Consumption of the Organic Layer in Southern Sweden During Fire Events and Correlations with the Canadian Forest Fire Weather Index (FWI) Risk Ratings

Blake Mccallum Jordan

Supervisors: Mats Niklasson, Swedish University Agricultural Sciences
Bronson P. Bullock, North Carolina State University
Richard R. Braham, North Carolina State University
James B. McCarter, North Carolina State University

Swedish University of Agricultural Sciences

Master Thesis no. 209

Southern Swedish Forest Research Centre

Alnarp 2013

Bilateral Cooperation

Consumption of the Organic Layer in Southern Sweden During Fire Events and Correlations with the Canadian Forest Fire Weather Index (FWI) Risk Ratings

Blake Mccallum Jordan

Supervisors: Mats Niklasson, Swedish University Agricultural Sciences
Bronson P. Bullock, North Carolina State University
Richard R. Braham, North Carolina State University
James B. McCarter, North Carolina State University
Examiner: Eric Agestam

Swedish University of Agricultural Sciences
Master Thesis no. 209
Southern Swedish Forest Research Centre
Alnarp 2013

Master thesis in Forest Management – Euroforester Master Program, Advanced level (A2E), SLU course code EX0630, 30 ECTS

Blake Jordan has studied at SLU (Swedish University of Agriculture Sciences), Alnarp, Sweden and NCSU (North Carolina State University), Raleigh, North Carolina, USA.

Her thesis represents a cooperative effort between SLU and NCSU within the Atlantis program. The Atlantis programme in-turn results from a co-operation between the European Union and the USA. It receives financial support from the European Commission, via the Education, Audiovisual land Culture Executive Agency (EACEA) and from the US Department of Education, via the Fund for the Improvement of Post Secondary Education (FIPSE).

Blake Jordan has studied at SLU (Swedish University of Agriculture Sciences), Alnarp, Sweden and NCSU (North Carolina State University), Raleigh, North Carolina, USA.

Her thesis represents a cooperative effort between SLU and NCSU within the Atlantis program. The Atlantis programme in-turn results from a co-operation between the European Union and the USA. It receives financial support from the European Commission, via the Education, Audiovisual land Culture Executive Agency (EACEA) and from the US Department of Education, via the Fund for the Improvement of Post Secondary Education (FIPSE).

ABSTRACT

The occurrence and thickness of organic layers in forests can significantly influence fire behavior. Complete understanding of the consumption of these layers during fire events is a knowledge gap that exists in southern Sweden. In this region, sixteen burned sites were measured for fermentation and humus layer thickness. These measurements were compared to those collected on an adjacent non-burned control site. Consumption was calculated to correlate with the numerical rating components of Duff Moisture Code (DMC), Drought Code (DC), Build-Up Index (BUI), and Forest Fire Weather Index (FWI) of the overall Canadian Forest Fire Danger Rating System (CFFDRS)

The FWI numerical ratings focused upon in this study were found to be appropriate indicators for relative amounts of fermentation and humus organic layer consumption attributed to fire events in southern Sweden. In particular, variation of fermentation layer consumption was most clearly associated with the DMC, humus layer consumption with the DC, and total (fermentation and humus) organic layer consumption with both the DC and the BUI.

On sites where root exposure and tree mortality were noted, consumption of the organic layer was relatively high and the DMC and DC numerical ratings were categorized as extreme or high risks. Site characteristics, in particular microtopography and vegetation, were significant factors in accounting for the amount of consumption of these organic layers. The efficacy of the FWI fire risk ratings for indicating organic layer consumption was bolstered when coupled with these site characteristics. Additionally, planning smoldering fires for forest ecological or management goals is facilitated by the FWI values.

Keywords: fire, Canadian Fire Weather Index (FWI), organic layer consumption, Sweden

DEDICATION

For my Grandfather, Francis Wayne McCallum, and my Mother, Elizabeth McCallum Jordan, who fostered my interest in nature at a young age and have always been good stewards to the lands they manage. Thank you for setting a wonderful example and teaching me that a little hard work never hurt anybody. To my Father, Gregory Lee Jordan, for providing me with a sense of humor that makes everything in life a little easier to manage. And to my Grandmother, Elizabeth Blake McCallum, who taught me that there is light at the end of any tunnel, as long as "I think I can" make it through.

ACKNOWLEDGMENTS

Sincere thanks and appreciation to:

Dr. Bronson Bullock for allowing me the opportunity to study in Finland and Sweden and for contributing his time and knowledge to my thesis work. Dr. Mats Niklasson for providing the concept of this project and many field sites, for his background and expertise, and for expanding my knowledge about fire ecology in southern Sweden. Dr. James McCarter and Dr. Richard Braham for their thoughtful insights and help. Dr. Eric Agestam for securing funding and a rental car for my field work—and consequently teaching me how to drive a manual transmission. Erik Nordlind of Länsstyrelsen Kalmar for supplying field sites and information to strengthen my research. The faculty and staff in the Department of Forestry and Environmental Resources at North Carolina State University and at the Southern Swedish Forest Research Center at the Swedish University of Agricultural Sciences (SLU), for their guidance, support, and enhancement of this thesis.

INTRODUCTION

In recent years, a desire to further understand the role of fire ecology in Swedish forest ecosystems has led to numerous research projects. Still, many knowledge gaps exist. One such gap, organic layer consumption characteristics during fires, is critical to further understanding fire ecology in southern Sweden during both wildfire and prescribed burn events.

The presence and depths of organic layers in forest ecosystems can greatly influence fire behavior and intensity. In the case of a deep soil profile, forest vegetation can be protected from high temperatures by organic layers (Schimmel and Granström, 1996). Depending upon the moisture levels within the forest and soil, organic layers can also be partially or entirely consumed in the event of fire (Wein, *et al.*, 1983).

The Canadian Forest Fire Weather Index System (FWI) is used in Sweden to predict the potential fire behavior based upon weather and fuel moisture data. This is necessary to forest managers to best plan prescribed burns or determine times of high fire risks (CWFIS, 2009). While there are 6 elements to the FWI system (3 fuel moisture, 3 fire behavior), this research concentrates on 4 of the components: Duff Moisture Code (DMC) Drought Code (DC), Build-Up Index (BUI), and Forest Fire Weather Index (FWI)..

This study focuses on consumption during fire events of the fermentation (F) and humus (H) layers of the organic soil horizon found in the forests of southern Sweden (Miyanishi, 2001). This research evaluates the mechanisms affecting the consumption of these organic layers during fire events as well as the relationships between the consumption rates and the Canadian Forest Fire Weather Index (FWI) numerical ratings of fire risk. Through this, the FWI system was evaluated to see if it is an effective indicator for fermentation and humus layer consumption and consumption characteristics during fire events in southern Swedish forests. Better understanding the predictability of organic layer consumption in forests under varying climatic and moisture regimes will aid Swedish forestland managers in understanding the effects of fire in the forest and planning management accordingly.

The motivation for this research stemmed from the general understanding that fire and organic layer consumption play major roles in forest ecology in Sweden. While studies from Canada have suggested there exist deleterious effects of deep, smoldering ground fires, there are some known ecological benefits (Otway *et al.*, 2007). Some of the positive effects can be seen in the seeds of fire-dependent species that need smoldering fires in the organic layers to occur in order to germinate and sprout (Schimmel and Granström, 1996; Johnstone and Chapin, 2006; Risberg and Granström, 2009). However, fires have become very uncommon in Sweden. Even in a dry season, only a small percentage of Swedish forest lands burn yearly (5,000 hectares as an upper limit), and this number decreases significantly in a wet year (International Forest Fire News (IFFN), 2004). This is approximately 0.00023% of the total Swedish forest land area burned annually (IFFN, 1998). Fire suppression has become the status quo in Swedish forest fire management, a trend that has allowed for build-up of fuels, increased hazard for forest fire risks, and potential ecological problems (IFFN, 2004).

By gaining greater understanding about the correlation between organic layer consumption and the FWI numerical risk ratings, land managers can then use prescribed burning on a larger scale. The outcome of the controlled fires could be better predicted, particularly in the planning of deep, smoldering fires for maximized depth of organic layer consumption.

