by limited or no consumption.

Logistic regression analysis is commonly used in survival, presence/absence, and response/dose studies where the response can be reduced to two or more discrete levels (Hosmer and Lemeshow 1988). In the current study, logistic regression analysis was conducted to determine the probability of sustaining combustion in root mat and soil core samples. A 'burn or no-burn' dichotomous response was the dependent variable, and site, moisture, and mineral contents were used as the independent variables in the analysis of the root mat samples ($n = 99$).

The output from this analysis is expressed in two forms. The first is a functional relationship to predict the probability of sustaining combustion over a range of moisture and mineral contents. Because there is always a degree of uncertainty associated with burning under any conditions, this probability distribution is a practical method of quantifying the uncertainty of sustaining smouldering combustion. The output is also expressed in the form of an odds ratio. In the present study, this ratio approximates how much more- or less-likely it is for sustained combustion to continue with incremental changes in the amount of moisture or mineral content.

Muck soil samples

Forty-five soil cores were collected from the low pocosin, high pocosin, and pond pine woodland vegetation types. The samples were obtained from areas of intermediate microtopography and included both root mat and muck material.

Frandsen (1997) was unable to collect cubical ($10 \times 10 \times 5$ cm) undisturbed muck soil samples on similar sites because disturbance of the muck colloidal soil structure breaks the weak bonds between soil particles and results in a semi-liquid organic slurry (Lilly 1981). Laboratory burning in that study was conducted with loose soil. To maintain soil structure, muck samples in the present study were collected using 30.48 cm in diameter well pipe with a bevelled cutting edge to minimise disturbance of the sample soil structure. The sampling tube was driven into the soil to a depth of 30 cm using a slide hammer, and then each sample was excavated with hand tools. The samples were easily extracted from the sampling tube after limited air drying, because the soil volume was dependent on moisture content.

Laboratory burning of the muck soil samples simulated field conditions during which an ignition source establishes a ground fire in the root mat and then smouldering continues into muck soil.

During dry weather conditions it is common to have a dry root mat and wet underlying organic soil (Lilly 1981). The experimental design for laboratory burning of the muck samples included three moisture treatment levels and four replications at each level for each site ($n = 36$). The surface root mat layer of each core was dried using infrared heat lamps, and ignition was initiated by a propane torch and a propane radiant heater 38.5 cm above the core surface. The sides of the soil cores were insulated with ceramic insulation material to minimise lateral heat loss. Once smouldering was established in the root mat, the radiant heater was turned off and the ground fire was allowed to proceed until it either stopped burning or consumed the sample. Sample response was recorded as the percentage of the root mat and muck material consumed.

Moisture treatment levels for the muck soil core samples were based on previous work with soil samples from North Carolina (Hungerford *et al.* 1996; Frandsen 1997), and observed smouldering behaviour in these soils. The lowest moisture treatment category, 140% or less, was expected to result in the greatest likelihood of sustaining combustion and consumption of the largest amount of muck soil. The intermediate moisture treatment, between 150 and 225%, was expected to result in a 50% chance of sustained smouldering. The highest moisture treatment, between 250 and 300%, was expected to result in low likelihood of sustained smouldering and limited consumption of the muck soil.

The low moisture treatment muck core samples were dried at room temperature (20–21°C) for a period of 5 to 10 days, to a moisture content of less than 140%. Sample in the intermediated moisture range were saturated and air-dried over a period of 5 to 10 days, to a range of 150 to 225%. The highest moisture treatment samples were saturated, allowed to equilibrate for 3 to 5 days, and burned. Moisture content of each muck soil core was determined at the time of burning.

The significance of the relationship between moisture content and smouldering combustion of muck soil was tested using ANOVA. The dependent variable was percent consumption of the muck soil, and the independent variable was moisture treatment level. In addition, a predictive relationship between consumption and moisture content was developed using logistic regression. Cores with less than 50% muck consumption were classified as no-burn, whereas cores with greater than 60% consumption were classified as burned. One soil core with 56% consumption was eliminated from the analysis by excluding the consumption range of 50–60%. This analysis was conducted with a binary response as the independent variable, and site and moisture content as the independent variables to determine the likelihood of sustaining smouldering after ignition.

Prescribed burning

Burn plans were developed to evaluate the laboratory results of the current study. Paired prescribed burn units, which were ~1.6 ha in size, were established in the Green Swamp Preserve. The vegetation, fuels, and soil characteristics on the burn units were similar to the Dare County and Croatan National Forest sample sites. Owing to suppression concerns, ditches (3.81 m wide by 1.67 m deep) were dug around the perimeter of each burn unit for water control, and an additional 21.34 m of bladed and mowed fireline was constructed adjacent to the ditch.

Two burn treatments were conducted. The wet burn was conducted with fuel and soil conditions expected to consume live and woody fuels, but with a low likelihood of root mat and muck soil consumption. A dry burn was conducted under conditions also expected to consume live and woody fuels, but with a high likelihood of consuming 30 to 60 cm of root mat and muck soil.

