Project Title: Influence of fuel moisture and density on black carbon formation during combustion of boreal peat fuels

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I. Abstract:

In this study, we quantified the production of fine particulate matter during smoldering combustion of organic peat soils common to boreal forested and non-forested ecosystems of the Great Lakes region, Northeast USA, Alaska, and Canada. Additionally, we investigated spectral reflectance-based methods for the non-invasive assessment of peatland water table position and surface peat moisture content. This study capitalized on management prescribed burns at the USFWS Seney National Wildlife Refuge (SNWR) as well as ongoing projects at the USFS Northern Research Station PEATcosm facility as well as the USFS Fire Sciences Laboratory facility. Using a handheld spectroradiometer, we evaluate the utility of a variety of near infrared spectral reflectance indices in predicting water table position and surface peat moisture content both in the field and in the PEATcosm water table manipulation mesocosms. We found a good agreement of water table depth and soil moisture with the narrow-band dynamic floating water band index ($fWBI_{980}$) and broad-band MODIS-derived SWIR, suggesting its utility for assessment of fuel condition and fire danger rating. During a wetland prescribed burn at SNWR and experimental burn trials at the Fire Sciences Lab we quantified smoke plume fine particulate matter ($PM_{2.5}$) emissions as they relate to natural or conditioned fuel moisture content to examine the influence of fuel condition on smoldering smoke emissions. Both the lab and field burns exhibited OC:EC signatures of low temperature smoldering combustion. While the controlled lab burns did not demonstrate a direct influence of peat fuel moisture or density on $PM_{2.5}$ emissions, the indirect influence of high fuel moisture (>200% GWC) on reducing the extent of smoldering resulted in a threshold response of total and organic fraction $PM_{2.5}$ emissions. Fuels conditioned to 50%, 110%, and 170% gravimetric water content averaged 83% dry fuel mass loss and showed greater total and organic fraction $PM_{2.5}$ emissions than those at 230% or 300%, which averaged (with high variance) 43% fuel reduction. Within the low-moisture treatments, surface (top 6cm) fuels produced lower organic $PM_{2.5}$ emissions than deeper (6-12cm), denser fuels. However, black carbon (BC) emissions were constant across all fuel moistures and sources. These findings highlight the importance of peatland fire emissions for regional inventories and their contribution to air quality and atmospheric forcing. Land and fire managers can use this information 1) in the development of fire danger and behavior assessment protocols using remote sensing platforms for expansive peatland landscapes, 2) when evaluating air quality and smoke management risk in prescribed fire planning or wildland fire suppression decisions, and 3) in the development of historical and current inventories of fire emissions in peatland areas based on qualitative assessments of peat smoldering. These findings and their implications will improve our understanding of peatland fire behavior, its consequences for local air quality, and its impact on global atmospheric forcing.

II. Background and Purpose:

Over the past decade, peat fires have emerged as an important issue for global climate change, human health, and economic loss (Morrissey and others, 2000; Page and others, 2002; Taylor, 2010). Smoke from burning peat threatens the health of local communities due to fine POM and mercury emissions (Turetsky and others, 2006). Boreal wildfires in Alaska and Canada have a disproportionately large influence on global black carbon (BC) and particulate organic matter (POM) emissions (Preston and Schmidt, 2006; Flanner and others, 2007). Black carbon is important in soil carbon storage (Preston and Schmidt, 2006), atmospheric radiative forcing (Jacobson, 2001), and melting of montane and high latitude snow and ice (Ramanathan and Carmichael, 2008; Chaubey and others, 2010). Once emitted to the atmosphere as aerosols or POM, BC can increase radiative forcing in the upper and lower atmosphere due to its ability to absorb solar radiation (Ramanathan and Carmichael, 2008).