Fire in Scandinavia

The hemiboreal forests of Scandinavia, such as those studied in this research project, are found between the boreal zone and temperate zone (Angelstam and Kuuluvainen, 2004). Forests of the hemiboreal zone are typified by a greater number of herbaceous species. The most widespread natural disturbance factor in many forests and those of the boreal and hemiboreal zone is fire (Essen *et al.,* 1997; Acuna *et al.,* 2010). Fires in the boreal and hemiboreal zone can be stand-replacing, partial, or create gap dynamics, all of which lead to various successional occurrences generating varying ecological benefits or consequences (Granström, 2001). Scandinavia in general is dominated by a fire regime of low intensity fires at variable intervals, from a few decades up to 300 years (Zackrisson, 1977; Niklasson and Granström, 2000; Wallenius *et al.*, 2010). Forest stands dominated by the two main coniferous species, *Pices abies* (L.) Karst. (Norway spruce) and *Pinus sylvesris* L.

(Scots pine), are common throughout Scandinavia (Tanskanen *et al.,* 2005) and were observed either in pure or mixed stands on the study sites of this research project.

Depending on how you classify forests and total land area, the percentage of Swedish forest burned every year can be as much as 0.00023% or as low as a calculated 0.000077% of the total forest land area burned annually. These statistics represent an average over a five-year period in 2005 for 2,190 hectares of forests and woodland areas burned during 2,579 fire events over 28.32 million hectares of total forested area (FAO, 2010). Fire suppression is standard operating procedure in Swedish forest fire management. Managers of boreal forests in Canada, Scandinavia, and other regions have often concentrated on fire suppression, at times with harmful consequences such as more intense fires due to increased fuel loading (Acuna *et al.,* 2010). In Scandinavia, the build-up is more visible on a long-term scale as the proportion of ladder fuels (especially in Norway spruce stands) increases. As a result, fire risks due to fuel build-up and challenges for fire-dependent species are apparent (IFFN, 2004).

Fennoscandian boreal forests have been altered by anthropogenic fire use for centuries (Granström and Niklasson, 2008). In addition, there has historically been a large scale land conversion from forests to agricultural land in the hemiboreal forest zone in Sweden. As a result, it has been difficult for researchers to study fire history and disturbance factors in southern Sweden because there are a limited number of natural forests (Niklasson and Drakenberg, 2001). In addition to human influences, climactic factors have since altered the occurrences of boreal forest fires (Wallenius *et al.,* 2010).

The hemiboreal zone has more red-listed and endangered species in comparison to the boreal zone. Red-listed species are identified as such by the International Union for Conservation of Nature (IUCN) due to their status as threatened or endangered. Some of these species found in the hemiboreal zone are fire dependent, so it is important to enhance the fire regime in this area to encourage the natural habitats of these species. Norra Kvill National Park was one of the study sites in this research that has also been examined to determine the fire history of southern Sweden. At Norra Kvill, dendrochronology studies revealed that fires generally occurred at an interval less than or equal to 40 years, with a mean gap time between fire events of 20 years. Fire suppression, in effect since 1770, has greatly altered the site characteristics and stand composition at Norra Kvill. In other instances, fire was introduced to enhance vegetation that benefits from a burn regime, such as heather (*Calluna* sp.), which is a plant that is often used for grazing. Studies suggest that reintroducing prescribed fire to mimic the natural fire regime would be a benefit to ecological conservation of the hemiboreal zone, including places such as Norra Kvill National Park (Niklasson and Drakenberg, 2001).

The ecological benefits of fire in ecosystems aside from fire-adapted coniferous stands has been studied in North America and revealed that oak and hickory shelterwood systems can profit from the inclusion of fire (Brose, 2010). Many flora and fauna species have adapted to the periodic effects of fire in the ecosystem (Essen *et al.,* 1997) and numerous saproxylic beetles and vegetative species have waned due to the reduction of fire in the ecosystem (Esseen *et al.,* 1997). The transition to managing forests for biodiversity in lieu of production will likely include more reintroduction of fire into boreal forest ecosystems (Esseen *et al.,* 1997). Prescribed fires, while not completely imitating a wildland fire, can provide similar ecological results, such as altering the understory vegetation (Nesmith *et al.,* 2011).

Historically, forest managers did not fully take into account the importance of wildland fires on forest ecology (Keane and Karau, 2010). The relevance of modeling these relationships, especially in fire-adapted systems, has caused researchers to create tools for predicting the ecological impacts of fires (Keane and Karau, 2010). Understanding the influence of duff ignition and consumption on fire behavior and activity is important for forest managers in order to maximize ecological benefits and to also control unforeseen deleterious consequences (Acuna *et al.,* 2010). Under natural conditions, the intensity and frequency of fires can be explained by the combination of fuel loading, the dryness of fuels, and climactic factors (Byram, 1959). These affect the stand characteristics and species composition. The conversion from non-industrialized to intensively managed forestlands has altered the disturbance factors in boreal forests in Quebec, Canada (Bouchard and Pothier, 2011). Changes in stand structures were noted as a result of this change in management regimes because clearcutting, while a disturbance, is not the exact same ecological phenomenon as a forest fire (Bouchard and Pothier, 2011). Forest management has changed ecosystems by altering stand age distributions and vegetation makeup. At present, it is difficult to know how considerable these modifications have been and will be for the natural ecosystem processes of these environments (Boucher and Grondin, 2012).

Organic Layer Consumption

The consumption of organic layers during fire events is an important ecological process in Scandinavia and is often used by land managers in evaluation of prescribed burn results. The components of the organic layer studied in this research are the fermentation and humus layers. Below the litter layer or “L” layer lies the fermentation and humus layers. The fermentation or “F” layer is comprised of partially decomposed litter and other organic matter, and below that the humus or “H” horizon which is comprised of more fully decomposed organic materials (Figure 1). These layers are below the litter layer, but above the mineral soil A horizon (Miyanishi, 2001). Duff has been a general term used to classify the organic (O) layers of the soil (referred to as O_F and O_H in the soil profile) (Hille and den Ouden, 2005). Organic soil material and layers must, in general, contain greater than 20 percent organic carbon by weight and have a thickness no greater than 40 cm. These organic layers lie above a mineral soil horizon with less than 20 percent organic carbon by weight (Soil Survey Staff, 1999).

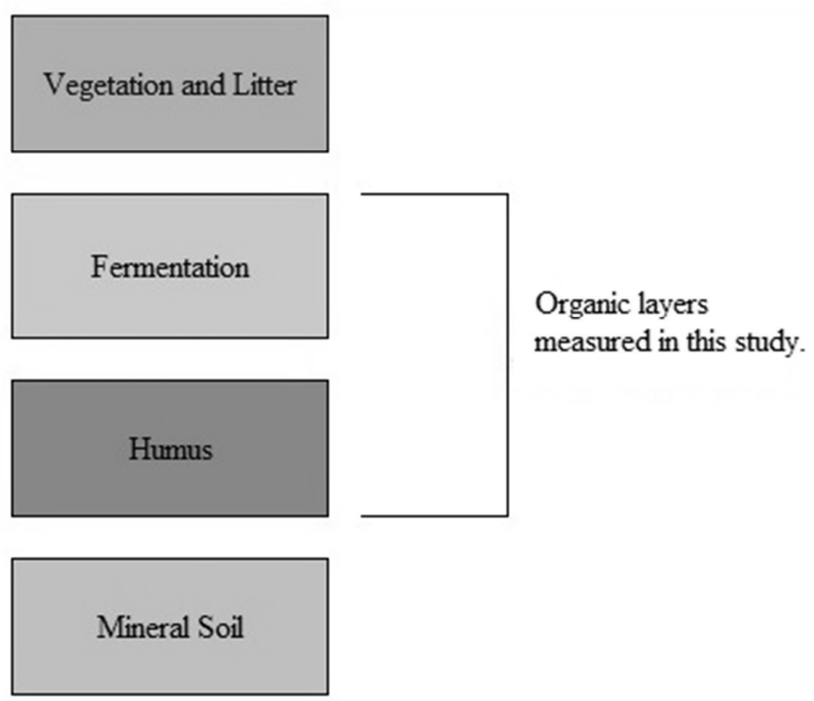

Figure 1. Basic profile of typical organic layers addressed in this study.

Soil humidity directly influences how much fuel is incinerated during a fire event (Byram, 1959; Van Wagner, 1987), and specifically whether or not the organic layer is consumed in a fire event hinges on the moistness of the soil at the moment that combustion first occurs (Robichaud *et al.*, 2004). The drier the forest soils, the greater the chance of an ignition (Bartsch *et al.*, 2009; Wein, *et al.*, 1983). Water content of F and H soil layers on a site can be explained in part by climactic factors and the vegetative cover (Hill and den Ouden, 2005). Research has also been conducted to estimate the water content of forest soil organic layers (Robichaud *et al.,* 2004). Understanding the moisture content of forest soils facilitates the usefulness and accuracy of extrapolative fire models to best forecast how much duff may be consumed in an ecosystem based upon the initial moisture levels of the soil (Robichaud *et al.,* 2004).