Burn plans for the wet and dry units called for 1 h fuels moisture less than 20% and 10 h fuel moisture less than 25%. Wet burn conditions were dependent on soil moisture levels of greater than 300% at depths of 5 cm, and the water table near the soil surface. Dry burn conditions were dependent on soil moisture levels of less than 250% in the upper soil horizon, and the water table at least 30 cm beneath the surface. All burns were hand ignited in strips with drip torches.

Two water level monitoring instruments were placed in depression areas in the burn units before each burn. Water table depth measurements are in relation to the pre-burn depression ground surface. Soil moisture samples were collected from plots adjacent to two water table well sites and at four additional locations. Moisture samples were collected at 6 cm depths to a depth of 24 cm.

Because the root mat soil horizon thickness is highly variable, post-burn measurements of consumption are reported relative to microtopograhic position. To address differences in soil horizon thickness, consumption was measured as differences in pre- and post-burn relative elevation along 40 m transects. The root mat/muck soil interface was established at the lowest transect depression point. Root mat and muck soil consumption were calculated using the elevation differences relative to the interface. Azimuth, distances, and elevations of hummocks and depressions were measured. Measurements were taken using a Criterion 400 survey laser. This instrument is an integrated unit consisting of a laser range finder, an electronic flux gate compass, and a fluid tilt sensor.

The first prescribed burn was completed in September 1997. At that time, the soil moisture and water table depth suggested that there was a high probability of root mat consumption, and a low probability of sustained combustion in the upper muck level. A subsequent burn was completed on the paired unit in September 1998. At that time the soil moisture and water table depth suggested there was a low probability of root mat and muck consumption. This unit was reburned under similar wet conditions in September 2001.

Table 1. Sampling site mineral content characteristics

Study site	*n*	Min.–max. (%)	Mean (%)	s.e.
Low pocosin/upper	26	3.1–7.2	4.3	0.17
Low pocosin/lower	24	1.0–4.0	2.3	0.16
Pond pine/upper	30	1.4–5.6	3.1	0.20
High pocosin/upper	5	3.2–9.1	6.2	1.15
Green Swamp/upper	17	2.0–8.0	4.3	0.36

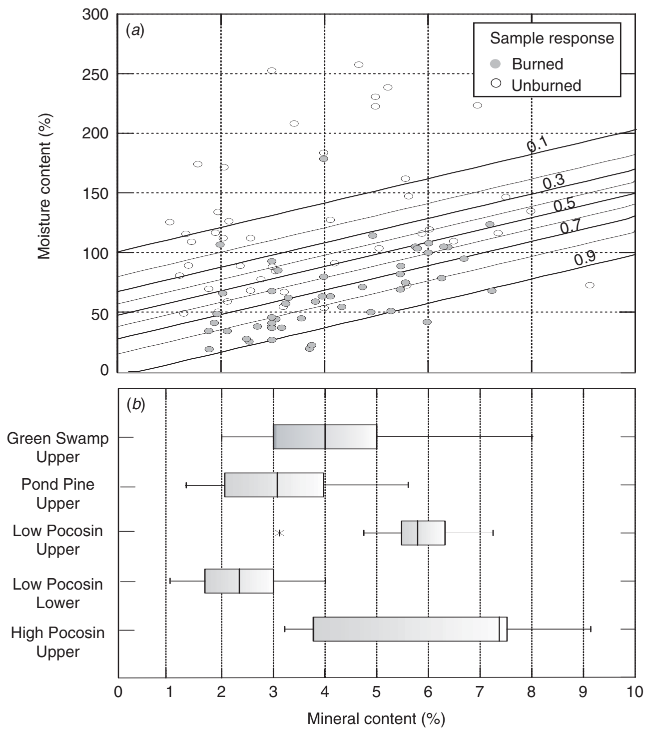

Fig. 2. (*a*) Contour surface fitted by the logistic regression of burned and unburned root mat sample response with moisture and mineral content. Increasing contour values (0 to 1) express an increased estimated probability of sustained smouldering in root mat soil. Open circles represent unburned samples and filled circles represent burned samples. (*b*) Box plots of sample site mineral content.

Results

Laboratory burning: root mat soil samples

The results show that the root mat soil had a narrow range of mineral content of 1.03 to 9.14%. There was overlap in the range of the mineral content between sites. The greatest mineral content and widest range of within-site variability was found on the DCBR high pocosin site, with a mean of 6.2% and a range of 3.2 to 9.1% (Table 1, Fig. 2*b*). The low pocosin site on the Croatan National Forest site showed a range in mineral content variability associated with depth. The mean mineral contents in the 0 to 10 cm upper layer and in the lower 10 to 20 cm layer were 4.3 and 2.3 respectively (Table 1, Fig. 2*b*).