From a fuel perspective, peat has a relatively high density and moisture content compared to typical forest or grassland fuel types. Smoldering is typically the dominant form of combustion in peat fuels due to greater fuel packing ratio and soil moisture compared to other fuel types (Frandsen, 1997). Surface peat fuels are capable of ignition at fuel moistures in excess of 120% (on dry fuel basis) ((Frandsen, 1997), although more dense peat can exhibit sustained smoldering at fuel moistures as high as 295% (Benscoter and others, 2011). The energetic constraints posed by moist, dense peat fuels increase the potential for incomplete combustion during peat fires (Benscoter and others, 2011), providing a potential mechanism for increased formation and emission of BC during boreal wildfires. As such, physical properties of surface fuels (such as bulk density and moisture content) affect burn characteristics (flaming vs. smoldering combustion; (Miyanishi and Johnson, 2002)), and also likely influence the conversion to BC (Kane and others, 2007; Kane and others, 2010) or fine particulate elemental C (Andreae and others, 1988). While the influence of fuel condition on peat combustion has been studied (Frandsen, 1997), the implications of fuel moisture and density on the formation and emission of BC and POM are lacking. As fires in primarily peat soils have an important role in global BC dynamics (Preston and Schmidt, 2006) and the role of wildfire in high latitudes is projected to increase with climate change (Flannigan and others, 2005; Turetsky and others, 2011; Turetsky and others, 2015), process-level information regarding BC emissions during peat fires is vital for regional modeling of black carbon.

In addition to understanding the controls on BC emissions, resource management and modeling activities need methods for rapidly assessing fuel conditions over relevant spatial scales prior to burning to estimate the potential for BC formation and emission. One of the challenges is that accurate determination of peat moisture is often destructive (as in gravimetric determination) or requires equilibration time with the soil matrix (as in moisture block techniques). However, recent developments in field portable spectral imaging devices, which measure reflectance in the near infra-red (NIR), provide a promising method for sensing changes in surface moisture characteristics over large areas. As such, spectroradiometry of the peat surface immediately prior to burning is likely to prove as an invaluable tool in assessing surface moisture controls on combustion. Moreover, overlaying pre-burn surface moisture data and fuel composition with post-burn characteristics is likely to provide mechanistic insight as to the controls over BC formation in wildfire.

In this project, we assessed 1) the utility of spectroradiometric techniques for quantifying surface peat fuel moisture and 2) the influence of peat moisture content and peat density on smoldering fuel consumption and BC emissions. This information on drivers of smoke BC emission during peat smoldering and the development of methods for non-destructively and rapidly assessing peat fuel moisture will help inform fire behavior and emission inventory models to provide guidance for fire and land managers and more informed estimates of peatland wildfire contributions to regional carbon cycling and atmospheric forcing.

III. Study Description and Location:

Spectral detection of surface peat fuel moisture conditions

This activity evaluated the utility of employing optical remote sensing in assessing the moisture status of peatland ecosystems. This was achieved through a series of experiments in peatland mesocosms as well as in the field. Specifically, we (i) investigated the relationship between the spectral response of the *Sphagnum* surface and both water table position and near surface moisture content under assemblages of vascular plants spanning a range of species compositions and densities, (ii) with the aid of extreme, experimental water table drawdowns, further investigated these relationships under an extended range of moisture conditions including conditions more commonly observed prior to wildfire, and (iii) conducted exploratory data analysis to further assess the ability of space borne sensors to monitor near surface moisture content and water table positions, which could ultimately be employed to dynamically assess the vulnerability and susceptibility of peatland ecosystems to wildfire.

This activity was conducted at an experimental peatland mesocosm facility (PEATcosm; facility description at http://www.fs.usda.gov/ccrc/climate-projects/research/soil-carbon-dynamics-peatlands-peatcosm), located as the USDA Forest Service Northern Research Station in Houghton, MI, and at a poor fen peatland field site near Nestoria, MI (field site). The PEATcosm experimental facility consists of 24 intact monoliths ($1m^3$) of peat extracted from an extensive oligotrophic peatland in Meadowlands, MN in 2010. Water table (WT) elevation regime for replicate monoliths was managed at either the long-term average WT (high WT treatment) or the low WT range recorded at Marcell Experimental Forest (near the collection site). As the water table and vegetation was recorded in detail and varied among monoliths, the surface characteristics could be directly compared to measured spectral reflectance. At the field site, volumetric surface peat samples were destructively harvested for assessment of gravimetric fuel moisture at the time of spectral data collection across a range of ground vegetation (moss) community types in a natural setting for comparison to the mesocosm results.

