Smoldering Combustion Limits of Organic Soils in the North Carolina

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ABSTRACT

This study focused on several subject areas to advance our understanding of organic soil smoldering and increase the potential management application of our results.

The smoldering combustion of organic soil is controlled by a number of interrelated factors including soil moisture, structure and chemical and thermal properties. Laboratory testing has shown the estimated moisture content limit at which smoldering is sustained in muck soil is greater than limit estimated for root mat soil. As expected soil moisture was a significant factor influencing smoldering in both soils but in root mat soil mineral content was also found significant. Little knowledge was available concerning the type of mineral and its distribution in the root mat soils on the North Carolina coastal plain. The results of this study show quartz sand was the dominate mineral in root mat soil on our study sites and was present in concentrations that were consistent with data used in the development of our estimated smoldering potential (ESP) model.

There was no significant difference observed in the heat output of the porous root mat and the denser muck soils. However, thermal analysis did show differences in the patterns of thermal decomposition of these soil horizons. The results suggest that soil structure and thermal decomposition differences strongly influence the smoldering limits of root mat and muck soils.

Laboratory testing showed a good to excellent fit in the ESP model's ability to discriminate between smoldering and non-smoldering conditions. In addition, prescribed burns were also conducted under a range of conditions to validate this model. Root mat and muck soil moistures of 170% and 270% respectively were used as a 'burn/no burn' decision threshold during these burns. Based on laboratory work a 5% mineral content was assumed for root mat soils.

The results were highly favorable. Six planned burns were conducted and five burns were successfully completed. Although residual smoldering was present on one burn, post burn examination showed that smoldering was primarily associated with fire line construction.

The results of the prescribed burning when compared with National Fire Danger Rating System (NFDRS) outputs showed that the adjective rating classes, Energy Release Component (ERC), the 1000 Hr. index and the Keetch-Byram Drought Index (KBDI) are insensitive to smoldering conditions. The latter two measures are commonly used to evaluate fire danger in these organic soils.

The practical application of the ESP model is limited by our ability to efficiently monitor changing soil conditions. Standard laboratory drying procedures are often impractical due to time and equipment requirements. Our laboratory results show drying time can be substantially reduced using microwave drying. Alternatively, automated data collection methods are becoming an increasingly attractive alternative due to decreasing costs and advances in cell phone technology. A prototype cell phone based sensor platform was developed and deployed to monitor pre burn conditions on our prescribed burn units.

Remote Sensing or satellite technology is an alternative to limited spatial/temporal scale soil moisture data. The SMAP (Soil Moisture Active and Passive) satellite mission is to map soil moisture and freeze/thaw states at 3 day return intervals. This instrument offers more remote sensing potential than other technologies currently in use. Our sensor platforms are currently deployed in anticipation of the February 2015 launch date.

The ESP model output is a measure of organic soil potential to sustain smoldering combustion. The model's ability to discriminate between smoldering and non-smoldering conditions was successfully validated by laboratory testing and prescribed burning. In comparison, the commonly used fire danger indices, which were developed as a measure of expected surface fire behavior, show low sensitivity to these conditions. Although this study was conducted in eastern North Carolina, the use of ESP is an alternative to these currently used indices and would be applicable to any fuel complex in the southeast comprised of similar organic soils or mineral soils with thick organic horizons.

Contents

Introduction/Background

Although a strong association between fire and wetlands seems improbable, the significance of fire in pocosin and other vegetation communities with thick organic soils has been reported in a number of studies (Kologiski 1977, Christensen et al 1988, Frost 1995). The existence and long term persistence of these communities is dependent on the formation and continued accumulation of organic soil. These soils are largely the result of a dynamic balance between productivity and decomposition. Fire and hydrologic processes are important elements of this dynamic. Increased understanding of the link between these factors will improve our ability to maintain these communities.

Fire in pocosins may consume above ground vegetation and organic soil. Due to heavy fuel loading surface fire behavior in the pocosin fuel type can be extreme. The Topsail Fire in May of 1986 made several major runs and remained uncontrolled for a week. A successful backfire operation involved the mass firing of 10,000 acres that created a convective plume reaching 15,000 feet and fire spread rates of 2 to 2.5 miles per hour. More recently, the Evans Road Fire, in June 2008, made major fire runs encompassing 7,000 to 12,000 acres per day. In the aftermath of these runs, ground fire in the organic soils consumed up to 36 inches of soil and generated massive smoke plumes that impacted communities along the eastern U.S. coast for two months (Bailey et al 2009).

One factor limiting increased prescribed fire use and the effectiveness of suppression tactics is the smoldering combustion of the organic soils. In areas characterized by thick organic soils, suppression alternatives are often limited by accessibility and soils which often cannot support the weight of heavy equipment. Frequently, the extent and severity of smoldering often makes flooding the only viable option for dealing with ground fires.

The availability of organic soil as a fuel varies seasonally and its potential to burn is dependent on soil properties and soil moisture; which is influenced by local hydrology. A wide range of moisture contents have been reported to limit smoldering combustion in organic soils. Limits as low as 40% on a dry weight basis have been reported for organic soils from Florida (Bancroft 1976) and limits as high as 500% in have been reported for organic soils in Russia (Artsybashev 1983). In an effort to improve understanding of smoldering combustion, studies were conducted by Frandsen (1987) and Hartford (1989) using commercial peat moss as a substitute for duff and organic soil materials. These studies demonstrated the influence of moisture, mineral content and bulk density on the limits of smoldering combustion. Later studies of sustained combustion limits in organic soils were conducted using samples from a wide range of wetlands and forest floor/duff from non-wetland sites (Hungerford et al. 1995; Frandsen 1997). These results were consistent with the earlier studies conducted with peat moss as a surrogate for organic soil. Subsequent laboratory work resulted in the estimated smoldering probability model (ESP) of sustained smoldering in organic soils from North Carolina (Reardon 2007).

The Estimated Smoldering Probability (ESP) model is a predictive tool developed for use in the organic soils of these shrub dominated communities (Figure 1). The ESP probability reflects the chance of continued smoldering after a successful ground ignition at which time smoldering becomes dependent on soil moisture and soil properties. These probabilities represent common situations where events such as lightning strikes, the flaming combustion front or burning embers establish smoldering in organic soil. At low probabilities continued smoldering is unlikely and control may require minimal resources while at high probabilities there is good chance that most ignitions will be sustained and control will be more difficult.

$$ESP_{Root\ mat} = 1/1+e^{(-2.033 + 0.043 * soil\ moisture - 0.44 * mineral\ content)}$$

$$ESP_{Muck} = 1/1+e^{(-7.653 + 0.038 * soil\ moisture)}$$

Figure 1. Estimated Smoldering Probability (ESP) Models

This study focused on several subject areas to advance our understanding of organic soil smoldering and to increase the potential management application of our results:

- The moisture content limit of sustained smoldering in these soil materials is influenced by soil mineral and thermal properties which determine the heat transfer processes within the soil. Characterization of these properties is needed to understand the significance of moisture limit differences between root mat and muck soils and the potential differences between sites.
- The ESP model was validated using additional laboratory testing and prescribed burning on study sites in North Carolina. This burning was conducted in collaboration with the North Carolina Division of Forest Resources, The Department of Defense at Camp Lejeune, and the North Carolina Nature Conservancy.
- The estimated smoldering potential of research prescribed burns was compared with NDFRS indices determined from local conditions. These comparisons were used to examine the possible links between organic soil smoldering and fire danger ratings.
- The lack of readily available soil moisture data is an important factor limiting the application of the ESP model in prescribed fire and fire danger rating programs. Alternative methods for soil moisture determination and monitoring were evaluated to improve the applicability of our current Estimated Smoldering Potential model (ESP).

Study Sites

Pocosins are unique fuel complexes common along the coastal plain of North Carolina. They are associated with areas of low relief and soils with poor horizontal and vertical internal drainage. These areas support extensive forest and scrub-shrub plant communities which are characterized by a wide range of properties that reflect hydrology, past fire history and organic soil thickness. The overstory on pocosin sites ranges from sparse very open canopies to dense closed canopies typically dominated by pond pine (Pinus serotina). Under the more closed canopies a midstory of evergreen loblolly and red bay species (Gordonia lasianthus and Persia borobonia) may be present. The understory on sites with closed canopies is commonly a shrub layer of fetterbush (Lyonia lucida), gallberry (Ilex glabra) and titi (Cyrilla racemilflora). Sites with open and sparse canopies support a tall (> 3 meters) dense shrub layer that is dominated by fetterbush, gallberry and titi. In general sites associated with thicker organic soils are less productive and do not support a closed canopy or as dense or tall shrub layer than sites with thinner organic soils.

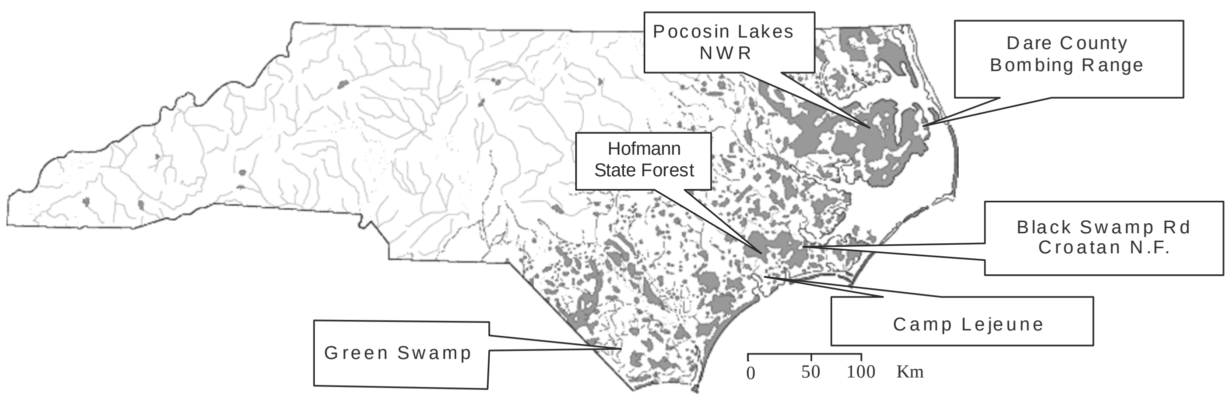

Figure 2 Study site locations in coastal North Carolina

The ground surface topography of the pocosin vegetation/fuel types is highly variable and is commonly described as hummock-and-depression micro-topography. Hummocks are higher in elevation and are usually associated with tree and shrub species while depressions are associated with an absence of woody vegetation. Individual hummock area is variable but 0.5 to 0.9 meter elevation changes are common in the transition from depression to hummock areas over distances of 1 to 3 meters. Changes in micro-topographic position influence soil drying processes and soil properties.

The soils commonly associated with pocosin sites are nutrient limited, very poorly drained and formed in organic material over marine sediments. These soils are characterized by organic soil horizons and are of concern in fire management. These horizons have different physical and chemical characteristics that affect smoldering combustion. The surface organic horizon (Oi) of a typical soil is composed of needle, leaf and twig litter of intermediate decomposition and this horizon is typically 0 to 10 cm thick. The root mat, an intermediate horizon (Oe1), is comprised of highly decomposed material of granular structure. This horizon is typically 30 cm thick. Under the root mat layer is the muck (peat) layer. It is comprised of the highly decomposed muck (sapric) soil horizon (Oa) of variable thickness. In North Carolina the average thickness of the peat is 1.4 meters with depths ranging from 0.3 to 4.6 meters (Ingram 1987).