Initial logistic regression analysis included site, moisture content, mineral content, and moisture × mineral interaction factors. The site and the interaction factors were not significant factors influencing smouldering limits and were not included in further analysis. Root mat burning response to changes in mineral and moisture content shows that the moisture content sensitivity of sustained smouldering is dependent on mineral content. Logistic regression produced moisture and mineral content coefficients that were significant at the 0.05 level (Table 2). Increasing moisture was correlated with a decreasing likelihood of sustained combustion whereas increasing mineral content was correlated with an increasing likelihood of sustained combustion:

$$\text{Probability of sustained combustion} = 1/[1 + \text{Exp}^{-(2.033 - 0.043 \times \text{moisture content} + 0.44 \times \text{mineral content})}]. \quad (1)$$

Table 2. Results of logistic regression analysis of root mat soil burn response with moisture and mineral content

Factor	Estimate	s.e.	*t*-ratio	*P*-value
Constant	2.033	0.768	2.649	0.008*
Moisture	−0.043	0.01	−4.375	0.000*
Mineral	0.444	0.167	2.66	0.008*

*Significant at the 0.05 level.

Table 3. Odds ratios from logistic regression analysis of root mat and muck soil burn response

Upper and lower bounds were calculated for a 95% confidence interval

Soil type	Factor	Odds ratio	Upper bounds	Lower bounds
Root mat	Moisture	0.958	0.97	0.94
	Mineral	1.559	2.16	1.12
Muck	Moisture	0.963	0.938	0.988

The samples with the highest mineral content were found on the DCBR high pocosin site. Predictions based on the logistic regression results show that root mat samples from this site, at a moisture content of 100% and an average mineral content of 6.0%, are expected to support sustained combustion 59% of the time (Fig. 2*a*). The lowest mineral content was found on the low pocosin site on the Croatan National Forest. Predictions show that samples from this site, at a moisture content of 100% and an average mineral content of 2%, are expected to support sustained combustion 19% of the time (Fig. 2*a*).

The root mat moisture content odds ratio represents a decreased chance that root mat samples will sustain smouldering with increase in moisture content. The root mat moisture content odds ratio shows that the change in odds due to an increase of 1% moisture is 0.958 (Table 3). The calculation of odds ratios at other moisture change increments is treated as a series of independent events. A 5% increase in moisture content will decrease the odds of sustained smouldering by $[1 - 0.958^5]$ or 0.193 (19.3%).

The root mat mineral content odds ratio represents an increased chance that root mat soils will sustain smouldering with an increase in mineral content. A 1% increase in the mineral content will increase the odds of sustained smouldering by 1.559 (155.9%) (Table 3).

Laboratory burning: muck soil samples

The ANOVA of the relationship between moisture treatment level and percent muck soil consumption was significant. Sample site was not a significant factor (Table 4). The consumption of the muck material was 100% when soil moisture was less than 140%. Soil cores with intermediate moisture levels between 150 and 225% had a mean consumption of 57.2%. The lowest percent consumption (23.8%) of soil was found when soil moisture was greater than 240% (Fig. 3).

The average mineral content of the muck soils was 3.4% and mineral content was not included in the regression analysis because of a lack of significance in Frandsen (1997). Initial regression analysis included both site and moisture content factors. Site was not statistically significant and was not included

Table 4. ANOVA results of the relationship of muck consumption and moisture content and sample site

Factor	Sum of squares	d.f.	*F*-ratio	*P*-value
Moisture	29 851.170	2	12.105	0.00*
Sample site	5931.868	2	2.406	0.11
Moisture × sample site	3025.445	4	0.613	0.65
Error	29 591.331	24		

*Significant at the 0.05 level.

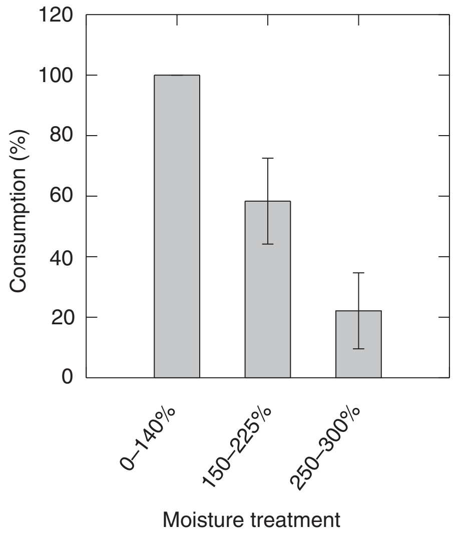

Fig. 3. Percentage and SE of muck consumption in relation to soil moisture treatment levels. Consumption of all samples in the 0–140% level was 100%.