The mechanism behind smoldering fires is the way they disseminate and spread gradually over time through the organic layers of forest soils (Rein *et al.,* 2008), which can continue long after the fire front has passed. Additionally, it was discovered that duff consumption was greater around the base of trees, where the crown of the tree provided a barrier for precipitation reaching the ground (Hille and Stephens, 2005). This could explain the phenomenon of root exposure after fire events around the bases of trees (Goepfrich, 2010). The smoldering intensity appears to be dependent upon fire temperature and the amount of time the fire smolders in the soil layers (Rein *et al.,* 2008).

In the Sierra Nevadas of California, research has been conducted on the relationships between location and duff consumption in coniferous forests (Hille and Stephens, 2005). The general pattern established was less consumption occurred in moist soils and more in drier soils, an expected relationship (Hille and Stephens, 2005). Soil burn severity refers to the amount of the F and H soil layers which remain unburned and begins to amass after a fire moves through an ecosystem. The organic layer accumulates and grows thicker and denser without the presence of fire, but eventually this accretion lessens and levels out over time, thereby reaching a steady state (Lecomte *et al.,* 2006).

Prescribed fires, though managed, can have unforeseen effects such as smoldering fires that can change the stand in both desirable and undesirable ways. There can be negative effects of deep, smoldering ground fires, such as excessive tree mortality, but in fire-adapted ecosystems, there are positive effects noted as well (Otway *et al.,* 2007). An example of a positive effect in a fire-adapted ecosystem would be the need that some vegetative species have for a smoldering burn to germinate and sprout dormant seeds lying deep within the soil, such as rare geranium (*Geranium* spp.) species (Schimmel and Granström, 1996; Johnstone and Chapin, 2006) found on some field sites in this study.

Smoldering fires can greatly affect forest ecology by altering the characteristics and mass of these soils (Rein et al., 2008). In a study in northern Florida by Varner *et al.,* (2009), smoldering duff fires in longleaf pine (*Pinus palustris* Mill.) forests increased the temperature of mineral soil to an extent that seemed to amplify the mortality of these pines. Additionally, growth rates for these tree species were subsequently observed at a decreased rate when mineral soils had been heated (Varner *et al.,* 2009).

Canadian Forest Fire Weather Index

The Canadian Forest Fire Danger Rating System (CFFDRS) includes a component called the Forest Fire Weather Index (FWI) (Figure 2). This element of the model focuses on meteorological data and fuel moisture to forecast fire behavior (Byram 1959; Van Wagner 1987; Stocks *et al.*, 1989) and this system is currently used in Sweden as a predictive fire behavior tool. There were two FWI fuel moisture codes and two FWI indices utilized in this study: Duff Moisture Code (DMC), Drought Code (DC), Build-Up Index (BUI), and overall Forest Fire Weather Index (FWI).

The Duff Moisture Code (DMC) is a numerical value representing the moisture levels of loose, organic layers of a mid-level depth. The DMC also accounts for the cumulative effects of temperature, relative humidity, 24-hour rainfall (CWFIS, 2009), day lengths, and the wet/dry weight percentage of these fuels (Van Wagner and Pickett, 1985). The Drought Code (DC) is a numerical value representing the moisture content of dense organic layers below the mid-level layer (deep). The DC also accounts for the cumulative effects of temperature, 24-hour rainfall (CWFIS, 2009), day lengths, evapotranspiration potential, and the wet/dry weight percentage of these fuels (Van Wagner and Pickett, 1985). The Build-Up Index relates a numerical value to the fuel that can be ignited and is derived from DMC and DC (CWFIS, 2009). Van Wagner and Pickett (1985), mathematically relate the BUI to DMC and DC using the following equation:

$$BUI = \frac{0.8\,(DMC)(DC)}{(\mathrm{DMC} + 0.4(\mathrm{DC})}$$

(1)

The Forest Fire Weather Index itself combines the BUI and another factor, Initial Spread Index (ISI) to yield an overall numerical score of fire intensity (CWFIS, 2009).

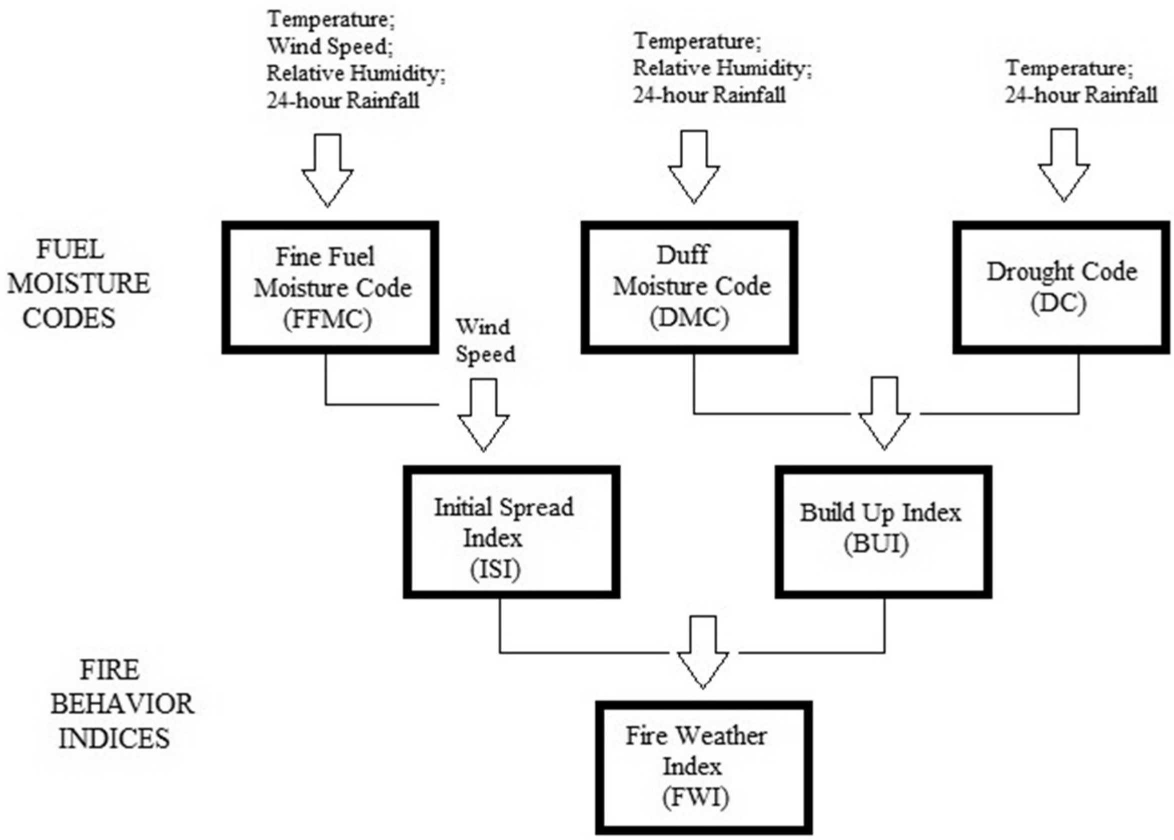

Figure 2. Chart of the Canadian Forest Fire Weather Index (FWI). (Source: CWFIS, 2009).

The FWI has been shown as a useful model for predicting and understanding fire activity and scale, especially at the beginning of the fire and growing season (late spring to early summer), when plants are emerging and dead vegetation has not yet fully accumulated to the extent that it will by late summer (Tanskanen and Venalainen, 2008). On the other hand, a lack of inclusion of geographic and topographic data in these indices can lead to inaccuracies between the observed fire activities and the behaviors forecasted by the FWI. This can often lead to fires at a time that the index would suggest that fire incidences should be low (Tanskanen and Venalainen, 2008).

Tanskanen *et al.,* (2005) studied the ignition occurrences in Finland compared to the stand type, stand composition, and the predictions of the Canadian FWI. The relationships between ignitions and the FWI predictions were appropriate in the months of June and July but not in August. Since Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) allow for different fuel loadings and site conditions, success of ignition varied depending on which species is dominant. Clearcut Scots pine stands had the greatest amount of ignition success, and Norway spruce stands ignited with less success than Scots pine. This indicates that the Canadian FWI and other fire indices need to be more specific for stand structure types (Tanskanen *et al.,* 2005). Comparing the DMC to monitored forest floor moisture was found to correlate suitably, encouraging the further use of this index (Wotton *et al*., 2005).