Soil samples for laboratory analysis were collected from Pocosin Lakes Wildlife Refuge, Croatan National Forest (Black Swamp Road), Green Swamp Nature Preserve, Hofmann State Forest and Camp Lejuene(Figure 2).

Methods and Findings

Laboratory analysis of organic soil properties

Analysis of mineral content

Previous studies of smoldering limits conducted with peat moss, organic soil and forest floor duff have reported that the smoldering moisture limits decrease with increasing mineral content (Frandsen 1987; Hartford 1989). However, Frandsen (1997) reported positive mineral content logistic regression coefficients for three of his lowest mineral content sites. The significance of those results was not discussed in that paper. The results of Reardon et al. (2007) also reported a positive relationship between the mineral content and the estimated smoldering probability of root mat soils from North Carolina.

Due to the inconsistencies in experimental results the role of mineral content in the smoldering process in root mat soil remains unclear. While studies have shown that mineral/ash content is negatively correlated with heat output and smoldering limits, other studies have shown that 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 increase smoldering in wood fibers (McCarter 1978). Frandsen (1987) concluded that some inorganics may alter the combustion process, in which case, it is important to know the amount and the composition of the inorganic material.

Mineral Content Distribution

Characterization of root mat mineral content is needed to understand its role in smoldering combustion and the significance of moisture content that limits sustained smoldering. Analysis in this study was conducted to determine the percent mineral content distribution of our study sites and the mineralogy of the root mat soil.

Mineral content was determined using oven dried root mat samples to remove soil moisture. Oven dried samples were placed in a muffle furnace at 450^{o}C for 24 hours. Mineral or ash content is reported as a percent relative to the sample dry weight (Figure 3.) The results were consistent with our previous work. Mineral content ranged between 2% to 19% with a median value of approximately 5%. There were no statistically significant differences between sites.

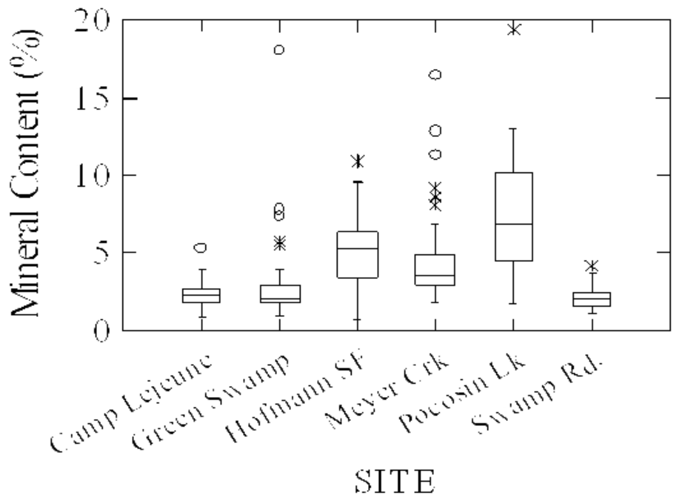

Figure 3. Mineral content of root mat soil

Mineral Content Mineralogy – X-ray Diffraction (XRD) Analysis

XRD is a laboratory analysis technique commonly used to determine the mineralogical characteristics of geologic or soil samples. The crystal structure of a sample is evaluated by the x-ray reflection/deflection patterns at different angles and intensities. This analysis was conducted to determine the type of mineral in the root mat soils. The results of XRD analysis are commonly expressed in three concentration categories: major (>20% by weight), minor (<20% and >5%) and trace amounts (<5% by weight).

This analysis was conducted using 25 root mat samples from 6 sites. The samples were ashed in a muffle furnace at 450^{o}C for 24 hours before XRD analysis. The results show that quartz sand ($Si\ O_2$) was a major component in samples from on all sites. Minor amounts of Calcite ($CaCO_3$) and anhydrite ($CaSO_4$) were present in 64 % of the samples tested. These latter compounds were formed during the ashing process and do not reflect preburn compounds expected to affect the smoldering process.

These results show that the dominant mineral in the sampled root mat soils is quartz sand. The presence of this mineral is most likely the result of windblown deposition or mixing from shallow subsurface features that include buried sand ridge or relic beaches. These features are common throughout the coastal plain (Figure 4).

Quartz is not expected to have a catalytic effect on smoldering processes. Small amounts however may affect the thermal properties of the soil. Heat capacity is a measure of the energy needed to raise the temperature of a material; it is a function of soil thermal conductivity and diffusivity. The results suggest that small amounts of sand may increase the thermal conductivity of the soil but not significantly change its heat capacity.

Figure 4. Fire line construction on the Fire Lab burn in the Green Swamp revealed pockets of shallow sand which is the dominant source of mineral content in these soils.

Thermal Analysis and Calorimetry

The results of our previous research on smoldering in organic soils showed a significant difference in the moisture limits that constrain smoldering in root mat and muck soils. This difference was attributed to differences in the heat of combustion that resulted from decomposition processes. Alternatively, these smoldering limit differences could also be due to thermal property differences produced by the highly porous structure of the root mat and the massive structure of the muck soils.

Two analysis methods were employed to explore these hypotheses. The heat of combustion of root and muck soil was measured using an oxygen bomb calorimeter and the temperature sensitivity of these soils during thermal decomposition was measured using thermal analysis techniques which will be discussed further in the Thermal analysis section of this report. The influences of soil structural differences are eliminated in both analysis methods because these methods utilize ground (highly processed) samples.

This laboratory analysis focused on potential differences in root mat and muck soil thermal properties attributable to the degree of decomposition. Decomposition and humification are import processes that influence the formation and properties of organic soil. The accumulation of humic substances in organic soil is linked to increases in water holding capacity (Schnitzer, 1986) and higher calorific values (Ingram and Otte, 1981). Both these properties are important in smoldering combustion processes.

During humification, abiotic and biotic processes transform dead and decaying plant material in the soil into three classes of humic substances; humic acid, fulvic acid and humin. Humic and fulvic acids are considered intermediary compounds in decomposition processes and these and other compounds are recycled within the soil numerous times. Humin is considered both a source of the inputs needed for decomposition and also an endpoint for the products of decomposition.

Humic substances are characterized by their solubility in mildly alkaline solutions. Humic and fulvic acids are base soluble, while humin is base insoluble. Determination of the relative amount of humic substances in our samples was conducted using the following standardized lab procedure. The samples were shaken in a 0.1 m NaOH solution for 24 hours then centrifuged to separate the humin from the humic and fulvic acids. The NaOH solution remaining in the supernatant liquid (humin) and precipitate (humic and fulvic acids) was allowed to evaporate and the ratio of dried humic and fulvic acid to humin was then determined gravimetrically. The total carbon content of the fulvic and humic acids and humin was determined using a LECO Tru-Spec CN analyzer.

One index of humification is the ratio of the carbon content of the humic and fulvic acid fraction of the soil to the total carbon content of the peat soil (Klavins and Melecis, 2008) (Figure 5). The carbon content of the fulvic and humic acids ranges between 41%-50% and 54-59 % respectively. The carbon

$$\mathbf{HI = Carbon_{\mathit{Ha\ \&\ Fa}} / Carbon_{\mathit{soil}}}$$

Figure 5. Humification Index (HI)

content humin materials can exceed 60% (Reddy and Delaune 2008).

The results of our analysis show that the humification index is consistently greater for muck soils across our study sites. This index ranges between 0.84 and 0.92 and 0.95 to 0.99 for root mat and muck soils respectively (Figure 6). Further analysis shows that a similar ratio of the carbon content in the

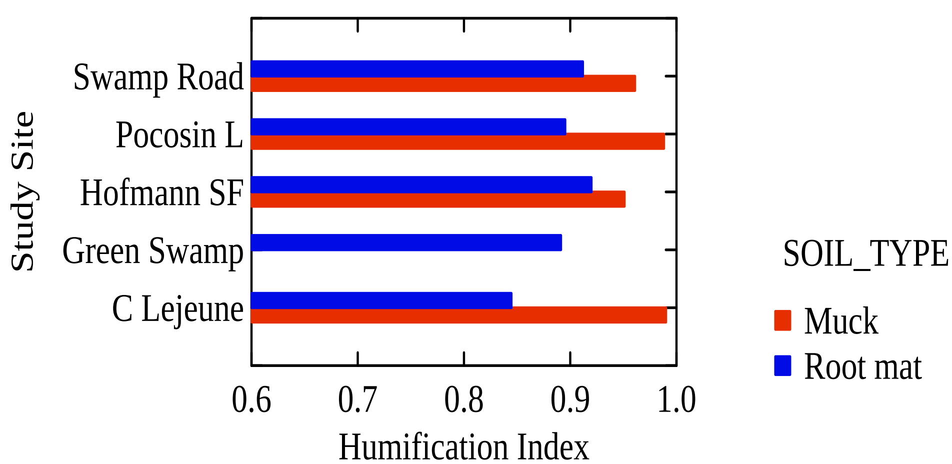

Figure 6. Humification Index of root mat and muck soil horizons showing the ratio of carbon present in the humic and fulvic acids to the total carbon present in the soil

humin to total soil carbon content is also much higher for the muck soils (Figure 7).

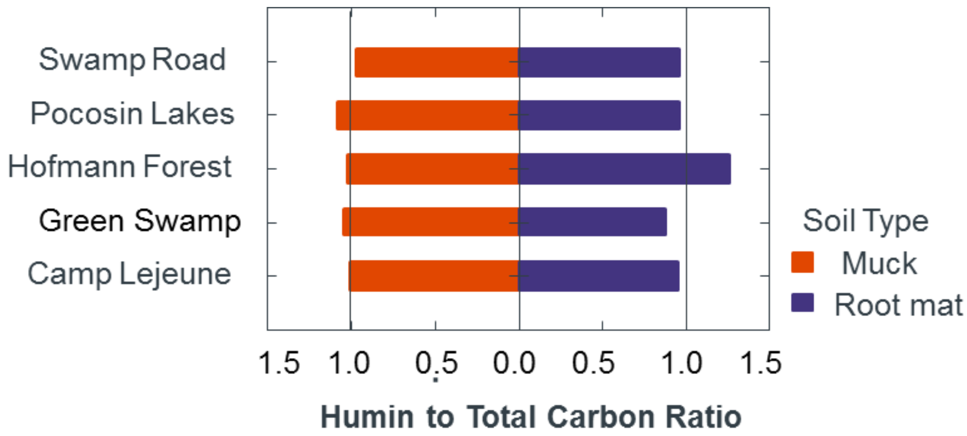

Figure 7. Index of carbon content in humin extracted from root mat and muck soils to the total carbon content of the soil

The degree of decomposition is expected to influence smoldering through the carbon content of the humic substances in the soil. Humic and fulvic acids comprised approximately 20 % of the root mat and muck soils by weight. The greater concentration of humin in the muck soil when considered with its higher index value and associated higher carbon content suggests that the thermal decomposition of the muck soils proceeds differently than the thermal decomposition of the root mat soils.

Heat Content

Heat content is a measure of the energy available from the combustion of a fuel. In peat soils it is strongly influenced by the degree of decomposition and mineral (ash) content. It is determined by combusting a weighed sample in an oxygen bomb calorimeter under controlled conditions. The heat content of a sample is computed from sample weight, calorimeter properties and temperature observations made before, during and after the combustion process,

Calorimetric analysis was conducted on 24 samples of root mat and muck soils. The mean heat content of the root mat and muck soils was 5068 and 5208 cal/g respectively. We found no significant difference in the heat content of root mat and muck soil (Figure 8.)