Table 5. Results of logistic regression analysis of muck soil burn response with moisture

Factor	Estimate	s.e.	*t*-ratio	*P*-value
Constant	7.653	1.324	2.259	0.024*
Moisture	−0.038	0.007	−2.249	0.024*

*Significant at the 0.05 level.

in further analysis. Logistic regression of the soil core data produced a moisture coefficient that was significant at the 0.05 level (Table 5). Increasing moisture content was correlated with a decreasing likelihood of sustained combustion:

$$\text{Probability of sustained combustion} = 1/[1 + \text{Exp}^{-(7.653 - 0.038 \times \text{moisture content})}]. \quad (2)$$

The logistic regression predictions show that sustained smouldering in muck soils is most sensitive between 140 and 250% moisture content. Moistures below that range will consistently support combustion, whereas moistures above that range will not sustain smouldering. Predictions based on the logistic regression results show that muck material at low moisture contents of 140% are expected to support sustained combustion more than 91% of the time, while muck materials at higher moisture contents, between 250 and 300%, are expected to support

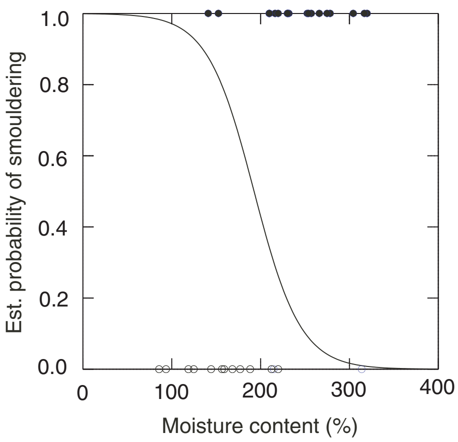

Fig. 4. Curve fitted by logistic regression of burned and unburned soil core response with moisture content. The curve expresses the estimated probability of sustained smouldering in muck soil in relation to moisture content. Open circles represent unburned samples and filled circles represent burned samples Increasing probability (0 to 1) represents an increased likelihood of sustained smouldering in muck soil.

sustained combustion less than 13 to 2 percent of the time (Fig. 4).

The muck soil moisture content odds ratio represents the decreased chance that muck soil will sustain smouldering with an increase in moisture. The muck soil moisture content odds ratio shows that the change in the odds of sustained smouldering, due to an increase of 1% moisture, is 0.963 (Table 3). A 5% increase in muck moisture content will decrease the odds of sustained smouldering by $[1 - 0.963^5]$ or 0.172 (17.2%).

Prescribed burning

Dry burn

Water table data for the Green Swamp dry burn unit shows that between May and late July of 1997 the water table fluctuated between 6.09 and 43.6 cm beneath the ground surface. On 16 July, when the water table depth was between 35.5 and 38.1 cm, root mat soils had an average moisture content of 250% at depths less than 25 cm. Muck soil samples taken at that time had an average moisture content of 364% at 25 cm depths.

There was no significant precipitation during the month of August or early September, and the water table steadily declined until the day of the prescribed burn (8 September), when it reached a depth of 66 cm. On the day of burning, soil moisture in the upper root mat from the surface to 6 cm was 84%, and the moisture of the lower root mat from 6 to 12 cm was 109.7%. The muck soil moisture between 12 and 18 cm had an average moisture content of 237%, and the moisture content between 18 and 24 cm was 254%.

Post-burn measurements at the soil moisture plots show total consumption associated with depression and hummocks ranged from 12.5 to 24 cm and 49 to 81 cm respectively. Post-burn microelevation transect measurements show muck soil consumption relative to the root mat/muck interface was 13.7 cm. The consumption of root mat soil was dependent on topographic position. The average root mat soil consumption associated with depressions and hummock surface features along the transect was 32.2 cm and 65.0 cm respectively (Fig. 5).

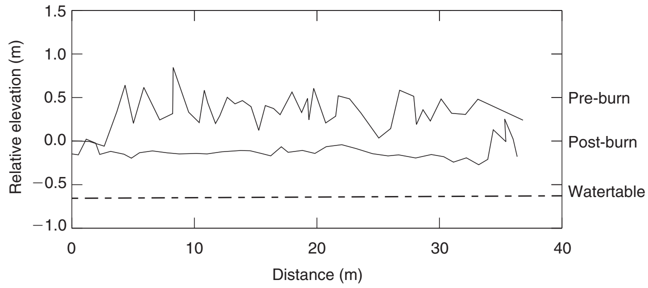

Fig. 5. Pre- and post-burn surface microtopography along an elevation transect established in the dry burn unit of the Green Swamp Preserve.

Differences in depression consumption between the soil moisture plots and microelevation transect were the results of sampling differences. The microelevation transects sampled a wider thickness range of depression features.

Root mat samples from the dry burn unit were higher in mineral content than the Green Swamp samples used in the logistic analysis. The measured mean mineral content for the surface to 15 cm root mat layer was 6.25% and the ranged from 1 to 9% and the mean mineral content for the 15–30 cm layer was 12.6%.

The predicted likelihood of sustained smouldering based on moisture content of the upper root mat material at 84% moisture and a mineral content of 6.25% was 74%. The predicted probability for the lower root mat layer soil at 109.7% and a mineral content of 12.6% was 94%. Although moisture content increased with depth, the predicted probability of sustaining combustion in the root mat was a function of increasing mineral content and increased with depth.