Currently, FWI is in use by the Swedish Rescue Services Agency (Statens Räddningsverket), or MSB, Swedish Hydrological and Meteorological Institute (SMHI), and other civil contingencies in Sweden. Numerical codes and indices can be classified into qualitative category levels to best summarize relative fire risk potential. Table 1 shows the ranges for high and extreme fire risk for the FWI indices investigated in this study.

Table 1. High and extreme fire risk numerical classifications for DMC, DC, BUI, and FWI. (Source: CWFIS, 2009).

CLASS	DMC	DC	BUI	FWI
High	30-40	200-300	40-60	17-31
Extreme	>40	>300	>60	>31

Objectives

Three main objectives were established for this research:

Determine the correlations between the given FWI values and calculated fermentation and humus organic layer consumption derived from measurements from recent fire (burned) and control (non-burned) sites in southern Sweden.

Model the relationships between site variables and observed burn characteristics.

Establish the relative efficacy of the FWI system as a predictive fire behavior tool for organic layer consumption in southern Sweden.

The core hypothesis for this research is that a strong relationship exists between the fermentation and humus organic layer consumption attributed to fire events and the numerical FWI ratings for the day of the burn. Additionally, organic layer consumption characteristics should be correlated with measured site variables and FWI ratings.

Due to the depths of the fermentation and humus organic layers, it is hypothesized that the Duff Moisture Code (DMC) will be more highly correlated with fermentation layer consumption, Drought Code (DC) with humus layer consumption, and Build-Up Index (BUI) with total (fermentation and humus together) organic layer consumption. Correlations between all of the numerical codes and indices and consumption of all organic layer types in this study will also be determined to establish other informative relationships.

METHODS

Site Description

Data was collected on 16 sites in total. The sites were located throughout southern Sweden (Figure 3- 5). Locations and GPS coordinates for pre-existing burn sites were established predominantly through contact with local forestry and land management officials. The contacts included administrators from Sveaskog and Länsstyrelsen, and Dr. Mats Niklasson from the Swedish University of Agricultural Sciences (SLU).

The most northerly field site was Fjällmossen (field site 15). The GPS coordinate for this field site (WGS 84) is 58° 41' 50.46" N, 16° 32' 18.22' E. The most southerly field sites were Kalmar 11A (field site 6) and Kalmar 11B (field site 7). The GPS coordinate for these field sites is (WGS 84) is 56° 36' 23.64" N, 15° 53' 24.39' E (Appendix I).

Across field sites, the mean summer temperature is 15° C and the mean winter temperature is -5℃. Being in the northern latitudes, these field sites experience short, warm summers and long, cold winters, but temperatures are moderated by the effects of the Atlantic Gulf stream. Most precipitation is from rain during the summer months, but is also consistent year-round due to snow events (National Climatic Data Center, 1990). In addition to the organic layers focused upon in this study, the field sites were all dominated by moraines, a mineral earth type very common throughout Sweden and initially deposited by glaciers. Moraines are often rich in boulders.

Figure 3. Overall map of Northern Europe and Sweden. Inset denotes boundary within which the field sites fall. Area of inset seen below with field sites noted. Accessed from maps.google.com on January 5, 2012 and maps.bing.com on March 4, 2012.

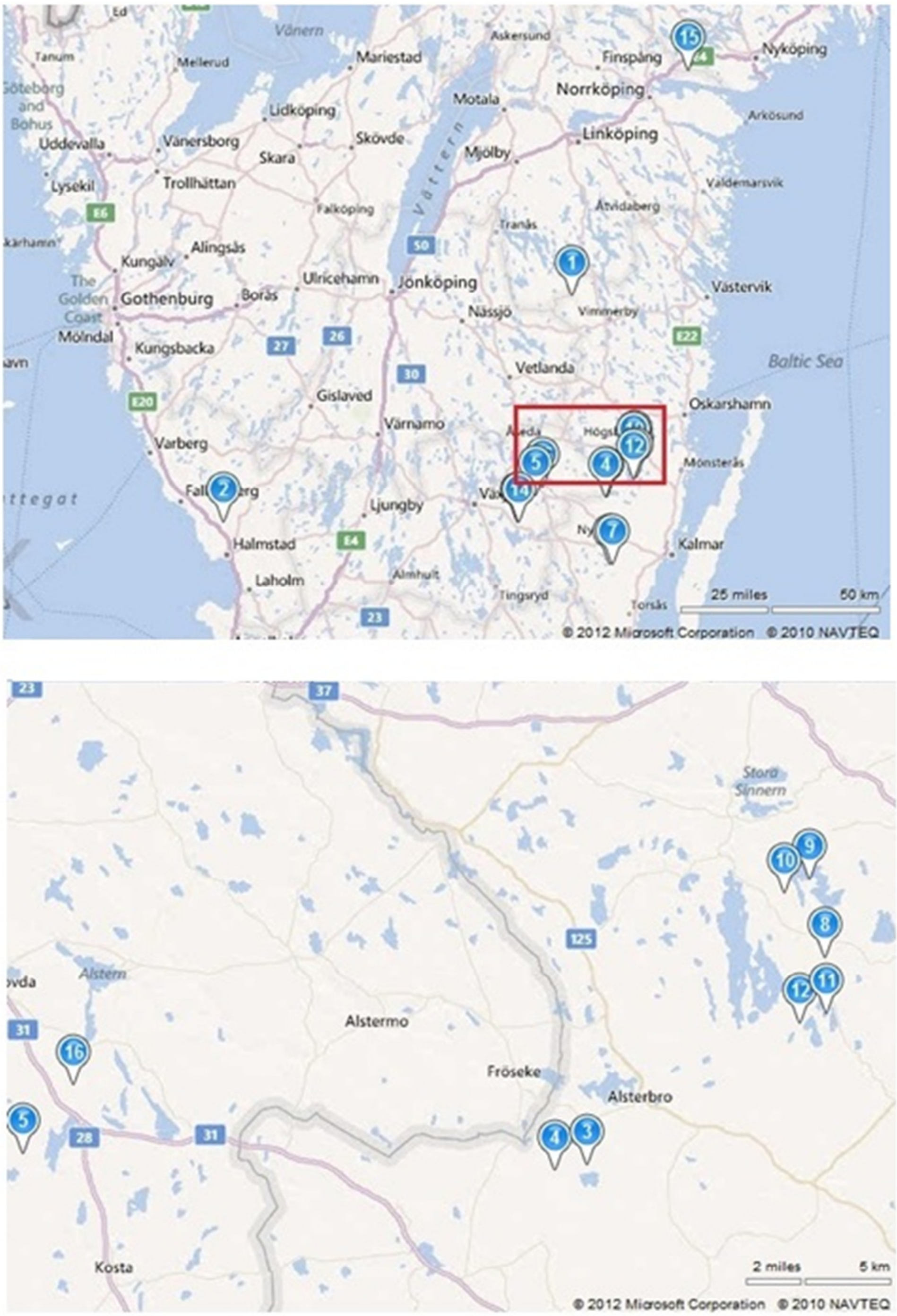

Figure 4. Zoomed in map of field site locations within southern Sweden, part 1. Accessed from maps.bing.com on March 4, 2012.