An ASD Fieldspec 3 spectroradiometer (Analytical Spectral Devices, Boulder, CO) was used to collect spectral data at both the PEATcosm facility and Nestoria field site under clear-low haze conditions from an elevation of 1m (14cm FOV). The spectral signatures were processed into narrowband and broadband spectral indices (MSI, $fWBI_{980}$, and $fWBI_{1200}$). These indices were then correlated to the measured VMC and water table position using linear mixed models with repeated sampling and the results and sensitivities of the relationships compared among dominant plant species.

Fuel condition controls on smoldering black carbon emissions

This activity used experimental combustion trials at the RMRS Fire Sciences Laboratory in Missoula, MT, to quantify the BC emissions generated by smoldering combustion of natural peat across a gradient of fuel moisture content with high and low bulk density. Peat samples were collected from the Nestoria field site in 10cm diameter soil sample tins to a depth of 6 cm for both the surface horizon (0-6cm) and the underlying horizon (6-12cm) as peat density increases with depth (low and high density treatments, respectively) and cumulatively would represent average (surface horizon only) and severe consumption scenarios (surface + deep horizons). Samples were transported to Missoula where they were dried to achieve the target gravimetric moisture content. As completely dried peat becomes friable and difficult to rewet consistently, the samples were partially dried using a microwave oven to achieve the target moisture content. A 2cm dia. core was extracted from each sample, weighed, dried, and weighed to quantify current moisture content and dry bulk density, which were then use to calculate the target wet sample mass corresponding to the appropriate fuel moisture condition. Once conditioned, the fuel samples were placed in individual ceramic fiberboard boxes (6 per moisture x density treatment) and moved to the indoor burn chamber at the Fire Lab. A feedback process controller connected to a cartridge heating element embedded in a 2cm dia., 6c, long aluminum spacer bearing (which acted as thermal inertia to increase surface area and prevent overheating) was used as the ignition device, with a “ramp and soak” ignition regime where the element was increased to 500 ^{o}C over a 20 minute interval and then held for 40 minutes before turning off. The bearing/heat element was inserted vertically into the center hole made when collecting the cores for conditioning and all six replicates were ignited simultaneously under the collection hood in the burn chamber and allowed to burn for an additional hour (total 2 hour burn time for each treatment). This process was repeated for each moisture x density treatment.

During the burns, the cumulative mass of the fuel platform was recorded. Particulate matter ($PM_{2.5}$) and BC emissions were monitored from the cumulative smoke plume from the platform above the smoke collection hood. Duplicate cyclone samplers collected $PM_{2.5}$ samples on preconditioned filters for the duration of the burn trials, which were later analyzed for organic and inorganic emission fractions using the IMPROVE_A protocol at the Desert Research Institute. Additionally, BC emissions were assessed using an AE51 microAeth (AethLabs, San Francisco, CA) real-time BC aethalometer installed at the same collection height in the smoke stack.

Following each trial, the final cumulative mass of the fuel platform was recorded and the individual samples reweighed to calculate mass loss. The residual fuels were then dried and weighed to determine dry fuel mass and water mass loss. Total and fractional emissions were regressed against the treatment fuel moisture conditions for the low and high density fuels separately, with and without adjustment for cumulative fuel mass consumption.

Smoldering emissions during peatland prescribed fire

This activity used prescribed burning at Seney National Wildlife Refuge (SNWR) in planned burn units with organic surface soils to correlate soil fuel conditions with particulate emissions in a field setting. Prescribed burns at SNWR were opportunistically coordinated with refuge management objectives. In order to minimize the likelihood of deep soil burning, burn prescriptions limited activities which were further limited by prevalent severe potential fire behavior conditions; as a result, the activity was limited to a single burn in 2013. Much of the area burned consisted of hydric soils dominated by wet sedge meadows and shrubs. These burn units predominantly had shallow organic horizons. However, within the burn units there were several 1 to 5 acre “pockets” of Sphagnum peatland ecosystems with black spruce and tamarack overstories.