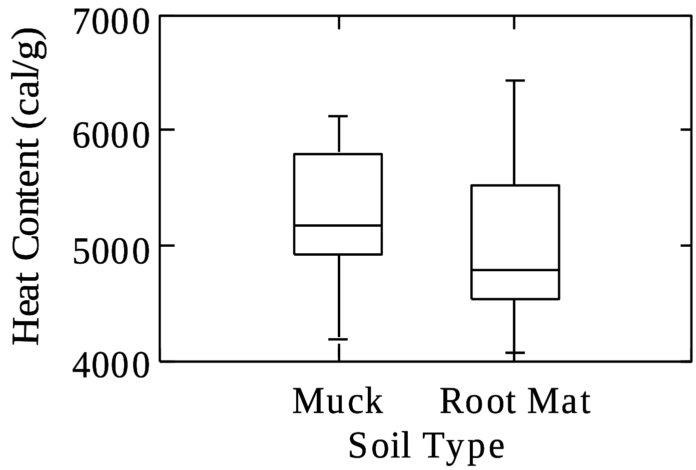

Figure 8. Heat Content of root mat and muck soils

Thermal Analysis

Thermal analysis is a general term for a group of related analytical techniques. The techniques used in this study were thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). TGA methods measure the changes in mass that occur as a result of controlled temperature increases (Vyazonkin 2012). DSC is a technique that measures the energy released or absorbed by sample as a function of controlled temperature increases. These techniques have been used to evaluate thermal decomposition and combustion dynamics of forest fuels (Susott 1980) and in predicting chemical properties of organic materials (Bergner and Albano 1993).

Simultaneous TGA and DSC analysis was conducted on 24 root and muck samples using a sample size of 9 to 10 mg. The analysis was performed in an air atmosphere with a controlled heating rate of 20°C min^{-1} from 20°C to 1000°C. The results of this analysis are commonly presented graphically as the relationship of sample temperature change with mass loss and energy output (Figure 9).

The TGA/DSC results of root mat and muck soils show that the thermal decomposition trends of these soils were similar. These trends can be summarized in four stages of temperature change. The first stage was associated with soil water and volatile losses. This stage was endothermic and accounted for mass loss between 21°C and 193°C. The next stage proceeded at temperatures between 193°C and 406°C; it was exothermic and associated with the loss of the lighter carbon compounds and char formation. Between 406°C and 544°C, the third stage was associated with the loss of denser carbon compounds and char oxidation. This stage was also exothermic and characterized by a higher loss rate and energy release than the previous stage. The last stage, which was above 550°C, was characterized by a low loss rate and energy release which resulted from limited consumption that occurred above 550°C.

The greatest proportion of mass loss and energy production occurs in stages two and three. The root mat and muck soil mass loss rates and energy production in step 3 are greater than the associated rates in stage 2. Muck soils show a strong correlation between per cent mass loss in stage 3 with total energy release (r=0.95) release while the correlation between these factors in root mat soil is significantly weaker (r=0.66).

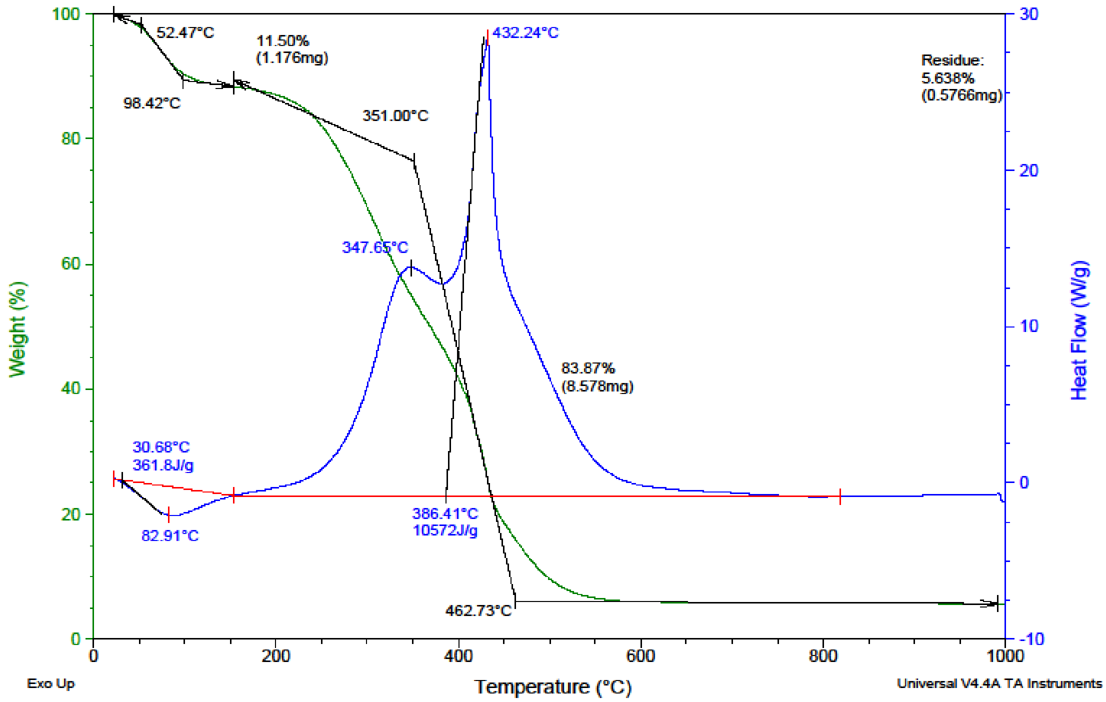

Figure 9. Thermal Gravimetric Analysis (TGA) and Differential Scanning Calorimetry outputs for root mat soil from the Hofmann Forest. The left axis (green) and green curve is the mass loss tracked by the TGA analysis. The right axis (blue) and blue line is the heat output tracked by DSC. The red line is the base line of heat output.

Laboratory validation of ESP model

Root mat soil horizon

The burn response of organic soil samples was tested using standardized methods developed by Frandsen (1997) and modified by Reardon (2007). Logistic regression analysis, which used the results of standardized testing, was conducted to quantify the relationship of organic soil smoldering to soil moisture and mineral content. This type of analysis is commonly associated with binary choice models where the response can be reduced to two discrete levels. In this case, the response to testing was classified as either ‘no sample consumption’ or ‘total sample consumption’.

The output of this logistic regression analysis is a probability of continued smoldering combustion after ignition. After ignition any continued smoldering is no longer dependent on the ignition source but on soil moisture content and soil properties. This probability estimate reflects conditions where smoldering can continue long after the passage of the surface fire or after an ignition from an event such as a lightning strike.

Assumptions can be made to generalize ESP model response over the entire moisture range. At an assumed mineral content of 5%, estimates of smoldering probability from the root mat model were greater than 50% for moisture contents up to 98% (Fig 10). The ESP is most sensitive to soil moisture content change between 68% and 128%, the. Within that range, the probabilities can be considered linear and change at a rate of 10% per 10% change in moisture content. Above and below that range however, the rate of change is nonlinear. For example, round a 150 % moisture content the probability change is 3 % for a 10 % moisture content change. Above that moisture content, the soil becomes increasingly saturated and the ESP becomes progressively more insensitive to additional moisture.

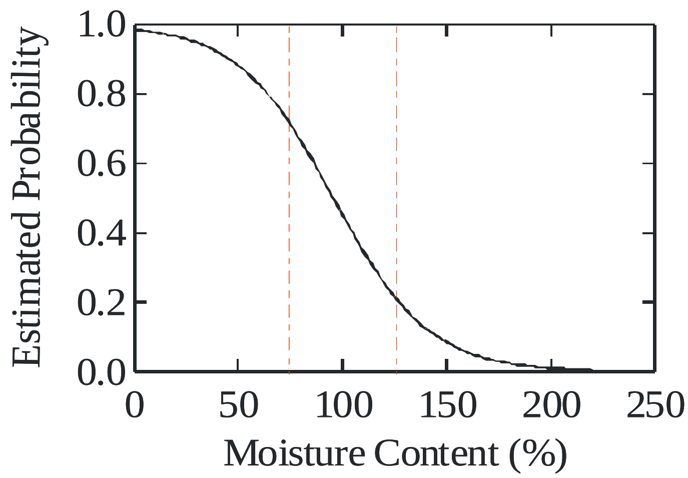

Figure 10 Root mat ESP model response assuming a 5% mineral content. Red lines delineate moisture contents between 68% and 128 %. The ESP is most sensitive to moisture content change within this moisture range.

Generalizations concerning the relationship between mineral content and the estimated smoldering potential in root mat soils are apparent when looking at the probability responses at 3%, 5% and 8 % mineral content levels (Fig 11). At a root mat moisture content of 170% and mineral contents between 3 and 8% the ESP values range from 1.8% to 9.7%. The influence of mineral content is also limited at very low moisture contents. However, intermediate soil moisture contents of 68% to 128 % show a wider range of ESP values. At a root mat moisture of 97%, the mineral content had a significant effect on the probability estimates. At that moisture content the ESP ranged from 30 to 70% for soils with mineral contents of 3% and 8% respectively.

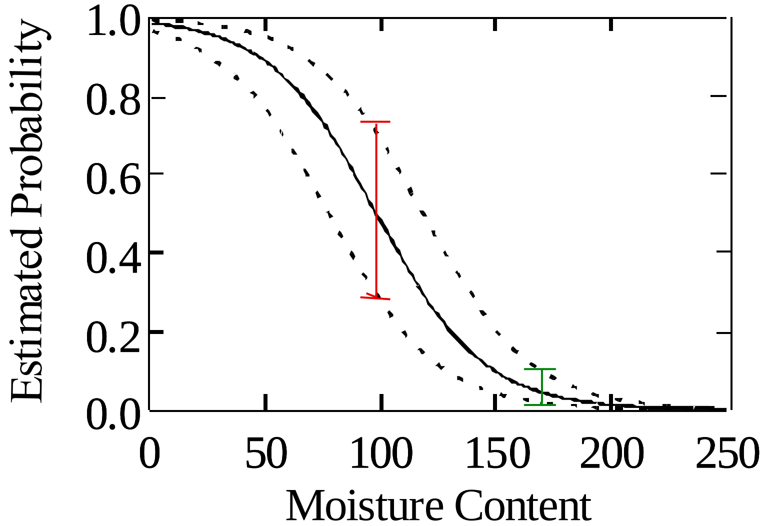

Figure 11. Root mat ESP model response assuming a mineral content of 3%, 5% and 8%. The estimated probability is most sensitive to mineral content in the mid-probability range; 50% (the redline) and least sensitive at 170% probability highlighted by the green line.

One way model goodness of fit can be accessed is by comparing model predictions with the results of testing soil samples under controlled conditions. Comparisons between testing and model predictions can be divided into four classes (Table 1). Correct prediction of the occurrence or absence of sustained smoldering is classified as either a true positive or true negative respectively. In contrast, a failure to predict correctly can be classified as either a false positive (Type I error) or a false negative (Type II error). The lack of smoldering, when predicted by the model, is classified a false positive (false alarm) while the occurrence of smoldering when not predicted is classified a false negative.