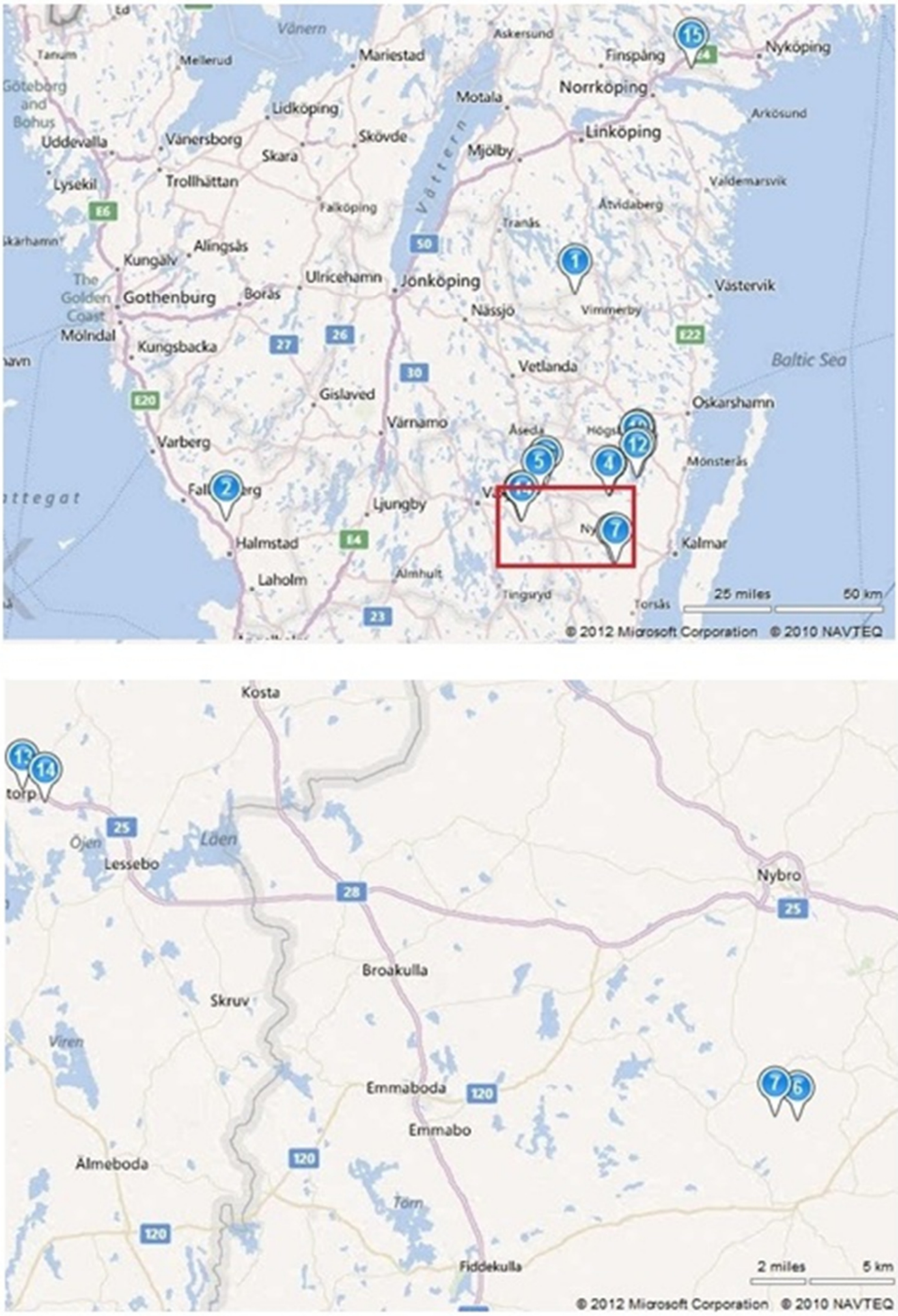

Figure 5. Zoomed in map of field site locations within southern Sweden, part 2. Accessed from maps.bing.com on March 4, 2012.

Before visiting the field sites, the burn date, type of fire (prescribed or wildfire), fire behavior, and who conducted or ordered the burn was obtained from local officials. All fire events took place in the months of May, June, and July and from 2007-2010. The time passed since the fire was restricted to within four years in an attempt to collect the most accurate data since organic layers begin to reform as litter collects and time passes. There were thirteen prescribed burn sites and three wildfire sites, site 13—Hovmantorp A, site 14—Hovmantorp B, and site 16—Vägershult (Appendix I).

After arriving to a field site, site characteristics were noted (Appendix II): species composition (trees, ground vegetation), topography, geographical location, ground cover (rocks, vegetation), and stand density. Many photographs were taken at each site for reference. Appendix III lists the dominant tree species and Appendix IV lists other common understory vegetative species found on these sites.

Fermentation and Humus Measurements

This project focused on the measurement of F and H organic layer thickness on 16 burn sites. Relative organic layer consumption was based on measurements from unburned surroundings of each studied field site. Figure 6 illustrates the typical field site layout. Transects consisting of both a non-burned control and burned area, both 50 meters in length, were established on the field sites. Measurements were taken at 1 meter intervals along the transect. The control transect was generally directly adjacent to the fire transect. In some cases, this meant extending a long transect and measuring 50 m transects through both the burn and control areas. Controls were chosen to be representative of the burn site at the time of fire. This included consideration of similar: tree density, stand type, vegetation cover, and topographical features.

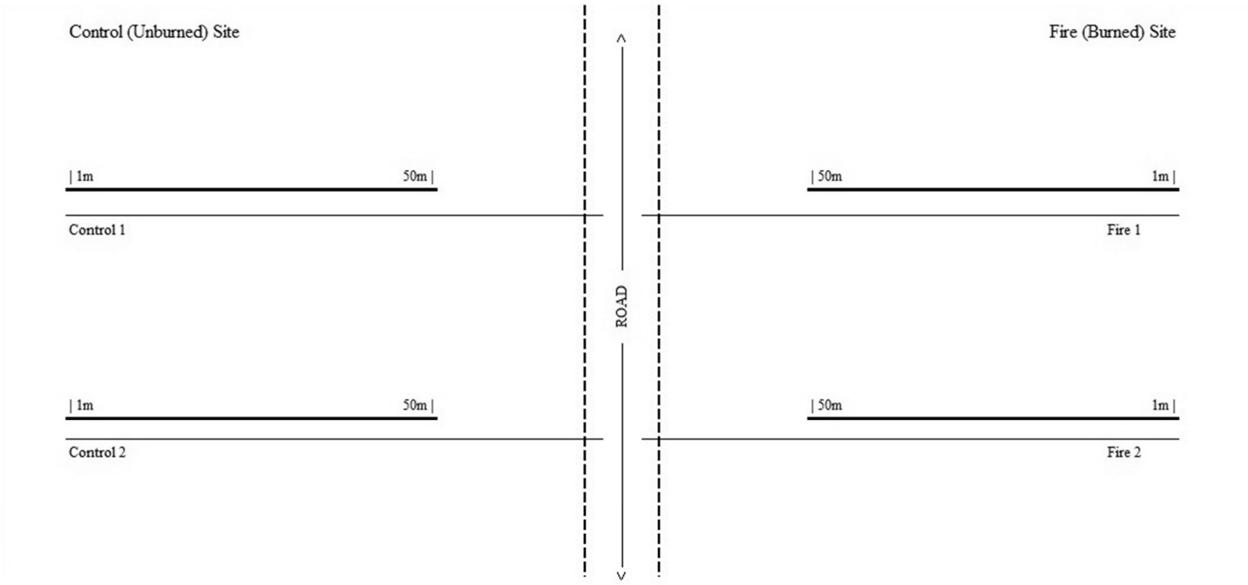

Figure 6. Typical field site setup for data collection for both fire (burned) and control (non-burned) areas.

The measurement of fermentation and humus layers at 1 meter intervals along the transect resulted in 50 observations per transect type (control or fire) per transect. Litter was removed from the sampling area in order to best measure the F and H layers (Goepfrich, 2010). Then, a spade was employed to dig a soil profile through the F and H organic layers down to mineral soil. The F and H layers were measured using a meter stick with a resolution to the nearest millimeter. Each time a measurement was collected, other microtopographical and vegetation characteristics were noted. These included, where applicable: nearby vascular species (and average height), slash cover (and average height), presence of boulders, presence of charcoal, and the microtopography for the measurement location (flat, slant, hummock, hollow). Rocks were also a microtopographical feature noted in data collection, usually if they were large and covering the meter mark area where a measurement should be taken. Appendix V includes a sample data collection sheet for sampling along transects.

Root Exposure Measurements

Root exposure trees (termed burnout trees) are trees whose roots have been exposed due to total or partial duff consumption by a smoldering fire. The rationale behind collecting information on burnouts was to gather additional information on organic layer consumption characteristics (smoldering vs. non-smoldering) and the intensity of the burns. This data is considered as a site characteristic factor for the purpose of this study.

For each site, where standing trees remained post-fire (i.e. not a clearcut), thirty trees were randomly selected within the burn site to determine the percentage of root exposure. The level of root exposure was classified as follows: 0 = None; almost no root exposure; 1 = Some; approximately 50% of root exposure; 2 = All; close to 100% of root exposure.

For all trees sampled, other variables were also collected, including: mortality (dead or alive), diameter at breast height (dbh, centimeters), char height (flame height on stem, meters), and tree species. Appendix VI includes a sample data collection sheet for sampling root exposure.