The predicted probability of sustaining combustion in the muck layers decreased with depth. The predicted probability of the 45–60 cm depths was 20% and the predicted probability of the 60–76 cm depths was 11.9%.

Wet burns

A wet treatment burn was conducted on 18 September 1998. At the time of burning the water table was between 30.4 and 38.1 cm beneath the soil surface. Soil samples collected on the day of burning show the mean moisture content in the 0 to 6 cm layer was 85.9%, whereas the mean moisture in the 6 to 12 cm layer was 144.5%. Assuming a mineral content of 4%, the predicted probability of sustained smouldering was 52.4% and 8.1% in the upper and lower root mat layers respectively. The mean soil moisture in the 12 to 18 cm muck soil layer was 250.9%. An estimate of the predicted probability of sustained combustion in the muck soil at the time of burning was 13%.

Post-burn measurements showed there was no consumption of root mat and muck soils at the soil sampling plot or along the established micro-elevation transects. Limited consumption of 4.0 cm or less was measured at insolated spots within the burn unit.

The wet burn site was burned again in September 2001. At that time the water table was near the surface and the root mat and muck soils were at saturation levels. Soil moisture from the surface to 6 cm depths was greater than 265%, and the soil moisture content at depths greater than 30 cm exceeded 337%. Assuming an average mineral content of 4%, root mat soils with a moisture content of 265% would have a probability of sustaining combustion of less than 1%. Muck soils with moisture content of 337% would also have less than a 1% probability of sustaining combustion. Post-burn measurements showed no consumption of root mat or muck soil.

Discussion

Previous experimental studies conducted using commercial peat moss as a surrogate for wetland soil found that organic mass, mineral mass, and moisture content were the dominant factors influencing smouldering combustion processes (Frandsen 1987; Hartford 1989). Moisture content has also been the focus of several studies of duff consumption in non-wetland forest communities, but the role of mineral content was not examined (Sandberg 1980; Brown *et al*. 1991; Miyanishi and Johnson 2002). However, Brown *et al*. (1991) did recognise the influence of mineral content on smouldering in thin duff. The results of the current study support the significance of both moisture and mineral content in smouldering organic soils from pocosin and pond pine woodlands in North Carolina.

The sustained smouldering of organic material is dependent on the balance between the energy released by the combustion process, and the energy required to continue combustion and vaporise the moisture present. Owing to the large amount of energy required to vaporise water, soil moisture is a significant heat sink during the combustion process and its evaporation is critical to sustaining smouldering. As a consequence, soil properties that influence water holding affect the smouldering behaviour of organic soils.

The water storage capacity of soils has been linked with increased organic content and the degree of organic matter decomposition (Boelter 1964; Dolman and Buol 1967; Stevenson 1974). Muck (sapric) soils are highly decomposed and have saturated moisture contents of less than 450%, hemic soils are intermediate in the level of decomposition and have saturation moisture contents between 450 and 850%, and fibric soils have a low level of decomposition and have moisture saturation contents greater than 850% (Collins and Kuehl 2001). Fibre analysis of peat samples from Dare County showed a wide range of decomposition levels; 54% sapric, 33% hemic and 13% fibric (Ingram 1987).

The water storage capacity of the root mat soil is influenced by the hemic needle, leaf and twig litter, and by the granular structure of more decomposed soil, whereas the characteristics of the muck layer are dominated by the massive soil structure and high decomposition level of the sapric material. The larger pore space of the root mat gives it a greater water storage capacity and infiltration rate at saturation than the muck soil. However, owing to smaller pore size associated with the massive soil structure the muck soils are more effective in retaining moisture.

Frandsen (1997) reported the smouldering moisture limits for organic soils as the moisture content with an estimated 50% probability of ignition or sustained combustion. The lowest mineral content soil, pocosin muck (sapric) soil from Alligator Wildlife Refuge in North Carolina, was reported to sustain smouldering at higher moisture contents than other low mineral content soils. Pocosin soils with a moisture content of 144% and an average mineral content of 2.5% had an estimated 50% chance of sustained smouldering, whereas less decomposed peat soils from Agassiz National Wildlife Refuge, Minnesota with moisture content of 64% and a mineral content of 9.4% had an estimated 50% probability of ignition. Higher mineral content samples of the organic soil horizons from a hardwood swamp site on the Okefenokee National Wildlife Refuge, Georgia at a moisture content of 81% with an average mineral content of 18.24% had an estimated 50% chance of ignition or sustained smouldering.

The results of the present study show sustained smouldering at higher moisture limits than reported in other studies (McMahon *et al.* 1980; Hungerford *et al*. 1996; Frandsen 1997). McMahon *et al.* (1980) reported that organic soil from Florida sustained combustion at a moisture content of 135%. Frandsen (1997) reported an upper limit of 160% for pocosin muck soil but also reported sustained smouldering at moisture contents between 224 and 300%. Predictions based on the results of the current study show muck soil with a moisture content of 201% had an estimated 50% probability of sustained smouldering and smouldering was observed at moisture contents as high as 270%. The results of the laboratory burning and prescribed burning support the higher moisture limits observed by Frandsen (1997).