		Predicted Response	
		Smoldering	**Non-Smoldering**
Observed Response	**Smoldering**	True Positive	False Positive
	Non-Smoldering	False Negative	True Negative

Table 1 Contingency Table

Laboratory burning of soil samples collected from five sites on the North Carolina coastal plain our study sites produced an independent data set that was used to validate the ESP model. A ROC curve was developed using the burn responses of these soil samples (n=235) and the model predictions for each sample. The soil samples used in the development of the ESP model were not used in this ROC analysis

The ROC analysis was conducted using the observed burn responses and estimated model probabilities (ESP). This analysis was conducted to evaluate the quality of the performance of the ESP model, model goodness of fit and the choice of a moisture content threshold for prescribed burning and fire danger rating. The ROC can be understood by a graphical representation of the relationship between the true positive (detection) and the false positive (false alarm) rates.

The units of the' x' and' y' axes of the ROC graph are the 'true positive fraction' which is the proportion of samples correctly predicted to sustain smoldering and the 'false positive fraction' which is the proportion of samples incorrectly predicted to sustain smoldering. A perfect model would correctly predict all occurrences of sustained smoldering and there would be no 'false positives'. A perfect model or test would produce an ROC curve that followed the 'y' axis and terminated in upper left corner of the graph (Figure 12).

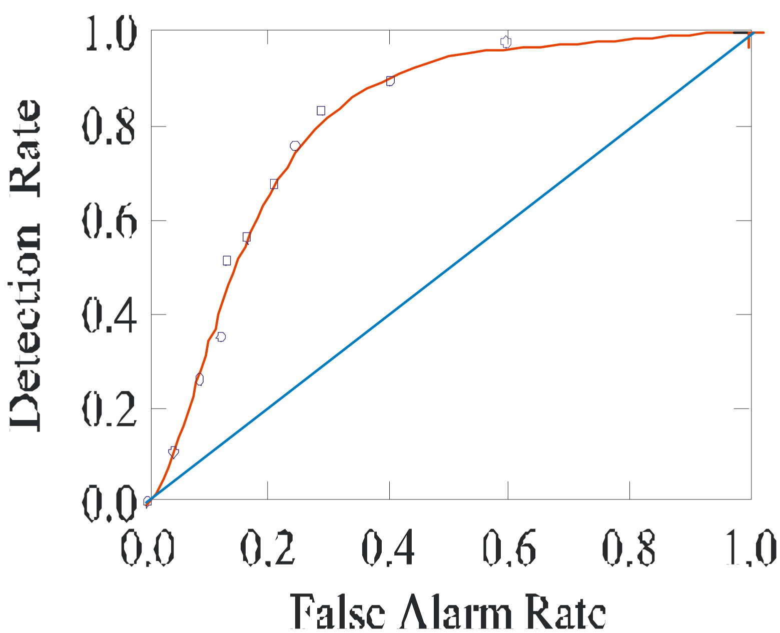

Figure 12. Receiver Operating Characteristic Curve (ROC) of root mat soil ESP analysis. The blue line represents a theoretical model in which the area under the curve is 0.5. The red curve is fit to the laboratory test data.

Since no model is a perfect predictor, the shape of the curve fitted using the laboratory burning data reflects the changing proportions of these two fractions as the estimated smoldering probability changes. The area under fitted curve (red curve) in figure 12 is a measure of model goodness of fit. In this case, this area reflects the model's ability to discriminate between conditions that will and will not support sustained smoldering. The area under a ROC curve ranges from 0 to 1.0 where an area of 1.0 represents a perfect test and an area of 0.5 represents a test that with no better than random discrimination (blue line, Figure 12). Acceptable discrimination for logistic models is reported if the area under the ROC curve is greater than 0.6 and less than 0.7; good discrimination is reported for areas greater than 0.7 and less than 0.8; excellent discrimination is reported for areas greater than 0.8 and 0.9 and outstanding for areas greater than 0.9 (Hosemer and Lemshow 2001).

The area under the ROC curve was 0.81 for root mat soil using measured soil moisture and mineral content as model inputs. In comparison, the area under the curve was 0.8 using the measured moisture content and an assumed mineral content of 5% for all samples (red line, Figure 12). The absence of an improvement in model fit is not consistent with the generalization previously presented which suggested the influence of mineral content showed increasing influence at intermediate soil moisture contents.

Further analysis shows that an 'optimal' probability can be determined from the fitted curve. This is the probability that maximizes the detection rate while minimizing the false alarm rate and it is the point on the curve that is nearest to the upper left corner. The ROC curve (red line, Figure 12) shows that the 'optimum' probability for decision making is approximately 70%. The usefulness of this optimal point is dependent on the assumption that the costs of an unexpected ground fire and the costs of a delayed or missed opportunity to burn are equal. In this case it is clear that a threshold probability that better balances these costs is more practical.

This threshold probability or moisture content is necessary for the application of ESP in either the prescribed burning decision making process or as an index of fire danger. The selection of a specific probability and its associated soil moisture content is a tradeoff between an acceptable risk of ground fire and the number possible burn days with soil moisture at or above this threshold. At a low threshold the associated soil moisture content is high and the likelihood of sustained smoldering is low. However, an unreasonably low threshold would limit the number of acceptable burn days and overestimate the true fire danger. In contrast, at higher thresholds the associated soil moisture content is lower and the likelihood of sustained smoldering is increased. While increasing the number of acceptable burn days, an unreasonably high threshold would most likely underestimate the fire danger. Although not statistically optimal, a soil moisture of 170% and its associated estimated probability of less than 5% were chosen as the operational thresholds for the prescribed burning portion of this study. The overriding concern in the selection of this threshold was a reduction in the risk of ground fire to less than 5%.

Muck soil horizon

Assumptions can be made to generalize ESP muck model response over the entire soil moisture range from dry to saturated conditions. Estimates of the smoldering probability from the muck soil model are greater than 50% at moisture contents up to 200% (Figure 13). The ESP is most sensitive to moisture content changes at moisture contents between 166 and 236%. Within that range the probabilities can be assumed to be linear and change at a rate of 8% per 10% change in moisture content. Above and below that range however, the ESP is less sensitive to soil moisture change. For example around 270% the probability change is 3% for a 10 % soil moisture change. Above that moisture content the soil becomes increasingly saturated and the ESP becomes progressively more insensitive to additional moisture.

Planned sampling of intact large muck soil cores using 12' (30 cm) diameter x 12' (30 cm) deep soil sampler was not practical. While this sampling method was successfully used in other areas, it was unsuccessful in this study due to dense roots in the upper soil horizons of our sample sites. The sample size was reduced to a smaller 4 inch diameter x 6 inch deep soil sampler.

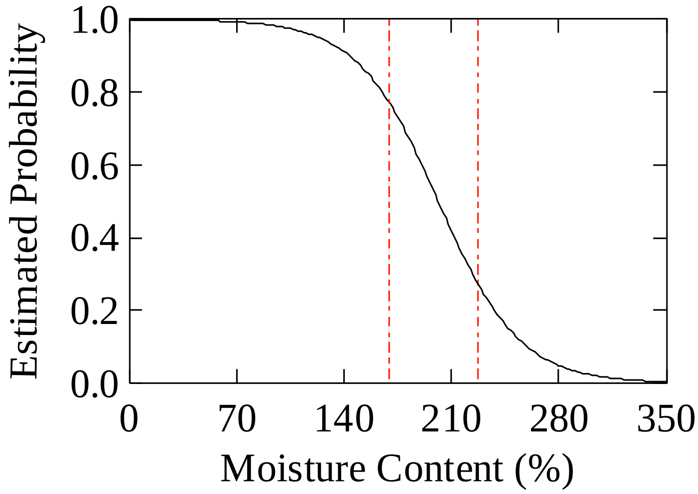

Figure 13. Muck ESP model response. The dashed red lines delineate moisture contents between 166% and 236%. The estimated probabilities in this region are most sensitive to moisture content changes.

The standardized laboratory testing of the muck soils was conducted with methods employed on our study of the root mat soil. This testing showed that samples from dry to moderate moisture contents failed to support smoldering. These results were not consistent with our prior results and observations in the field. Previous work with large muck soils included root mat material and the total burn time for those cores exceeded 12 hours, while the standardized testing time in this case was significantly shorter. The lack of realistic results suggests the ignition and dominant heat transfer mechanisms in the porous root mat soil horizons were substantially different from the ignition and the dominate heat transfer mechanisms of the less porous muck soil horizons. These results suggest that additional work is needed to develop a standardized testing method for the muck soils.

Field validation of the ESP model

Previous research conducted to field test our laboratory findings utilized a series of small scale (4 to 6 acre) research burns. These small scale burns were conducted to test the moisture content limits of smoldering in these soils. These burns also tested some widely accepted assumptions which were based on fire managers' past experiences and observations.

In this study, field validation of the ESP model was conducted using larger operational prescribed burns (100 to 800 acres). The previous small scale research burns were conducted with limited soil and fuel variability. These larger scale burns tested the influence of soil property and moisture variability on the application of the ESP model at levels of variability normally encountered during operational burning and wild land fires. These prescribed fires were conducted as part of the North Carolina Division of Forest Resources' Operational Research Evaluation Burn Project (ORREB program) which was created to facilitate the use of new research findings and fire management tools to advance prescribe fire.

The monitoring and evaluation of pre-burn ground fire potential was an important part of the planning of these larger burns. A concise way of incorporating our research results into the decision making process was a simple “Burn / No-Burn” moisture content threshold based on an acceptable ESP level. The decision point was set at a moisture content threshold of 170% for the root mat soil horizons on these sites. This moisture threshold represents an estimated smoldering potential (ESP) of less than 5% with an assumed average mineral content of 5%. Burning at lower moisture contents and correspondingly higher ESP levels was considered an unacceptable risk at this time due to the uncertainty of soil moisture and mineral content variability within the burn units.

Myers Tract/Green Swamp - February, 2009

The Myers tract was a mixed conifer (pond pine /loblolly) site with a scattered but significant shrub understory dominated by gallberry. The soils were a mix of sandy soils with a thin organic (duff) horizon and poorly drained mineral soils with a thick organic soil horizon.

This prescribed fire was conducted at the upper limits of acceptable burning conditions. The fire danger adjective rating on the day of the burn was high. The ERC was 40 with strong surface winds of 12 mph These conditions generated a BI of 102 which was the highest BI of all our prescribed fires (Attachment #1) One factor that offset the high fire danger was cool air temperature, 59^{0}F or less. At the time of burning the root mat mean moisture content was 225% with an ESP of less than 1 %.

Fuel consumption of the foliage and one hour fuels in the shrub understory was high. Duff consumption transects in areas dominated by mineral soil with a thick organic soil horizon showed consumption of the surface litter layer but no consumption of the underlying organic soil horizon below.

JFSP-Fire Lab burn/ Green Swamp - February, 2009

This unit was a mixed conifer (pond pine/loblolly) site with a scattered to sparse overstory. The unit had a significant shrub understory dominated by fetterbush and gallberry. This unit was a mosaic of vegetation and soil types that are typically considered pocosin fuels (Figure 14). The soils were a mix of sandy soils with a thin organic horizon (Foreston soil), poorly drained mineral soil with a thick organic horizon (Torhunta soil) and deep organic soils with a thick root mat (Croatan Muck Soil).

Past burning of this unit was limited to the sand ridge areas. Typically, little burning is conducted on the thicker organic soils due to the uncertain risk of ground fire and the high fuel loadings. Fuel accumulation on these sites is often greater than 20 tons per acre and is dominated by the fine fuel classes.

This unit was burned under a “high fire danger” adjective rating but both the ERC (36) and BI (83) values were lower than the Myers tract burn. The average moisture content of the root mat and muck samples associated with the Croatan muck soil area were greater than 200% and 350% respectively. In contrast the moisture content of the duff soil horizon on the sandy Foreston soils, which was present on slightly elevated well drained areas, was greater than 110%.