FWI Values and Organic layer Consumption

The Swedish Civil Contingencies Agency (hereafter, MSB) provided data from the Swedish Meteorological and Hydrological Institute (SMHI, 2011). This included weather data, such as temperature and relative humidity, and the Canadian Forest Fire Weather Index (FWI) fire risk ratings utilized in this research. In particular, these are: Duff Moisture Code (DMC), Drought Code (DC), Build Up Index (BUI), and Forest Fire Weather Index (FWI). The values are given for 11 x 11 kilometer cells. Using the GPS data points for each site, the 11 x 11 kilometer cell that the site fell within was identified. Nearby cells were compared for any differences in values and to determine if there was need to weight values across cells. In the case of these study sites, it was deemed unnecessary due to a lack of large difference between adjacent cells. Using the data collected on non-burned (control) and burned (fire) sites for fermentation and humus thickness, a consumption rate was calculated and compared to the FWI values for each site.

Methodology Assumptions

This research assumes a static ecosystem. Although static ecosystems do not actually occur, this study is meant to provide a snapshot of the influence of fire disturbance in organic layer consumption. For the purposes of this study, it has been assumed that fire is the only main disturbance factor. While fire is the main disturbance factor on the sites studied in this project, it is not the only possible disturbance. Therefore, this study does not take into account the influence of forest machinery, animals, edge effects or other aspects that can manipulate organic layer thickness. The influence of edge effects was minimized during sampling by not beginning transects directly beside roads or along the edge of a forest stand. When placing a transect, care was taken to account for any edge effects so that an unbiased measurement of organic layer consumption specifically related to the fire event as opposed to foot, automobile, or machine traffic was obtained.

Steps were taken to ensure that these assumptions did not affect the validity of this research. Assuming a static ecosystem was necessary to give an idea of the effects of fire on fermentation and humus consumption within the scope and time limit of this research. Since this study focuses on organic layer consumption due to fire, and this was the main disturbance on the study sites, it was not essential to focus on the other potential influences on these sites. The pre-existing influences of rainfall, temperature, and sunlight that affect organic layer consumption were not specifically collected here, but these effects are captured by the FWI in the numerical ratings of the codes and indices.

The thickness of the topmost organic layer of the forest floor, litter (L), was not measured in this study. In some studies of duff and humus measurements (Goepfrich, 2010), the litter layer is removed before measuring the organic layers in an attempt to eliminate the recently added litter from the study. On the control (non-burned) sites, the litter layer was present to varying extents, but on the fire (burned) sites, the litter layer had generally been completely consumed. Another reason to exclude litter is that this study specifically focused on consumption of the F and H organic layers as they reflect the DMC, DC, and BUI for mid-and-deep depth organic layers.

RESULTS

Microsoft Excel and SAS 9.2 (SAS Institute Inc. 2008) were used for all statistical calculations in this research. An alpha-level of 0.05 was used to determine statistical significance for all tests.

Fermentation and Humus Measurements

Summary statistics for each site by layer were calculated, including the number of sampling points along the transect measured, the average organic layer thickness, standard deviation of thickness, and the minimum and maximum thicknesses found at each site (Table 2). The sample sizes (n) of the sites differed because some points along the transect were not measured due to a large rock impeding the measurement location. Another reason sample sizes differed was because some burned areas were small and only one transect of a shorter length (30-meters) could be placed for measurement.

Table 3 shows the mean thickness of the consumed organic layer by site for each layer type. Some sites had greater organic layer thicknesses to begin with, such as site 7—Kalmar 11 B, which partially accounted for the larger mean consumption across layers. This table also highlights the minute amount of the organic layer consumed at site 5—Hammarby, by far the lowest across all sites.

Figures of the mean fermentation layer (Figure 7), mean humus layer (Figure 8), and mean total (fermentation and humus) layer (Figure 9) show the noticeable differences between means of layer thicknesses on control and fire sites. These figures also show that on most sites when two transects of each type were sampled, mean differences were generally minute within the two control (non-burned) transects and two fire (burned) transects.

Table 2. Summary statistics across sites by transect type. Units for this table are in centimeters (cm).

Site	Transect Type	Fermentation Layer………… n	mean	std	min	max	Humus Layer ………………. n	mean	std	min	max	Total (F+H) Layer………… … n	mean	std	min	max
1	Control	96	2.2	1.1	0.5	6.0	96	5.9	2.5	0.5	17.0	96	8.1	3.1	1.0	22.0
1	Fire	96	1.2	1.6	0.0	8.0	96	4.6	2.6	0.3	12.0	96	5.8	2.5	0.3	13.5
2	Control	86	1.6	0.9	0.0	4.0	86	6.8	2.3	3.0	14.5	86	8.4	2.6	4.0	17.0
2	Fire	89	0.2	0.5	0.0	3.0	89	4.0	2.6	0.0	11.0	89	4.1	2.7	0.0	11.0
3	Control	92	4.2	2.4	0.0	12.0	92	7.9	4.8	2.0	38.0	92	12.0	5.7	4.0	42.0
3	Fire	90	2.2	1.8	0.0	10.0	90	5.2	4.2	0.0	20.0	90	7.4	5.6	0.0	24.0
4	Control	30	4.7	2.6	1.5	12.0	30	9.2	6.5	3.0	24.0	30	13.9	8.1	5.0	34.0
4	Fire	28	3.5	2.6	0.0	9.0	28	4.8	1.7	2.0	8.0	28	8.3	3.7	3.0	14.0
5	Control	84	2.5	1.4	0.5	8.0	84	3.4	1.8	0.5	10.0	84	5.9	2.7	1.0	14.0
5	Fire	79	2.0	1.6	0.0	8.0	79	3.2	2.8	0.0	16.0	79	5.2	4.0	0.0	20.0
6	Control	92	3.5	1.3	1.0	6.5	92	5.9	2.3	1.0	15.0	92	9.4	2.8	2.0	18.0
6	Fire	92	1.6	1.3	0.0	6.0	92	2.7	1.4	0.5	7.0	92	4.3	2.4	0.5	13.0
7	Control	30	15.2	2.5	11.0	19.5	30	22.3	3.3	12.5	25.0	30	37.5	4.7	23.5	41.5
7	Fire	30	8.9	2.6	5.5	14.0	30	12.6	4.3	7.0	24.0	30	21.5	6.3	14.5	35.0
8	Control	95	2.5	1.3	0.0	6.0	95	2.6	1.8	0.5	10.0	95	5.1	2.8	1.0	15.0
8	Fire	93	1.4	1.3	0.0	5.0	92	2.3	1.5	0.0	6.0	92	3.7	2.4	0.0	10.5
9	Control	92	3.1	1.5	1.0	10.0	92	3.6	1.8	1.0	11.0	92	6.7	3.1	2.0	21.0
9	Fire	92	1.8	1.5	0.0	6.0	92	2.7	1.9	0.0	8.0	92	4.5	2.9	0.0	11.5
10	Control	30	8.4	5.0	2.0	17.5	30	12.7	7.8	2.0	22.0	30	21.1	11.	4.0	38.0
10	Fire	29	4.8	2.8	0.0	10.0	29	9.6	4.4	1.5	19.0	29	14.3	5.9	3.0	25.0
11	Control	93	3.0	1.5	0.5	8.5	93	3.7	1.7	0.5	8.5	93	6.6	3.0	1.0	16.0
11	Fire	90	1.2	1.4	0.0	7.0	90	2.5	1.5	0.0	7.0	90	3.7	2.6	0.0	12.0
12	Control	92	3.8	1.5	1.0	9.5	92	4.6	1.9	1.0	9.5	92	8.4	3.1	2.5	17.5
12	Fire	93	1.9	1.5	0.0	5.5	93	2.7	1.7	0.0	8.5	93	4.6	2.9	0.0	12.0
13	Control	91	2.1	1.0	0.5	5.0	91	3.3	1.7	0.5	8.0	91	5.4	2.4	1.0	12.5
13	Fire	92	0.5	0.8	0.0	4.0	92	2.2	1.8	0.0	7.5	92	2.7	2.2	0.0	10.0
14	Control	86	2.8	1.8	0.5	9.0	86	2.6	1.7	0.5	9.0	86	5.4	3.3	1.0	17.5
14	Fire	89	0.8	0.8	0.0	4.0	89	1.9	1.2	0.0	5.0	89	2.7	1.7	0.0	9.0
15	Control	96	3.8	2.3	1.5	18.0	96	8.4	4.1	3.0	19.0	96	12.2	6.0	4.5	34.0
15	Fire	97	1.1	1.4	0.0	7.0	97	4.7	3.7	0.5	20.0	97	5.8	4.8	0.5	27.0
16	Control	97	3.3	1.2	1.5	8.0	97	5.8	2.0	3.0	13.0	97	9.1	2.6	5.5	16.0
16	Fire	95	0.8	0.7	0.0	3.5	95	3.6	2.1	0.5	10.0	95	4.4	2.3	0.5	11.0
Overall	Control	80	4.2	1.8	1.4	10.0	80	6.8	3.0	2.2	15.8	80	11.0	4.2	3.9	23.5
Sites	Fire	80	2.1	1.5	0.3	6.9	80	4.3	2.4	0.8	11.8	80	6.4	3.4	1.4	16.2

STD in this table represents "standard deviation."