Differences in ignition methods, sample size, and sample properties are important considerations in the comparison of the predicted moisture limits with the results of these other studies. Frandsen (1997) attributed inconsistent smouldering behaviour in the pocosin soils in the 224 to 300% moisture content range to sample preparation and ignition methods, and restricted his analysis to an upper moisture limit of 219%. In comparison with the results of the present study, the lower muck soil smouldering limits reported in Frandsen (1997) were most likely the consequence of the restricted moisture content range used in that study.

The results of the present study show that root mat soils with a moisture content of 93% and an average mineral content of 4.5% had an estimated 50% probability of sustaining combustion. The root mat moisture limits were consistent with results reported for other similar organic soil material (Frandsen 1997). The 93% moisture content is slightly lower than the 105% theoretical limit for peat moss at the same mineral content (Frandsen 1987). The moisture limit was higher than the limits of peat from Agassiz National Wildlife Refuge and hardwood duff from the Okefenokee Swamp, which were cited previously.

Previous studies of smouldering limits conducted with peat moss, organic soil, and forest floor duff have reported that the moisture limits of smouldering decrease with increasing mineral content (Frandsen 1987; Hartford 1989). The results of the present study show a positive relationship between the mineral content and the likelihood of sustained smouldering in root mat soil.

Frandsen (1997) reported positive mineral content logistic regression coefficients for three of his lowest mineral content sites but the significance of the coefficients was not discussed. The four lowest average mineral contents reported in that study were 18.1% in Feather moss and 12.4% in Sphagnum moss dominated soils from Tetlin Wildlife Refuge (Tok, Alaska), 9.4% in a peat soil from Agassiz Wildlife refuge (Thief River Falls, Minnesota) and 2.5% in pocosin muck soils from Dare County North Carolina. Positive mineral coefficients were reported for the first three sites and a non-significant mineral content coefficient was reported for the lowest mineral content pocosin site. The positive mineral content coefficient reported for root mat soils in this study is consistent with the values reported in Frandsen (1997) for other low mineral content soils. The results suggest that at low mineral contents, either the mineral component or other factors correlated with its presence may be linked to an increase in the likelihood of sustained smouldering in root mat soil.

Mineral input into these soils is limited to flooding by storms, deposition by wind or biological sources (Ingram 1987). Root mat samples in the present study showed a range of variability and a lack of relationship between vegetation type and mineral content. A similar finding was reported in a study of the peat deposit distribution in Alaska, where no correlation between mineral content distribution and vegetation type was found (Huck and Rawlinson 1982).

The role of mineral content in the smouldering process in root mat soils is not clear. Energy output of smouldering peat decreases with increasing mineral content (Ingram 1987), and decreases in energy available for combustion processes due to mineral content increases have been shown to lower the moisture limits that will sustain combustion (Frandsen 1987). In contrast, the addition of mineral salts of calcium and magnesium, which are common in plant material and soil, can act as catalysts in the oxidation of char and have been shown to increase the tendency to smoulder in wood fibres (McCarter 1978). Increases in total calcium concentrations have been reported in peat burns of southern Florida wetlands (Smith *et al*. 2001). Frandsen (1987) reported that because some inorganics may alter the combustion process, it is important to know not only the amount but also the type of inorganic content. Additional study is needed to determine the type of inorganic material present in these soils.

Relatively low amounts of calcium or magnesium are normally present in these organic soils, but higher concentrations of minerals may be possible due to concentration by past fires (Dolman and Buol 1967). Although all the study sites have burned in the past, the concentration of cations may be influenced by the severity, frequency, or time since last burning. The sites with the highest mineral content samples were the high pocosin site in Dare County and the low pocosin site on the Croatan National Forest. The high pocosin site that was burned by a wildland fire in 1981 still shows evidence of widespread ground fire. The root mat from the low pocosin site, which has been prescribed burned at regular intervals, contains visible char in the root mat.

Frandsen (1997) reported that pocosin muck soils sustained combustion at higher moisture contents than other low mineral content samples. The results of the present study support the previous findings. Highly decomposed muck soils will sustain smouldering at greater moisture contents than the less decomposed root mat soils at similar mineral contents.

The difference in ignition method between the root mat and muck soil samples is an important factor to consider in moisture limit comparisons as several studies have demonstrated relationships between duff consumption, moisture content, and the energy supplied by the surface fire (Sandberg 1980; Peter 1992; Hawkes 1993). Peter (1992) found the moisture content limits were not sensitive to low levels of additional heat, whereas Hawkes (1993) reported that at higher heat loads the moisture limit sustaining smouldering increased.