Within the burn units, we measured surface soil moisture gravimetrically the day prior to the scheduled burn. We set up a High Volume air sampler downwind of the burn, with its generator also being located downwind of the collector. Filters were harvested at regular intervals and stored in mylar bags until analysis. Ratios of organic carbon to elemental carbon (OC:EC) were measured using a Sunset Labs analyzer at MTU.

IV. Key Findings:

Spectral reflectance is an effective predictor of peatland ground fuel moisture and water table depth.

Spectral indices in the near-infrared (NIR) band can be used to predict surface fuel moisture conditions in highly organic (peat) soils across a wide range of soil moisture conditions, including those supporting peat combustion during wildland fire. The dynamic $fWBI_{980}$ and WI outperformed indices using the visible spectrum in prediction of both water table depth and surface soil moisture. However, ericaceous shrubs may disrupt the spectral reflectance signal by occluding the moss-covered ground surface; therefore, the use of NIR or visible band spectral reflectance may be limited in peatlands with high ericoid shrub cover. Lastly, there was a high degree of congruence between narrow- and broad-band spectral indices and their capacity to predict water table depth and surface soil moisture in peatlands. Therefore, large area monitoring of peatland hydrologic condition and fire risk may be possible from broad-band multispectral Earth Observation (EO) platforms like MODIS.

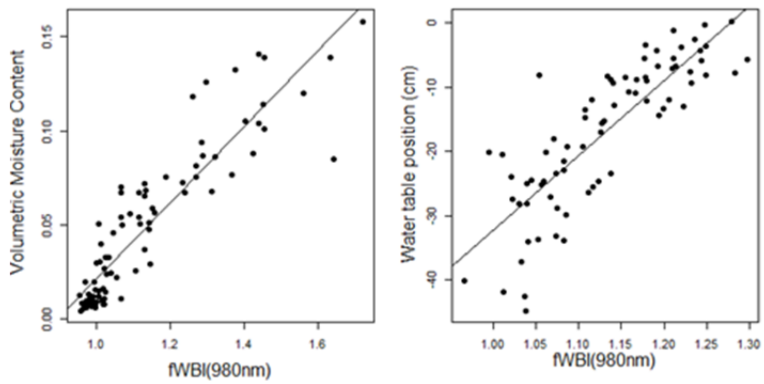

Figure 1. Correlation between the dynamic floating Water Band Index ($fWBI_{980nm}$) and peat volumetric water content (g cm^{-3}; left) and peatland water table elevation (right; (Meingast and others, 2014)).

Peat fuel moisture does not directly influence smoldering $PM_{2.5}$ or BC emissions, although indirect influence on fire behavior can increase organic $PM_{2.5}$ smoke emissions.

No significant relationship was found between fuel moisture and the emissions produced during smoldering. However, fuel moisture indirectly influenced particulate emissions through 1) promoting smoldering over flaming combustion and 2) controlling the rate of smoldering and subsequent emissions. Smoke emissions from the prescribed burn had high OC:EC (~20) and low EC:TC (0.05) in the $PM_{2.5}$, indicating relatively incomplete fuel combustion and low combustion temperatures that would be expected during smoldering ground fire. Likewise, the burn trials at the Fire Research Lab produced smoldering soil combustion across the full range of fuel moistures and both fuel density classes, although brief flaming was observed in the low density fuels at the lowest moisture content (50% GWC). Overall, OC:EC was greater for high density fuels (72±8) than surface fuels (46±5), with both indicating incomplete combustion products similarly to the prescribed burn. However, fuel consumption (% dry mass loss) showed a threshold response to GWC regardless of density, with treatments of GWC<200% consistently averaging 84±7% dry mass loss and those over the 200% threshold averaging nearly half (43±35% dry mass loss) with a high degree of heterogeneity among the six replicates for each treatment. The high moisture treatments had reduced total $PM_{2.5}$ emissions compared to the low moisture treatments, although there were no significant differences in EC from the quartz filter samples or BC from the MicroAethalometer. Within the low moisture treatments with near complete fuel consumption, the high density (deep) soils had greater total $PM_{2.5}$ emissions due to increases in the organic fraction. These results suggest peatland burning during low water table or surface GWC conditions can result in not only increased depth of burning and soil carbon loss but can also increase the rate and quantity of $PM_{2.5}$ emissions. Considering the fuel bed used in these emissions estimates represents less than 500 cm^2 of peat surface, smoldering during peatland fires can have a substantial impact on regional $PM_{2.5}$ and BC emissions in the Great Lakes region as well as the Northeast US and Alaska where peatlands are prevalent on the landscape.