Table 3. Mean thickness of all organic layers consumed on each site. Units for this table are in centimeters (cm).

Site #	Site	Fermentation Layer	Humus Layer	Total (F + H) Layer
1	Norra Kvill	1.04	1.33	2.38
2	Kalvaberget	1.37	2.85	4.22
3	Smedjevik A	2.02	2.69	4.71
4	Smedjevik B	1.27	4.40	5.67
5	Hammarby	0.53	0.27	0.80
6	Kalmar 11 A	1.85	3.21	5.07
7	Kalmar 11 B	6.32	9.65	15.97
8	Ekopark Hornsö 6	1.12	0.36	1.46
9	Ekopark Hornsö 7A	1.26	0.97	2.23
10	Ekopark Hornsö 7B	3.57	3.15	6.72
11	Ekopark Hornsö 8	1.76	1.18	2.94
12	Ekopark Hornsö 2	1.86	1.95	3.81
13	Hovmantorp A	1.60	1.07	2.67
14	Hovmantorp B	2.02	0.66	2.68
15	Fjällmossen	2.76	3.76	6.51
16	Vägershult	2.51	2.19	4.70

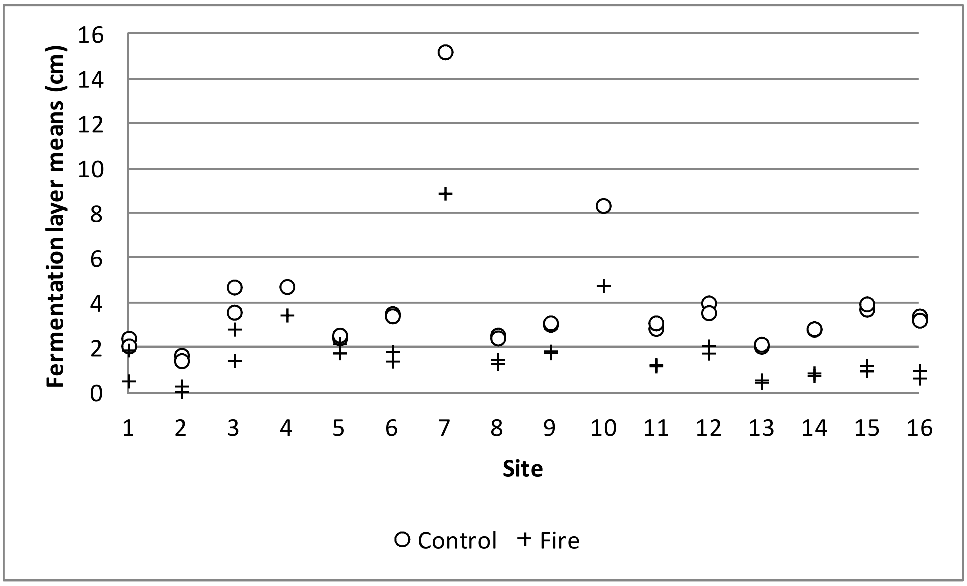

Figure 7. Mean thickness of the fermentation layer by transect for each site.

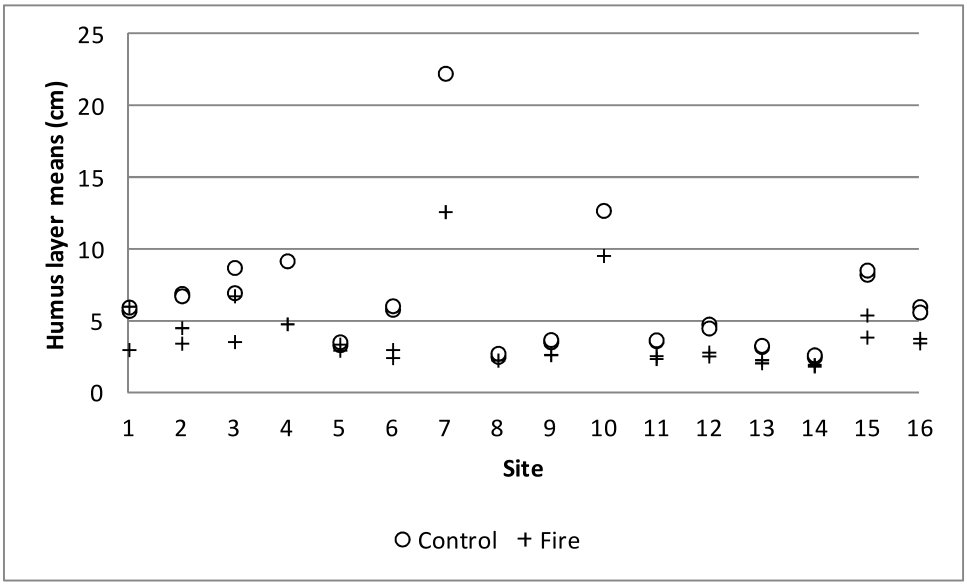

Figure 8. Mean thickness of the humus layer by transect for each site.

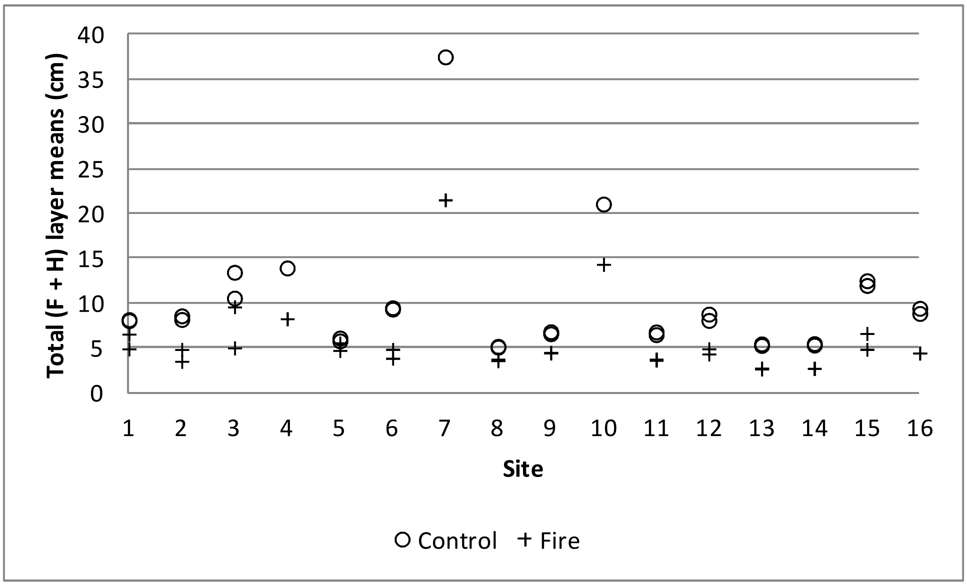

Figure 9. Mean thickness of the total organic layer sampled (fermentation and humus together) by transect for each site.

In SAS 9.2, proc GLM was used when calculating ANOVA across fermentation and humus transect sampling variables. The Generalized Linear Model method was more appropriate for this due to the uneven sample sizes of the variables in this study.

Both the variable site (degrees of freedom (DF) = 15) and transect type (control or fire) (DF = 1), were significant (p-value <0.0001 for both) across all organic layer types measured (Table 4). This provides insight to variability between sites and assumed differences in organic layer depths on control (non-burned) and fire (burned) transects.

After accounting for site and transect type, microtopography (DF = 3) was also a significant variable (p-value <0.0001) across all organic layer types (Table 4). This eludes to microtopography being an important variable for both initial fermentation and humus layer thickness and the consumption of these soils during fire events. Significance of vegetation (species type) (DF = 20) and vegetation height (height in centimeters of nearest vegetation to or on transect) (DF = 96) were also tested for significance after accounting for site, transect type, and microtopography (Table 5). Both of these variables were significant (p-value <0.0001) across all organic layer types. Based on the significance test, vegetation types and vegetation heights vary across sites, between control (non-burned) and fire (burned) transects, and across different microtopographies.