Low energy level ignition sources were used in the present study to ignite the root mat and muck soil. Smouldering combustion was established on a lateral side of the root mat samples, whereas smouldering was established in the muck soil core samples at the interface between the root mat and muck soil horizon. The smouldering or ignition of solid material is classified as either transient, and stops after the removal of the ignition source, or sustained, and continues until the fuel is consumed (Babrauskas 2003). After the initial ignition, the transient or sustained smouldering state of the soil was a function of the moisture content, mineral content, and soil properties. The results of prescribed burning were consistent with the estimated limits of both root mat and muck smouldering and suggest that the ignition methods reflect realistic field conditions.

The difference in sample depth between the root mat and the muck soil samples is also a factor to consider in comparison of the estimate moisture limits of the two soil types. Peter (1992) reported the minimum depth needed to support smouldering in peat moss was 2 cm, and Brown *et al.* (1985) found the relationship between duff consumption and moisture content was inconsistent when duff thickness was less than 2 cm. Smouldering moisture limits were also positively correlated with increasing fuel depth in peat moss over a 0–4 cm depth range (Miyanishi and Johnson 2002). Studies by Frandsen (1987, 1997) and Hartford (1989) conducted with peatmoss and organic soils assumed stable smouldering conditions at 5 cm depth fuel depths. Peter (1992) reported that moisture content limits were insensitive to increasing fuel depths of 5.9–8.4 cm with low additional heat loads, whereas Hawkes (1993) found that smouldering moisture limits decreased with increased fuel depths over a 3.5–14.0 cm range when smouldering conditions were supplemented with higher heat loads. Because these studies have focused on relatively thinner soil, the role of fuel depth in the smouldering combustion of root mat and muck soil that are characterised by different soil properties and depths of 45 to 60 cm and 152 cm respectively, is not clear.

Root mat and muck soils differ in physical and chemical characteristics expected to influence smouldering behaviour. Moisture content, mineral content, density, and heat content have been identified as important factors influencing sustained smouldering in organic soils and forest duff (Artsybashev 1983; Frandsen 1987; Hartford 1989; Hungerford *et al*. 1996; Frandsen 1997; Miyanishi and Johnson 2002). The formation of muck soil has led to increases in density, smaller soil particle size, changes in water holding characteristics, and increases in waxes, resins and bituminous compounds.

Hartford (1989) found that increased density and smaller particle size resulting from physical decomposition was correlated with decreases in the moisture limits sustaining combustion. The density of the undisturbed muck soils from similar sites decreased with depth, and ranged from 0.164 to 0.13 g cc^{-1} (Badr and Skaggs 1978). The muck soil bulk density was greater than the bulk density of the root mat samples, which ranged from 0.7 to 0.16 g cc^{-1}. In contrast with the results of Hartford (1989), the results of the present study show that the higher density muck soils sustained smouldering at higher moisture contents than lower density root mat soils. Because the smouldering limits are greater in muck soil, the results suggest that smouldering moisture limits are influenced by factors other than soil particle size and bulk density changes resulting from increased decomposition.

In addition to bulk density and particle size changes, decomposition and the formation of muck soil is also associated with changes in chemical characteristics that influence the heating value (Ingram 1987). Heating value is a measure of the amount of energy released per unit mass that is commonly used to evaluate energy resources and in peat soils. It is influenced by several factors including mineral content, botanical composition and bitumen content (Artsybashev 1983; Ingram 1987). An increase in the heat available to combustion processes would translate into an increase in moisture and mineral content smouldering limits; however, the potential increase in limits is balanced by changes in soil properties that affect the rate of heat release (Frandsen 1987).

Decomposition in North Carolina peat soils is correlated with increasing bitumen concentration, which is composed of waxes and resins (Skopec 1983). Smouldering at moisture contents of 500% in Siberian peat has been attributed to the high heat value and bitumen content of those soils (Artsybashev 1983). Hungerford *et al*. (1996) attributed higher smouldering limits of the pocosin muck soils to the higher heat content of the muck soil.

The results of the present study suggest that the higher smouldering limits of muck soils were the result of higher heating values and water holding changes resulting from decomposition and soil formation. However, additional study of the relationship between soil properties and smouldering limits is needed.

The results of the Green Swamp dry burn conducted in September 1997 show the interrelationships of water table and soil moisture in the root mat and muck. The soils in the present study are saturated several times each year when the water table is at or near the soil surface. In the month before the prescribed burn, the water table declined steadily. As the water table declined from July to September 1997, moisture content changes showed a faster drying rate in the root mat soils.

At the time of burning in September 1997, the water table depth was deeper than 66 cm. Field conditions were comparable to our controlled laboratory conditions. The root mat and muck soil moisture at that time matched our laboratory burning conditions, where a dry root mat layer with a high likelihood of sustaining combustion was above a wet muck layer with a low probability of sustaining combustion.

The measured consumption at soil plots and along the microtopographic transect were consistent with the predicted probabilities from the laboratory data. Ground fire consumed the root mat and stopped its vertical spread into the organic muck soil at depths where pre-burn moisture exceeded 250%. The 13.2 cm mean depth of consumption of the muck soil was significantly less than 66 cm water table depth at the time of burning.