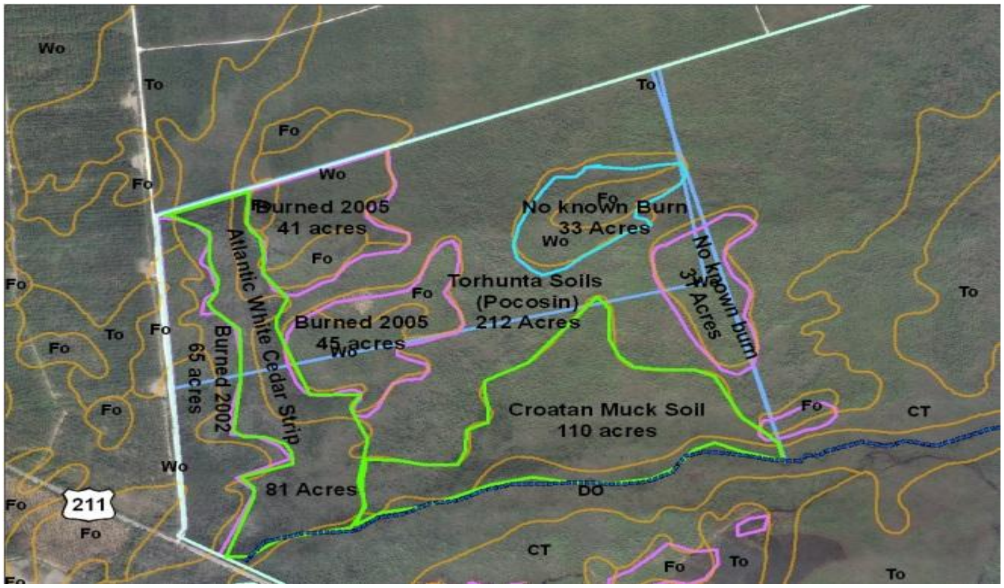

Figure 14. Soil Type and burn history of Green Swamp Fire lab burn illustrating the spatial complexity that is common in pocosin fuels. Croatan Muck soils (CT), Torhunta Soils, (To) and Foreston Soils (Fo)

These root mat soils were well above the moisture levels expected to support sustained smoldering the ESP was less than 5%. Post burn measurements showed consumption of the surface litter layer but no consumption of the underlying organic sol horizon below.

Camp Lejeune - Feb and April, 2010

Two prescribed fires were conducted at Camp Lejeune. The first site was characterized by a mixed conifer canopy of pond and loblolly pine with understory fuel loadings that ranged that ranged from 3.2 to 7.4 tons per acre. The soil type of this unit was a poorly drained mineral soil with a thick organic horizon.

At the time of burning in February the adjective rating was high and the associated ERC and BI were 44 and 91 respectively (Attachment #1). The average soil moisture of the top 10 cm of the organic soil horizon exceeded 250 % with an ESP of less than 1%. Standing water was present in low spots throughout the unit. Post burn measurements showed fuel consumption was limited to the litter, live foliage and 1 hour fuels. There was no consumption of the organic soil horizon.

The second burn in April was conducted on a site dominated by dense shrub fuels (20 – 27 tons per acre), a scattered/sparse pond pine overstory and thicker organic soils. At the time of burning the Adjective rating was 'extreme' and the associated ERC and BI were 48 and 83 respectively. The measured root mat soil moisture exceeded the acceptable moisture content threshold on all sites. The average soil moisture was greater than 200% and the ESP was less than 3%.

This pocosin burn was a significant test of ESP research results. The unit had a high fuel loading and was burned at extreme fire danger levels. In anticipation of this planned burn, management units surrounding this unit were burned in the 9 months preceding this planned burn. The ‘Burn / No-Burn ‘decision process included the evaluation of the seriousness of burning conditions and integrated current information and previous experience burning in the pocosin fuel type. On the day of the burn the NFDRS values warranted a stand down from igniting the burn unit (No Burn Decision). The treatment of the fuels in the surrounding units and soil moistures at levels not expected to support ground fire trumped other information and led to the ‘Burn’ decision.

Post burn measurements showed that consumption of the surface fuels was limited to the litter, live foliage, 1 hour fuels, and suspended dead and fuel consumption was estimated at approximately 10 tons per acre. Even though there was intense surface fire behavior there was no consumption of the root mat soil horizon or residual smoldering.

Inman Unit/ Green Swamp April, 2012

This burn was conducted in April during early spring fire season. At the time of burning, the ERC and BI were 36 and 76 respectively. Moisture sampling showed the surface litter moisture content was 88% to 131%; the top two inches of the organic soil root mat beneath the litter ranged from 251% to 334%; while the moisture content 2 to 4 inches below the surface litter showed more variability and ranged from 141% to 264%. Although one soil sample was below the 170 % threshold value, the mean moisture contents of the top and lower root mat soil were 299% and 221 % respectively. These values with an ESP of less than 1%   which the decision to proceed with the burn.

The planned ignition of the unit was unsuccessful and after several days the unit was re-ignited. The occurrence of ground fire was noted and this burn was later declared a wildfire because of persistent ground fire, periodic surface fire runs and smoke issues. Due to the high soil moisture levels at that time, it was determined that the best suppression technique was to ‘walk’ the suppression tractors without plowing into the areas where there was smoldering. The purpose of this technique was to mix the smoldering material with the excess soil moisture while minimizing soil disturbance. Smoldering combustion and the resulting smoke production were reduced by bringing the soil moisture in contact with the smoldering combustion zone and within 1 to 2 days and it was no longer causing smoke impacts to a nearby highway.

The unit was resampled twelve days following the burn date. Drying during this period resulted in the top two inches of the organic root mat averaging 213% with bottom 4 inches averaging 193% which was a reduction of 86% and 28 % respectively. At that time the ESP was below 5% and the root mat soil moisture remained above the levels expected to support sustained smoldering. Post burn observations suggested that the residual smoldering was associated with two conditions. The first was where root mat soils that were overturned and exposed to drying by fire line construction and other pre-burn fire management activities. The other was where charred 100 and 1000 Hr. fuels were observed on the soil surface but the smoldering combustion zone was limited to the soils adjacent to these fuels. In both cases the high soil moisture levels apparently constrained the spread of smoldering.

JFSP- Fire Lab burn/ Green Swamp- March, 2014

This prescribed fire was re-burn of the research unit burned in 2009. Conditions at the time of burning in April showed the lowest ERC (29) and BI (56) of all our prescribed fires (Attachment #1). Prior to burning, soil moisture was highly variable. Several weeks before burning the water table dropped to greater than 16 inches below the root mat/muck soil interface and soil moisture was declining (Figure 15). Limited sampling in late February showed surface moistures along the disturbed fire line of 157% and 170 %. Several organic soil root mat samples were within 30% to 40% of the critical moisture threshold of 170% and the root mat soil was in a drying trend.

However, the drying trend was reversed by storms in early March. Precipitation recorded from the nearest NFDRS station totaled 2.72 inches over a 28 hour period. On the day of the burn the water table was 9 inches below the root mat/ muck soil interface and the muck soil moisture levels were greater than 440% (Figure 15). Litter moisture contents ranged from 37 to 48% with an average of 38%. Upper root mat moistures ranged from 328% to 382 % with an average of 244% while the lower depth root mat moistures ranged from 147% to 341% with a mean of 271%. The lowest root mat moisture was associated with a mineral content that exceeded 40%. The ESP value for the upper and lower root mat soils was less than 1% while the ESP of the muck soil was less than 1%.

The observed fire behavior was more moderate than observed during the previous burn on this unit. There were reduced flame lengths and less crown scorch of the overstory and the consumption of the foliage, fine and litter fuels was high. There was no consumption of the root mat soil and these results were consistent with the ESP model estimates..

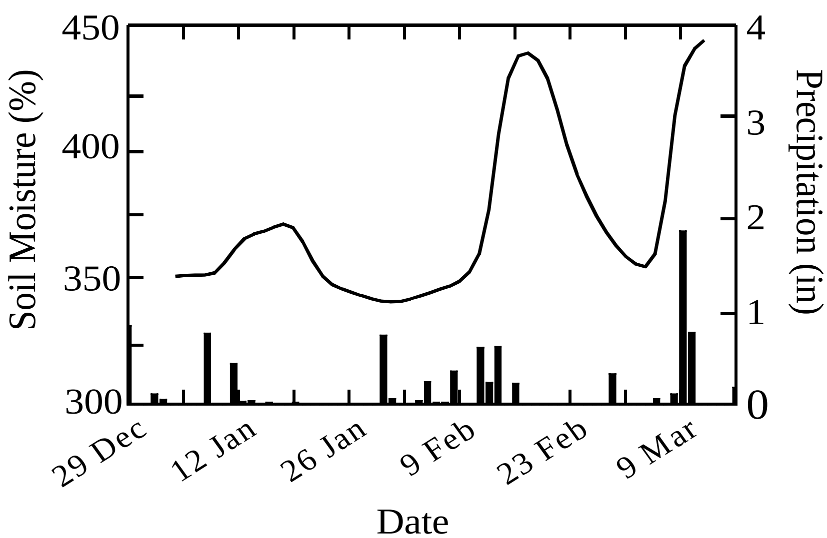

Figure 15. Pre-burn muck soil moisture and precipitation data for Green Swamp/ Fire Lab burn conducted in March 2014

National Fire Danger Rating System (NFDRS) and Estimated Smoldering Potential (ESP) use in prescribed burns and wildfires.

During this study prescribed fires were conducted under a range of fire danger conditions to validate our laboratory work and also investigate the link between fire danger rating and the potential for ground fire. Burning conditions of six prescribed fires, four recent wildfires with extensive ground fire and three previous research burns were compared using the National Fire Danger Rating System (NFDRS) (Attachment #1)

NFDRS provides information about the current and projected burning conditions of naturally occurring surface fuels. The NFDRS model integrates meteorological data with fuel properties to predict the moisture contents of live and dead solid woody fuel moisture contents in four time lag classes (1, 10, 100 and 1000 hour fuels). These outputs are used to produce four indices of expected fire behavior: Ignition Component (IC), Spread Component (SC), Energy Release Component (ERC) and Burning Index Although not part of the original system, the Keetch- Byram Drought Index is associated with the system in an attempt to quantify fire danger in duff and organic soil.

The sensitivity of these outputs to burning conditions was accessed through the analysis of fire occurrence and historical weather data. The NC Forest Service Fire Environment Branch determined that ERC and the BI were the most suitable for monitoring burning conditions on a daily basis. The Energy Release Component reflects the potential energy released from forest fuels at the head of a fire's flaming front. This index is calculated from precipitation, temperature, and RH. It paints the best composite picture of fuel conditions regardless of wind speed. The BI incorporates the effects of wind. These two indices are the principal factors used in the Fire Danger Pocket Card developed for pocosin fuels on the coastal plain of North Carolina (Attachment #2).

A number of guidelines are in use to anticipate fire behavior in pocosin fuels. Rapid ignition and increased spotting potential are expected when the Ignition Component exceeds 20. Intense burning and the need for aerial suppression support are expected when the ERC is 41 or greater. Extreme fire behavior and crown fires runs are likely when the ERC is 41 or greater and the BI is 70 or greater. Given a fire start in a fuel with a high ERC, fire containment can be expected to be difficult. ERC is used to assess the depth of a burn, consumption of the various fuel classes, residual burning, mop-up requirements & air tanker support.