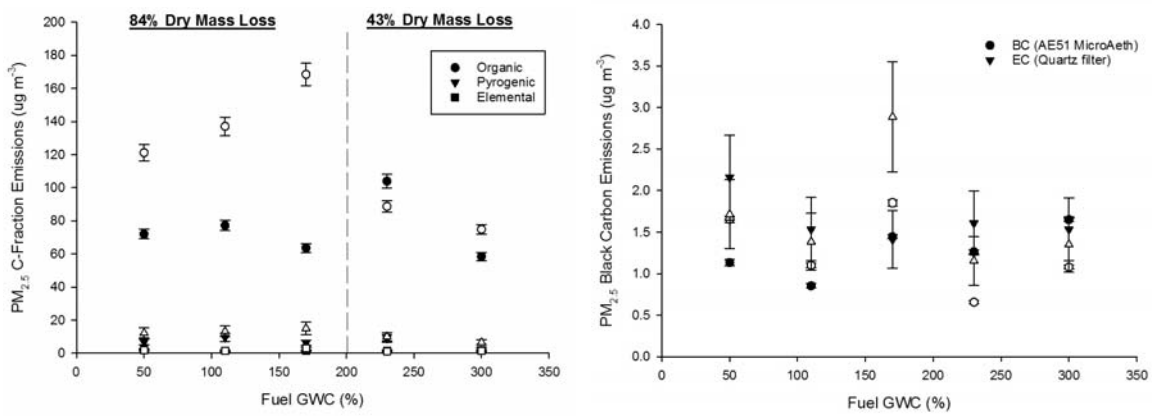

Figure 2. Influence of GWC on $PM_{2.5}$ emissions for all fractions from quartz filter samples (left) and elemental/black carbon from quartz filters and an AE51 MicroAethalometer (right). Solid symbols denote surface (low density) fuels and closed symbols are deep (high density) fuels. Error bars reflect the uncertainty in estimates from quartz filters received from the Desert Research Institute and the standard error of the estimate for the AE51.

V. Management Implications:

Remote sensing applications can be used for estimating peatland water table position and surface soil fuel moisture, which can inform fire behavior assessment models.

The spectral reflectance-based methods and their potential implementation from EO remote platforms can provide valuable information on surface fuel conditions that can be used by fire managers for predicting fire behavior and fire danger in land management units with expansive peatlands. While the application is currently limited by the resolution of MODIS, other hyperspectral EO platforms have the potential to expand the application to small peatland extents. These tools and information can be valuable for non-fire related management purposes, such as hydrologic monitoring and management and evaluation of landscape productivity and carbon cycling, which are strongly linked to water table position and peat moisture conditions in peatlands.

Expanded capacity to represent and accurately estimate $PM_{2.5}$ emissions during peatland fires for regional or national air quality and emissions inventories.

Smoldering particulate emissions exhibited a threshold response to fuel moisture that was more directly related to the extent of smoldering combustion. Therefore, qualitative post-fire assessments of smoldering (e.g., high vs low extent) can be used to extrapolate the emissions found here to assist in the development of smoke inventories for prescribed or wildland fires. This can be of particular use during wildfires where monitoring resources or site access may be limited due to fire management priorities. This information can also be of use in the development of regional or national BC and $PM_{2.5}$ inventories to more accurately represent the influence of prescribed and wildland fires on air quality and atmospheric radiative forcing.