Although there is substantial work in the western USA and Canada on the prediction of duff consumption, study of smouldering organic soil consumption in the south-eastern USA is limited. The belief that smouldering organic soils will consume soil to within inches of the water table (Christensen 1981) is currently the most common guideline in use by fire managers in North Carolina. The results of the present study do not support this conclusion, and show that the depth of consumption is dependent on the soil moisture profile, not the water table depth.

Prescribed burns were also conducted during wet soil conditions in September 1998 and 2001. In contrast with the dry burn, the water table was near the ground surface during these burns. These conditions were comparable to the controlled laboratory conditions using a root mat with a low probability of sustaining combustion and wet muck layer with a low probability of sustaining combustion.

Predictions based on the soil moisture content from the September 1998 field burn show the likelihood of sustaining combustion in the 0 to 12 cm root mat layer was 52.4%. The predicted probability appears higher than consumption measurements support. Mineral content measurements were unavailable for the 1998 burn, and the results suggest that the assumption of a 4% mineral content was high. Decreases in the assumed mineral content would lower the likelihood of sustained smouldering and reflect lower consumption rates. The predicted probabilities for lower root mat and muck soil were consistent with the low consumption. Smouldering combustion was limited to isolated locations in the upper root mat, and after ignition by an active spreading surface fire the root mat material would not sustain smouldering combustion.

Moisture content measurements of root mat and muck soil from the 2001 burn show that the predicted likelihood of sustained smouldering for both root mat and muck soils was lower than 1%. The predicted probabilities were consistent with the lack of organic soil consumption of this burn.

Forest duff consumption resulting from smouldering that was supplemented with the additional heat from surface fires was modelled by Peter (1992) and Hawkes (1993). The fuel loadings reported in those studies simulated fuel loadings of 50–100 t ha^{-1} and 66.0–128.9 t ha^{-1} respectively. The fuel loadings that characterised the Green Swamp burn were much lower, between 14.5 and 34.6 t ha^{-1}, and were dominated by 1 h fuels (Scott 1999). The results of the prescribed burning during wet conditions in 1998 and 2001 are consistent with the results of Peter (1992) and Hawkes (1993) and suggest that there was not sufficient energy from the surface flaming combustion to dry the upper root mat to moisture levels that would support smouldering.

Ground fire in organic soil is an important concern in the wetland management. It presents serious and expensive containment challenges, but is also an important process in the maintenance of diverse wetland communities. At present, tools for evaluating the potential for ground fire in these south-eastern United States wetlands are limited. The Keetch–Byram drought index, which is a cumulative index based on soil moisture and weather parameters, is commonly used to evaluate both surface and ground fire potential on regional and local scales. Indexes such as the Palmer Drought Severity Index (PDSI) and the Standardised Precipitation Index (SPI) have also been used to track soil wetness in North Carolina (Sims *et al*. 2002), but have not been related to ground fire risk. Undocumented guidelines are often used in fire planning and suppression and are based largely on managers' experience.

The utility of predictions based on the results of the present study are dependent on the measurement or estimation of moisture and mineral content distributions. Direct measurements produce localised estimates of soil conditions. The heterogeneity of the root mat soil properties complicates non-destructive measurement by commercially available moisture sensors, and destructive sampling appears the only practical alternative at this time. Owing to the homogeneity of muck soil properties direct measurement of muck soil moisture is possible using several commercially available soil moisture probes.

Several possible alternatives exist for larger scale moisture content estimation. Hydrological models such as DRAINMOD (Skaggs *et al*. 1991) have been developed and successfully used to simulate pocosin systems; however, the model inputs are complex and not readily available to fire managers. The National Fire Danger Rating system (NFDRS), which is based on weather measurements, is in wide use throughout the south-east United States. It provides regional estimates of burning conditions, but does not incorporate organic soil moisture in its predictions. Current studies are being conducted to relate NFDRS outputs, meteorological factors, evapotranspiration, and other factors to soil moisture dynamics on pocosin study sites throughout the North Carolina coastal plain (Bartlette *et al*. 2005).

Mineral content measurement and estimation is problematic. There are no methods to estimate mineral content in the field, and laboratory determination, although not a complex analytical procedure, requires a high temperature muffle furnace that is not commonly available to fire managers. The development of efficient mineral content estimation methods is dependent on an understanding of the type and source of soil mineral content.

The smouldering limit moisture and mineral content relationships developed in the present study are a tool for the evaluation of ground fire potential. Currently, mineral content information on these organic soils is limited, but the results of the present study provide a range root mat mineral content that is representative of similar North Carolina plain sites.

The smouldering of root mat and muck soils plays an important role in the creation and maintenance of wetland communities. The results of the present study show that smouldering in root mat soils is constrained by moisture and mineral content, and in muck soils is constrained by moisture content. The results provide a method for the evaluation of ground fire risk and are applicable to sites with similar soil characteristics.

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