When SC is 40 or greater, rapid fire spreads are expected and they are not 'catchable' by direct ground suppression techniques. In this SC range, wildfires usually will not be run down by tractor plow units unless there is a change in burning conditions and/or aerial suppression support is used to retard the fire's spread.

Surface fire spread in the pocosin fuel type has been hypothesized to be based on the significant contribution factor (SCF). This is based on the abundance of aerially suspended decadent stem wood & pond pine needle drape. When present these fuels make the pocosin brush fuels a flash fuel especially during early spring growth. When wildfires occur in this fuel complex in eastern North Carolina, they frequently become dangerously explosive blowup fires. This has taken place in October through November and from March through June representing the fall and spring fire seasons.

Adjective Rating and ERC

Our prescribed fires were conducted from February through early April which coincided with pre and early spring fire season (Figure 16). The March burn in Camp Lejeune was conducted under 'extreme' wildfire conditions with an ERC of 48 and a BI of 83. This burn was conducted under upper air conditions that are known to produce large fire growth in eastern North Carolina. Although there was significant surface fuel consumption there was no organic soil consumption. The February burn in Camp Lejeune was conducted a month earlier while the fire danger was 'very high' but surface fuel consumption and fire behavior were constrained by wet site conditions. Four other burns were conducted under high fire danger conditions with ERC values of 40 and below. These burns resulted in low to moderate surface fuel consumption and no organic soil consumption.

In comparison with these prescribed fires, recent wildfires occurred later in the fire season from April to mid-June. While the fire danger adjective ratings were 'very high' to 'extreme', the ERC values were comparable to the Camp Lejeune and a previous research burn on the Croatan National Forest. These prescribed fires resulted in no organic soil consumption. These comparisons demonstrate that the ERC and the adjective rating classes are not reliable predictors of the smoldering potential or risk of ground fire of organic soils

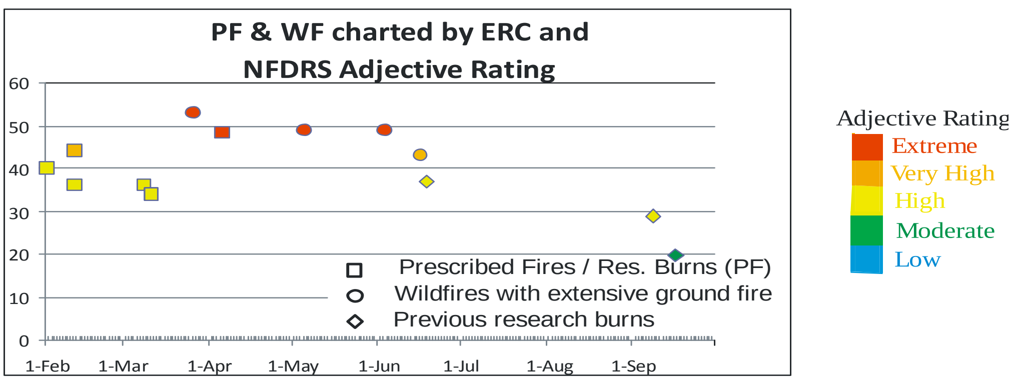

Figure 16 NFDRS Adjective Rating and ERC values for research burns and recent wildfires

1000 Hour Fuels

The 1000 Hr fuel moisture and the Keetch-Byram Drought Index are two NFDRS indices commonly used to track fire danger in these soils.

The 1000 Hr. fuel moisture has been commonly considered an index of ground risk because organic soils and these large fuels require extended drying time before they become available for burning. Review of the southern NC Coastal Plain 1000 hour fuel moisture history has shown the moisture content range of these fuels ranges from 15% to 55%. Only 1 % of all historic values are above 29% (completely saturated) while 12 % of the values are at or below 18%.

Mean monthly values for 1000 hour fuel moistures drop below 20% from mid-April to mid–August. A threshold of 19 % is sometimes considered an index of fire danger in organic soils. Several prescribed fires were conducted at 1000 hour moistures below 20% (Fig 17). The results show that the 3 burns did not support any consumption of the organic soil horizons. The study plan for the fourth burn called for conditions that would support soil consumption. These results suggest that the 1000 Hr fuel moisture is an inconsistent measure of fire danger in these soils

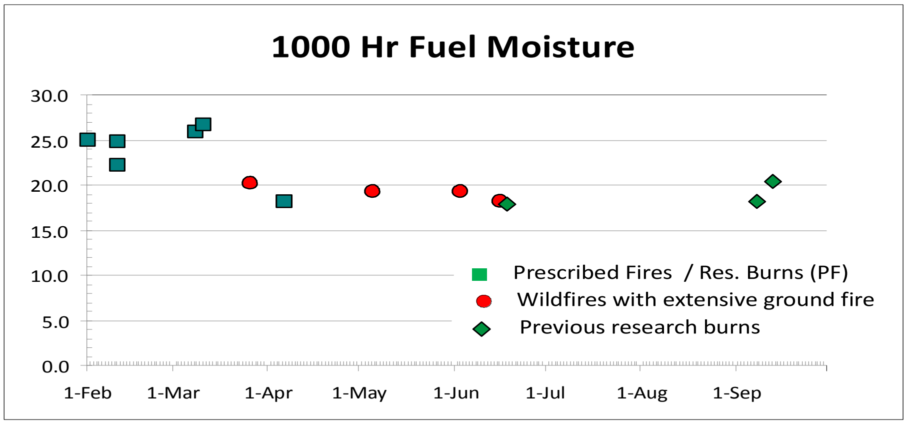

Figure 17 NFDRS 1000 Hr. fuel moisture for research burns and recent wildfires

Keetch-Byram Drought Index (KBDI)

The KBDI was developed as an index of the 'flammability of the organic material in the ground (Keetch and Byram 1968) and is used by fire managers as an index of the ignition and smoldering potential of duff and organic soils. It is useful over a range of climatic conditions because it utilizes mean annual rainfall as an expression for several interrelated assumptions. These assumptions are centered on generalized vegetation, rainfall and moisture loss relationships. As a result there is no expression of plant community, soil or hydrologic control of moisture dynamics or productivity in this index.

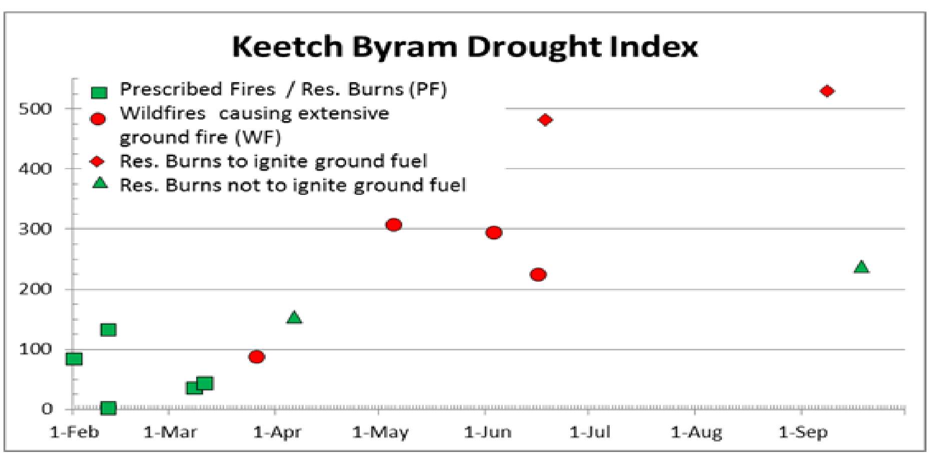

Figure 18. NFDRS- Keetch Byram drought index for research burns and recent wildfires

At landscape scales on the southeastern coastal plain, plant communities on thick organic soils and mineral soils often function in under very different soil moisture regimes. In comparison with mineral soils, root mat soils are highly porous and the amount water stored and drained by gravity is significantly greater. Due to the larger pore size this water is not held as 'tightly' as expected in a sand, silt or clay soil and as a result these soils discharge more water than mineral soils under similar conditions. The results in significant water movement between the root mat and the underlying muck soils. The moisture change gain resulting from water table movement is an important process that is not part of KBDI.

The results of this study show the limited sensitivity of the KBDI to soil and hydrologic differences in the pocosin communities. KBDI values of the burns conducted for this study were below 200. The Edna Buck Fire however occurred when the index value was 87 when one would assume that ground fuel would be fairly wet and potential for ground fire was low. This was also the case for the other recent wildfires examined. The Pains Bay, Evans Road, and Dad wildfires began with KBDI Values of 307, 294, and 224 respectively. All these fires were below the 400 to 450 values that are considered a threshold indicator of increased fire danger. These wildfires burned surface and grounds fuels over a land area of +100,000 acres. In comparison, our research burns were conducted at KBDI vales that ranged from 200 to 585. The results show there was no soil consumption on two of the units and the consumption of the third unit was consistent with our ESP predictions.

Soil moisture measurement/monitoring methods

The root mat ESP model requires only soil moisture and soil mineral content as inputs. While an "average" mineral content can be assumed, real time soil moisture inputs are difficult to obtain. Efficient soil moisture data collection is a major constraint on the application of this research. While there are costs associated with the purchase of laboratory oven and balances are apparent, the true cost of a moisture monitoring program includes both equipment and a time commitment. Over time, the costs associated with sample collection and processing become greater than the initial investment in equipment.

Several alternatives were considered for possible improvement in soil moisture measurement monitoring: the use of microwave oven to reduce soil drying time; a remote data acquisition platform for real time data collection and the use of the planned SMAP satellite program.

Microwave Drying

Several factors limit the use of laboratory soil drying procedures in the prescribed fire preburn decision making process. The time needed for sample collection and the 24 hour drying time necessary for analysis limits the practical use of this method for moisture measurement. Microwave drying was evaluated as an alternative to conventional oven drying. Microwave ovens are an attractive alternative owing to a greatly reduced sample drying time and the availability of inexpensive and portable units.

Typically organic soils or forest duff placed in a microwave on high for extended periods of time will combust. We have developed a simple procedure that combines a lower power setting of 0.7 with alternate heating and cooling periods. Using heating and cooling periods of 3 and 10 minutes respectively, we have dried high moisture content samples in 40 to 50 minutes. Multiple small samples can be dried at one time in a similar time period. The drying procedure is described in Attachment #3.

This method was evaluated using a comparison of oven and microwave dried root mat soil samples from the Myers tract and Swamp road study sites. Paired samples with moisture contents between 25% and 210 % were dried in a standard laboratory and microwave ovens. The dried microwave samples were then oven dried to determine the residual moisture content.

Analysis shows a high correlation between the sample moisture contents determined using the two techniques. The results of linear regression between oven dried and microwave dried moisture contents showed a correlation of 0.99 and significant intercepts and coefficient terms (Table 2). The results show high predictability with a standard error of the estimated moisture content of (+ −) 3.116.