Inform guidelines of air quality risk and smoke management for prescribed burn permitting and wildland fire management decision-making.

As peat smoldering and its emissions exhibit a threshold response at 200% GWC, with diminished smoldering extent and particulate OC emissions above this tipping point, prescribed or wildland fire management decisions can be structured to minimize the likelihood of burning when direct measurements or indirect indices (such as the spectral indices investigated in this study) suggest a high smoldering risk due to low peat fuel moisture content.

VI. Relationship with recent findings and ongoing research:

Investigators Benscoter, Kane, and Falkowski, in collaboration with a multidisciplinary team of remote sensing and fire science researchers, are currently investigating the role of peat fuel moisture content on Fire Radiative Energy (FRE) emission during peatland fires. Coupled with process based models of lateral and downward heat transfer and smoldering potential in peatlands (Chen and others, 2015; Huang and Rein, 2015; Lukenbach and others, 2015) as well as heat transfer by flaming fire fronts to the soil surface (Finney and others, 2015; Thompson and others, 2015), our findings can contribute to a comprehensive understanding and modeling fire behavior, combustion severity, and resulting atmospheric emissions in peatlands as well as northern coniferous forests with thick duff layers.

Waddington et al. (2011) found the drought code (DC) component of the Canadian Fire Behavior Prediction system to be an effective indicator of peatland fire risk, although the weak link between precipitation-driven water table position and actual peat surface moisture limits the direct assessment of surface smoldering risk and they suggest the development and incorporation of peat moisture index to better reflect ground fire behavior potential. The spectral reflectance applications for detecting surface moisture may provide insight for the development or evaluation of such an index, as well as the assessment of first-order fire effects in peatlands.

Recent work by French et al. (2014) highlights the need for remote sensing-based estimation of historical fire activity and smoke emissions, in particular for informing the Wildland Fire Emissions Information System (WFEIS). As WFEIS couples MODIS land cover products of burn area with CONSUME derived emissions estimate, the relationships between MODIS-derived fuel moisture indices and $PM_{2.5}$ emissions for peatlands developed in this study can be used to validate or refine the emissions assessments through the WFEIS.

VII. Future Work Needed:

To improve assessment of peatland burning effects on air quality and atmospheric forcing, future work is needed to:

- Develop emissions factors of $PM_{2.5}$ fractions during peat fuel smoldering and evaluate their relationship to modified combustion efficiency (MCE) to improve rapid assessment capabilities based on trace gas measurement.
- Link particulate emission rates to process models of fire behavior to provide tools for assessing impacts of peatland burning either for the development of improved smoke inventories or for risk assessment and fire management decision-making.
- Quantification of the contribution of peatland surface (i.e., shrubs and sedges) and canopy fuels 1) to total smoke emissions and 2) to heat transfer to soil (duff) fuels and the effect on smoldering propagation.
- Evaluation of the effect of overstory canopy on MODIS or other multispectral derived estimation of surface soil moisture and water table position in peatlands, and incorporation of fuel moisture-emissions relationships into smoke inventory systems like WFEIS.

VIII. Deliverables Crosswalk Table:

Proposed Deliverable	Deliverable Status
Progress Reports	Progress reports were submitted for each year of the project period
Conference Presentations (2 proposed)	3 presentations delivered (North American Carbon Program 2013; American Geophysical Union (AGU) 2014; Botanical Society of America 2014) 2 presentations pending (2016 Ecological Society of America (ESA) and Society of Wetland Scientists conferences)
Conference Symposium (1 proposed)	1 organized session at the 2014 AGU conference Tentative session on wetland fire at 2016 SWS conference
Refereed Publication (2 proposed)	1 publication in print (Meingast et al. 2014) 1 manuscript in draft Contribution to one tentative review manuscript
Master's Thesis (1 proposed)	1 Master's thesis completed (K. Meingast, 2013, Michigan Tech University School of Forest Resources)
Stakeholder Seminar (additional deliverable)	Seminar contribution by Co-I Kane to a Project Scientist Planning Meeting at the USFS Forest Products Laboratory in Madison, WI (Apr. 2015)

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