Perfect agreement between the estimates from the two techniques would result in a zero intercept and a slope coefficient of one. In this case the microwave estimates were lower than the oven dried estimates and the results suggest that the intercept term (-5.507) reflects the amount of residual water remaining in the sample. The range of the residual moisture remaining in the samples ranged from 2% to 6% with a mean of 4.1%

Dep Var: Oven Moisture N: 30 Multiple R: 0.999 Squared multiple R: 0.998

Adjusted squared multiple R: 0.998 Standard error of estimate: 3.116

Effect	Coefficient	Std Error	Std Coef	Tolerance	t	P(2 Tail)
CONSTANT	5.507	1.132	0.000	.	4.866	0.000
MICROWAVE	1.014	0.008	0.999	1.000	120.043	0.000

Oven Moisture Content = 5.507 + 1.014 * Microwave Moisture Content

Table 2. Regression analysis of oven and microwave drying techniques

This microwave procedure is a multistep drying process where the final heating/cooling step is determined by the comparison of the current sample weight with the weight of the previous heating cooling period. A lack of weight change at that time indicates no additional drying is necessary. While results show a bias toward low levels of residual moisture; the estimates are within 5% of the oven dried value.

ESP Stations

ESP stations are a prototype sensor platform built to monitor the smoldering combustion potential on organic soil sites (Figure 19). The function of these stations was to supplement local RAWS station capabilities with additional measurements that are of importance in estimating ground fire potential. In addition to their use in evaluating the usefulness of this technology these stations were also used during the course of this study to monitor prescribed burning conditions on 5 sites on the North Carolina Coastal Plain.

The stations were developed using "off the shelf "components and readily available sensors. The unit is powered by a sealed rechargeable battery (26 amp hour) and charged by a solar panel. Each station is controlled by a programmable GSM/GPRS modem (Terminus module from Janus Remote Communications). The sensors are interfaced to the modem through an RS232 4 port smart switch (BB Electronics).

The modem receives data from the sensors and transmits it to the cellular network and a gateway internet connection where it is currently directed to Xlively.com (formerly COSM.com). Xlively.com formerly charged nothing for their services but currently is a pay for service site. Two other similar web sites are Open.Sen.Se.com and Nimbits.com.

The use of cellular and internet communications for data transmission and collection applications is rapidly growing. The cost of equipment is dropping and there are an increasing number of Machine to Machine (M2M) and "the internet of things" sites that will host applications with little or no charge. In addition to data collection, storage and graphic display these sites (www.Xlively.com and www.Open.Sen.Se) also incorporate a number of features such as automatic notification by email or text when data values such as soil moisture exceed a programmed threshold or notification of presence of

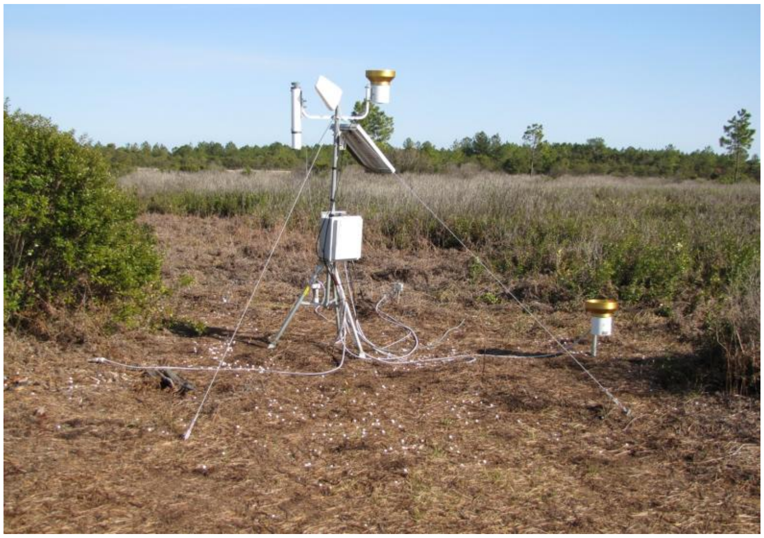

Figure 19. ESP sensor platform located at Pocosin National Wildlife Refuge

local lightning activity. These features show great potential for broadening our abilities to monitor changing fire danger or prescribed burning conditions.

A number of different sensor types were integrated into our design to demonstrate the potential of this technology. At each location the array of sensors measures soil moisture and temperature; fuel moisture and temperature; lighting activity; water table depth; evapo-transpiration; and rainfall data every 2 hours.

- Precipitation was measured using simple tipping buckets. Paired buckets were deployed to track precipitation at the top and within the pocosin shrub canopy.

- Evapotranspiration was measured with an ET gauge (Loveland, Colorado). This device is an automated atmometer which mimics the solar energy absorption and vapor diffusion resistance of irrigated crops.

- 10 Hour fuel moisture was monitored using electronic fuel sticks (Campbell Scientific, CS-505).

- Root mat soil moisture was measured using a number of prototype sensors that measured soil humidity as a surrogate for soil moisture. Unlike the homogenous structure of the muck soils, the structure of the root mat soils is highly porous. Soil moisture probes that are dependent on consistent contact along the probe surfaces do not provide reliable measurements in the porous root mat soil.

- Sapric muck soil moisture was monitored with soil moisture probes (Campbell Scientific, CS-615). These instruments were low maintenance and provided muck soil moisture data.

- Lightning Activity was measured by counting static discharges. This sensor provided an indication of local activity. No distance information or number of strikes is available from this sensor.

- Soil and fuel temperatures were monitored using a DS18B20 1-wire sensor element with 0.1^{o}C temperature resolution.

- Ground water surface levels were monitored using an Ecotone WM (Remote Data Systems, Navassa, North Carolina). This unit is an integrated data logger and water level sensor that was modified to respond to queries from the modem.

SMAP Satellite Program

An important constraint on the ESP use or the use of similar soil/duff consumption models is the limited spatial/temporal scale of the soil moistures collected on site or collected using automated soil moisture measurements. While the ESP sensor platform has provided us with ‘real time’ data, this data is an estimate of changing conditions at one point over time.

The purpose of the SMAP (Soil Moisture Active and Passive) satellite mission is to map soil moisture and freeze/thaw states on a global scale at 3 day return intervals.

The accuracy of soil measurements using radar is greatly influenced by the measurement frequency. Currently the EOS Advanced multichannel scanning radiometer and other instrument platforms use’ C’ and ‘X’ band channels (6 to 11 GHz) while the SMAP platform will utilize’ L’ band channels (1.4 GHz). The ‘C’ and’ X’ bands are highly sensitive to both soil moisture and vegetation while the lower frequency of L band response show a high sensitivity to soil moisture under a range of vegetation conditions.

The SMAP satellite combines lower frequency L-Band radar and radiometer measurements to estimate soil moisture. L-band radar is sensitive to soil moisture but is influenced by surface roughness and vegetation, while the radiometer is sensitive to soil moisture in areas with vegetation at high moisture contents but is limited by the coarse scale of its measurements. This combination of the two instruments offers more remote sensing potential than other technology currently in use.

The SMAP data products will be available at a number latencies and resolutions. Level I products will be available with latencies of 12 hours while intermediate Level 3 soil moisture products that combine the radar and radiometer data will be available at 50 hour latencies with resolutions of 9km.

More advanced modeling outputs to estimate soil moisture in the surface and root zone soils are available at 7 day intervals at a 9 km resolution. The SMAP algorithms have been field validated at a number of locations but this work has not incorporated any forested sites or sites with thick organic soils. Additional work is needed to investigate alternative ways of efficiently using this data as an input into our existing ESP models.

The timing of SMAP satellite deployment and our acceptance into the ‘early adopters’ program is a unique and unexpected opportunity to improve the application of our results. An application developed from the successful integration of the ESP model with satellite derived soil moisture data could be extended to similar soils from Virginia to Georgia. At present we have received limited funding to continue the use of ESP monitoring stations on the Dare County Bomb Range through September of 2015.

Summary

The estimated moisture content limit at which smoldering is sustained in muck soil is greater than limit estimated for root mat soil. In root mat soil, mineral content was an additional factor identified as significant. The mean mineral content of the study sites was consistent with our previous work and with the data used in the development of the estimated smoldering potential (ESP) model. XRD analysis showed that quartz sand was the dominate mineral on all study sites. At low concentration, such as present in root mat soils, the mineral content is expected to change the thermal conductivity without significantly changing the heat content of the soil. Although the density of sand is higher than water, the thermal conductivity and heat capacity of water are significantly greater than that of the mineral fraction. This makes soil moisture the dominant factor driving the heat transfer processes within the root mat and muck soil.

Soil structure and heat of combustion are two factors affecting the root mat and muck soil moisture limit difference. Structure is a major factor determining the water holding characteristics of these very different soils. Root mat soil is more readily drained and dried due to its porosity and its position at the surface of the soil profile. Through its connection with soil moisture and density, structure also influences the soil volumetric heat capacity which is the amount of energy needed to raise the temperature of a volume of soil. There was no significant difference observed in the heat output of the root mat and muck soils with the structure differences removed. However, TGA and DSC thermal analysis did show root mat and muck soil differences in thermal decomposition patterns in the absence of structure. The latter result suggests a connection between the thermal sensitivity of these soils and humic decomposition products.

Comparison of the root mat and muck ESP model outputs show that the low density porous root mat soil does not support smoldering at moisture contents above 170% while muck soils support smoldering at a greater moisture content of 270%. This analysis suggests that this moisture limit difference is the result of structural and chemical differences which determine soil thermal properties and effect the energy release and heat transfer within these soils.

Laboratory testing conducted to validate the root mat ESP model, showed a good to excellent fit in the model's ability to discriminate between smoldering and non-smoldering conditions. A prescribed burning moisture threshold was established based on model output and an assumed mineral content of 5%. At this threshold the root mat soil had an estimated smoldering potential of less than 5% which minimized the risk of ground fire. Although mineral content was a significant factor in the ESP model, the results of the ROC analysis show that the use of measured mineral content in place of an assumed 5% mineral content did not increase the model goodness of fit significantly.

The prescribed burns were conducted under high to extreme fire danger conditions to validate the model and investigate the possible linkage between surface fire behavior and smoldering. These burns were conducted at average root mat soil moistures above 170%. During these burns, the lower horizon muck soils were saturated (< 270%) and were not considered as 'available fuel'. The results were highly favorable. Five burns were successfully completed. Residual smoldering was present on one burn and suppression activities were conducted. However post burn examination of this unit showed that smoldering was associated with fire line construction.

The results of the prescribed burns, previous research burns and recent wildfires showed that an NFDRS output, which includes adjective rating classes, Energy Release Component (ERC), the 1000

Hr. index and the Keetch-Byram Drought Index, were insensitive to smoldering conditions. The latter two measures are commonly used to evaluate fire danger in these organic soils. These indices are derived from metrological data and while they reflect regional trends they are frequently used to access local conditions.

While these fire danger indices are insensitive to smoldering conditions, the practical application of the ESP model in prescribed fire and fire danger rating programs is limited by our ability to efficiently monitor changing soil conditions. Standard laboratory drying procedures are often impractical due to the time and equipment requirements. To reduce drying time, we developed a procedure utilizing an inexpensive microwave oven. Our laboratory results show drying time can be substantially reduced using a multi step drying procedure. Drying time was reduced from 24 hours to between 30 and 40 minutes or less depending on moisture content. Although this method reduces sample processing time, the time required for sample collection is a significant consideration.

As an alternative to soil sample collection and drying, sites can be monitored using automated data collection methods. Real time measurements are becoming increasingly attractive due to decreasing costs and advances in cell phone technology. A prototype cell phone based sensor platform was developed and deployed to monitor pre burn conditions on our prescribed burn units. These cellular units have several communication options. In addition to regular scheduled data transmission, there are opportunities for text messaging and email notification when data values such as soil moisture or lightning activity exceed programmed limits.

Remote Sensing or satellite technology is an alternative to the limited spatial/temporal scale soil moisture data obtained through a sparse network of automated data collection sites or limited soil sampling. The SMAP (Soil Moisture Active and Passive) satellite mission is to map soil moisture and freeze/thaw states at 3 day return intervals. This instrument offers more remote sensing potential than other technology currently in use. Based largely on the work presented in this report we became members of the NASA's SMAP early adopters group. Our sensor platforms are currently deployed in anticipation of the February 2015 launch date.

The ESP model output is a measure of organic soil potential to sustain smoldering combustion. The model's ability to discriminate between smoldering and non smoldering conditions was successfully validated by laboratory testing and prescribed burning. In comparison, the commonly used fire danger indices, which were developed as a measure of expected surface fire behavior, show low sensitivity to these conditions. Although this study was conducted in eastern North Carolina, the use of ESP is an alternative to these currently used indices and would be applicable to any fuel complex in the southeast comprised of similar organic soils or mineral soils with thick organic horizons

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Attachment #1 NFDRS outputs for prescribed burns and recent wildfires.

Previous Research Burns

	Croatan NF	Green Swamp	Green Swamp
Date	18-Jun-96	8-Sep-97	18-Sep-98
ERC	37	29	21
BI	47	27	20
IC	12	16	6
KBDI	482	530	238
SC	11	4	3
AT	86	86	85
RH	64	55	70
WSPD	7	7	6
1 Hr	8.5	7.4	11.2
10 Hr	10.3	9	12.3
100 Hr	17.5	15.6	16.6
1000Hr	17.9	18.2	20.4

Current Research Burns

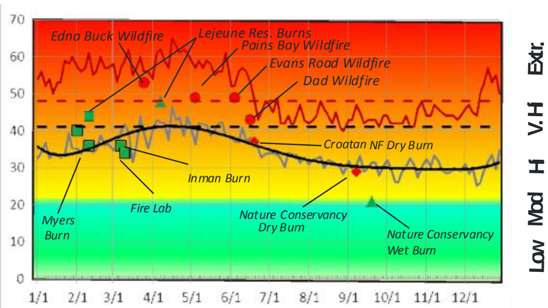
	Myers Tract	Fire Lab	Inman	Lejeune Rough	Lejeune Pocosin	Fire Lab
Date	1-Feb-09	11-Feb-09	8-Mar-12	11-Feb-10	6-Apr-10	11-Mar-14
ERC	40	36	36	44	48	34
BI	102	83	76	91	83	83
IC	35	18	22	28	25	30
KBDI	84	132	35	2	154	43
SC	70	70	70	70	70	70
AT	59	71	75	47	83	77
RH	34	59	41	38	49	36
WSPD	12	11	8	9	7	8
1 Hr	5.8	9	7.2	5.9	6.7	5.8
10 Hr	8.6	10.7	9.7	8.1	8.5	8.5
100 Hr	19.9	17.7	19.7	16.9	15.4	19.3
1000Hr	25	22.1	19.7	24.7	18.5	26.8

Recent Wildfires

	Edna Buck	Evans Rd	Pains Bay	Dad Fire
Date	26-Mar-08	3-Jun-08	5-May-11	16-Jun-12
ERC	53	49	49	43
BI	104	85	87	93
IC	46	27	31	23
KBDI	87	294	307	224
SC	42	29	30	41
AT	70	84	68	78
RH	23	39	35	52
WSPD	9	7	7	13
1 Hr	3.7	6.1	5.2	7.9
10 Hr	6.2	7.9	7.5	9.4
100hr	16.3	15.2	16.6	15.3
1000Hr	20.2	19.3	20.2	18.1

Attachment #2 Fire Danger Pocket Card for Pocosin Fuels in North Carolina

FIRE DANGER– Whiteville District (D- 8)
Maximum, Average, 91st & 72nd Percentiles



- Prescribed Fires / Res. Burns (PF) not to ignite ground fire
- Wildfires causing extensive ground fire (WF)
- Res. Burns to ignite ground fuel
- Res. Burns not to ignite ground fuel

Fire Danger Area:

NC Coastal Plain / Southern

NWS Forecasting Office Wilmington

Whiteville RAWS – a mainstay station for

Fire Danger Interpretation:

EXTREME -- Use extreme caution
(Caution) -- Watch for change
Moderate -- Lower potential, but always be aware

Maximum -- highest ERC by day for 2002 -09
Average -- Shows the past fire seasons averaged for Whiteville SIG
91st Percentile -- **Only 9%** of the days from 2000 -14 had an **ERC above 48**. On 3/26/08 the **Edna Buck Fire** (1,154acs.) **ERC was at 49**.
72nd percentile - At this threshold, an ERC of 41, Airtankers are usually requested to support suppression efforts

Local Thresholds -- *Watch out* : Combinations of any of these 3 factors can greatly increase fire behavior. Notable fires have **averaged Wind speed** 7mi/h, **RH** 38 %, & **Temperature** 77° F.

revised 10/7/2014	ENERGY RELEASE COMPONENT Average Seasonal Values	Average High Values	Max Value Observed
January	34	40	60
February	36	44	61
March	38	46	62
April	42	50	65
May	40	48	61
June	37	44	57
July	33	39	49
August	31	38	48
September	31	38	47
October	30	40	48
November	30	39	47
December	30	38	57

Remember what Fire Danger tells you:

- ERC gives general seasonal trends calculated from precipitation, temperature, and RH.
- Wind speed is not part of the ERC calculation.
- Watch local conditions and variations across the landscape--Fuel, Weather, Topography
- Listen to weather forecasts-especially WIND.

Energy Release Component is a number relating to the available energy released from forest fuels at the head of a fire's flaming front. ERC is a composite of live & dead fuel moistures. It is a very good reflection of drought conditions. It is a "build up" type index. Given a fire start in a fuel with a high ERC, fire containment can be expected to be difficult. ERC is very valuable in assessing the depth of a burn, consumption of the various fuel sizes, residual burning , mop -up requirements & Air Tanker support.

Attachment #3 Microwave Oven Drying Procedures.

MICROWAVING TO FIND PERCENT MOISTURE

- Place glass Petri dish on scale and tare to "0".
- Put sample into glass Petri dish – enough sample to adequately cover the bottom of the tray without mounding.
- Record sample weight – this will be your **Start** weight.
- Put sample into microwave, set microwave for 5 minutes on power (5). Power level is based on an 1100 watt microwave. Start microwave.
- Once microwave has stopped, remove sample from the microwave (using a gloved hand) and place on scale.
- Set timer for 10 minutes and start.
- After 10 minutes, record the weight and put sample back into microwave.

** Microwave sample until weight has become stabilized. This should be approximately 30 – 40 minutes of cool time per sample.

Example:

Microwave Time (min)	Power	Weight	Cool Time (min)			
Start		5.25				
5	5	1.82	10			
5	5	1.72	10			
5	5	1.72	10			
Total: 15			**30**			
Cruc # 69	Cruc + Sample	Wet Wt	Post Oven Wt	Dry Wt	% Moisture	
31.48 g	32.53	1.05	32.5	1.02	3 %	

- To find the % moisture for the original sample you will take the start weight (1st weight before microwaving) and subtract the final microwave weight from that number. The remaining number will be divided by the final microwave weight again to provide the % moisture.
  - Example (using numbers from table above):

    (5.25-1.72)/1.72 = 2.05 * 100 = 205%

** 205% is the original sample moisture.

Deliverable Crosswalk

Field and Laboratory Studies.

Conducted six prescribed fires to validate the ESP model and demonstrate the use this model to fire managers. These burns were also used to evaluate the sensitivity of the currently used NFDRS indices to smoldering in organic soils.

Conducted laboratory studies to address gaps in our understanding of smoldering in these soils. This work included: the measurement and analysis of the mineral fraction of these soils; the characterization of the degree of soil decomposition and its effect on heat output and the moisture limits of sustained smoldering; the laboratory testing and validation of the ESP model and the characterization of the ESP model goodness of fit and sensitivity to moisture content.

Publications:

Smoldering Combustion Limits of Organic Soils in North Carolina. Spring 2009. J.Reardon and G.Curcio. The Stand Manager, Volume 4, Issue 1. North Carolina Division of Forest Resources

Estimated Smoldering Potential (ESP). August 2009. J. Reardon and G.Curcio. US Forest Service Southern Smoke Issues Volume 2. Issue 2. Southern Research Station-Center for Forest Disturbance Science and High Resolution Modeling Consortium

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Estimated Smoldering Probability: A New Tool for Predicting Ground Fire in the Organic Soils on the North Carolina Coastal Plain. Fire Management Today Vol(7) No 3 2011

Presentations :

Estimated Smoldering Potential (ESP): a decision support tool for prescribed fires on Organic Soils in North Carolina. James Reardon, RMRS Fire Science Laboratory and Gary Curcio, North Carolina Division of Forest Resources. 8th Symposium on Forest and Fire Meteorology sponsored by the American Meteorological Society, Kalispell, MT

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A Case Study of the Pains Bay Fire, Stumpy Point North Carolina Gary Curcio and Jim Reardon Fire and Forest Meteorology Conference Oct 2011, Palm Springs, CA

Status of current research on moisture limits of smoldering combustion in organic soils, NWGC Fire Danger, Smoke and Fuels management committees, May 2012

"Smoldering Combustion of Organic Soils on the North Carolina Coastal Plain, INTECOL - International Wetland Conference, Orlando FL, June 2012

Blending Fire Management Tools In Support Of Planned Fire Ignitions On Organic Soils A Case Study at Camp Lejeune / Jacksonville, North Carolina. Gary Curcio, North Carolina Division of Forest Resources and James Reardon, RMRS Fire Science Laboratory.

Emission Inventories- Informing Emerging Issues, 19th Emission Inventory Conference. . Sponsored by the EPA .

Tech Transfer / Workshops

Estimated Smoldering Limits of Organic Soils. NWCG Fire Environment Committee Meeting, Silver Spring,MD, 06/02/09.

Estimated Smoldering Limits of Organic Soils. NCDFR Forest Protection Meeting, Raleigh, NC. 09/04/09

Estimated Smoldering Limits of Organic Soils. NCDFR Region 1 District Supervisors Meeting, Kinston, NC 09/09/09

Current research on moisture limits of smoldering combustion in organic soils, NWGC Fire Danger, Smoke and Fuels management committees, May 2011

Estimated Smoldering Potential - a decision support tool, Fire and Pocosins Workshop , Maple Hill North Carolina, Oct 2011

Current research on moisture limits of smoldering combustion in organic soils, NWGC Fire Danger, Smoke and Fuels management committees, May 2012

The Estimated Smoldering Probability use in fire danger rating. NWGC Fire Danger Subcommittee meeting . Missoula, Mt. 5/2012

Development of a smoke management card and knowing your ESP, Southern Blue Ridge Fire Network Learning workshop, Ashville ,NC May 1012

Estimated Smoldering Potential - an operation tool for fire practitioners, Wildland Fire PM Emission Factor Work shop, EPA regional Office, Atlanta GA

Tech Transfer/ software development

The ESP model will be incorporated in FOFEM in the latest version that is due to be released in 2015. It was thought to be more practical to incorporate this model in an existing accepted software platform rather than develop a standalone application.

A prototype sensor platform was developed to supplement the existing RAWS network with measurements needed monitor changing soil moisture conditions. This platform necessitated the development of web site software and cellular modem programming needed to collect data from the sensors and transfer it through a cellular gateway to the data collection website. At the time of development commercial option were expensive and limited. Commercial alternatives are available today due to Technological improvements and decreasing costs