Table 4. ANOVA for site and transect type for all organic layers.

Layer	Variable	DF	Type III SS	Mean Square	F-Value	P-Value
Fermentation	Site	15	7776.02	518.40	186.64	<0.0001
	Transect Type	1	2134.47	2134.47	768.48	<0.0001
Humus	Site	15	18142.19	1209.48	150.59	<0.0001
	Transect Type	1	2608.17	2608.17	324.74	<0.0001
Total (F+H)	Site	15	46099.10	3073.27	197.51	<0.0001
	Transect Type	1	9455.75	9455.75	607.71	<0.0001

Table 5. ANOVA for site, transect type, and microtopography for all organic layers.

Layer	Variable	I F	Type III SS	Mean Square	F- Value	P- Value
Fermentation	Site	15	7173.40	478.23	179.56	<0.0001
	Transect Type	1	1885.18	1885.18	707.84	<0.0001
	Microtopography	3	299.64	99.88	37.50	<0.0001
Humus	Site	15	17324.84	1154.99	153.33	<0.0001
	Transect Type	1	2117.37	2117.37	281.08	<0.0001
	Microtopography	3	1287.99	429.33	56.99	<0.0001
Total (F+H)	Site	15	43169.44	2877.96	198.98	<0.0001
	Transect Type	1	7998.35	7998.35	552.99	<0.0001
	Microtopography	3	2824.58	941.53	65.09	<0.0001

Table 6. ANOVA for site, transect type, microtopography, vegetation, and vegetation height for all organic layers.

Layer	Variable	DF	Type III SS	Mean Square	F-Value	P-Value
Fermentation	Site	15	3460.90	230.73	90.89	<0.0001
	Transect Type	1	424.44	424.44	167.20	<0.0001
	Microtopography	3	131.80	43.93	17.31	<0.0001
	Vegetation	20	202.87	10.14	4.00	<0.0001
	Vegetation Height	96	685.45	7.14	2.81	<0.0001
Humus	Site	15	9923.80	661.59	93.59	<0.0001
	Transect Type	1	686.98	686.98	100.30	<0.0001
	Microtopography	3	647.89	215.96	31.53	<0.0001
	Vegetation	20	393.94	19.70	2.88	<0.0001
	Vegetation Height	96	1250.26	13.02	1.90	<0.0001
Total (F+H)	Site	15	22929.92	1528.66	112.76	<0.0001
	Transect Type	1	2191.39	2191.39	161.65	<0.0001
	Microtopography	3	1363.88	454.63	33.54	<0.0001
	Vegetation	20	989.71	49.49	3.65	<0.0001
	Vegetation Height	96	3100.82	32.30	2.38	<0.0001

After accounting for site, transect type, and microtopography, location on transect (the location of the point along the 50-meter transect line) (DF = 49) was not significant across all organic layer types (Table 7). The p-values for this were as follows: fermentation layer (p-value of 0.0784), humus layer (p-value of 0.6869), and total (fermentation and humus) layer (p-value of 0.3730). All of the p-values were >0.05, the threshold for significance testing. This test suggests that there was no strong dependency of thickness based on where these measurements were found along the transect. Based on this lack of dependency, this variable was not considered in subsequent analysis.

Table 7. ANOVA for site, transect type, microtopography, and location on transect for all organic layers.

Layer	Variable	DF	Type III SS	Mean Square	F-Value	P-Value
Fermentation	Site	15	6902.79	460.19	173.90	<0.0001
	Transect Type	1	1884.99	1884.99	711.91	<0.0001
	Microtopography	3	286.70	95.57	36.09	<0.0001
	Location on Transect	49	168.97	3.49	1.30	0.0784
Humus	Site	15	16788.76	1119.25	148.27	<0.0001
	Transect Type	1	2115.73	2115.73	280.28	<0.0001
	Microtopography	3	1246.96	415.65	55.06	<0.0001
	Location on Transect	49	329.72	6.73	0.89	0.6869
Total (F+H)	Site	15	41618.49	2774.57	192.03	<0.0001
	Transect Type	1	7994.78	7994.79	553.32	<0.0001
	Microtopography	3	2722.15	907.38	62.80	<0.0001
	Location on Transect	49	746.07	15.23	1.05	0.3730

Root Exposure Measurements

Root exposure measurements, including mean root exposure, mean tree mortality, mean tree char height, and mean diameter at breast height, were taken at burn sites where applicable. These site characteristics can be an indication of fire severity and behavior, important insights in a study of organic layer consumption. Summary statistics were calculated for these root exposure variables. Mean root exposure (Figure 10), mean tree mortality (Figure 11), mean tree char height (Figure 12), and mean diameter at breast height (Figure 13) are presented for all sites where the root exposure characteristics were measured.

The possible mean values for root exposure were between 0 and 2 with sites closer to 2 representing the most root exposure and sites closer to 0 representing the least root exposure. Mean root exposure was most severe on site 15—Fjällmossen, followed by site 14—Hovmantorp B, site 3—Smedjevik A , and site 4—Smedjevik B The mean values for mortality were between 0 and 1 with sites closer to 1 representing less mortality (alive trees were coded as 1) and sites closer to 0 representing more mortality (dead trees were coded as 0). Mortality was highest on site 14—Hovmantorp B, followed by site 5—Hammarby, site 6—Kalmar 11A, and site 12—Ekopark Hornsö 2. Char height was measured as a continuous variable, but trees sampled fell within 0 to 3.5 meters. Mean char height was highest on site 12—Ekopark Hornsö 2, followed by site 14—Hovmantorp B, site 1—Norra Kvill, and site 3—Smedjevik A. The diameter at breast height (DBH) was also a continuous variable and trees sampled fell within 12 to 28 centimeters. Mean DBH was highest on site 16—Vagershult, followed by site 15—Fjällmossen, site 4—Smedjevik A, and site 12—Ekopark Hornsö 2.

In addition to the summary graphs of means for the root exposure variables, trends between all variable combinations (results not shown) were determined. Two interesting relationships are shown graphically: mean tree mortality as a function of mean tree char height (Figure 14) and the correlation between total organic layer consumption and mean tree char height (Figure 15). As tree char heights increased, mortality also increased, with an R-square value of 0.4802. In the case of total organic layer consumption, there was no relationship between consumption and tree char height, with an R-square value of 0.0003.

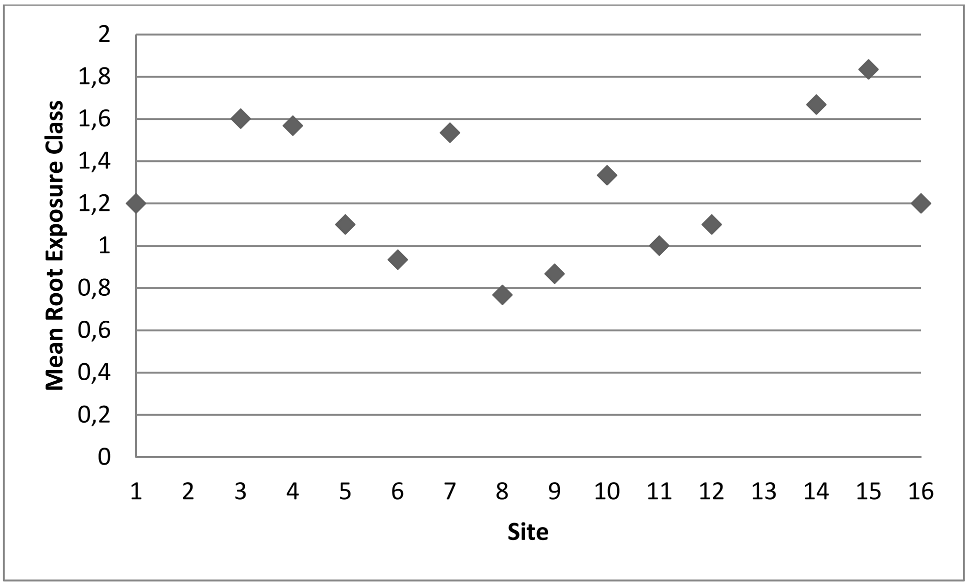

Figure 10. Mean root exposure (tree burnout) classes for each site. The possible values were from 0 to 2, with 2 being the most root exposure and 0 being close to none. Note: some sites (2, 13) had no standing trees which is why some values are missing.

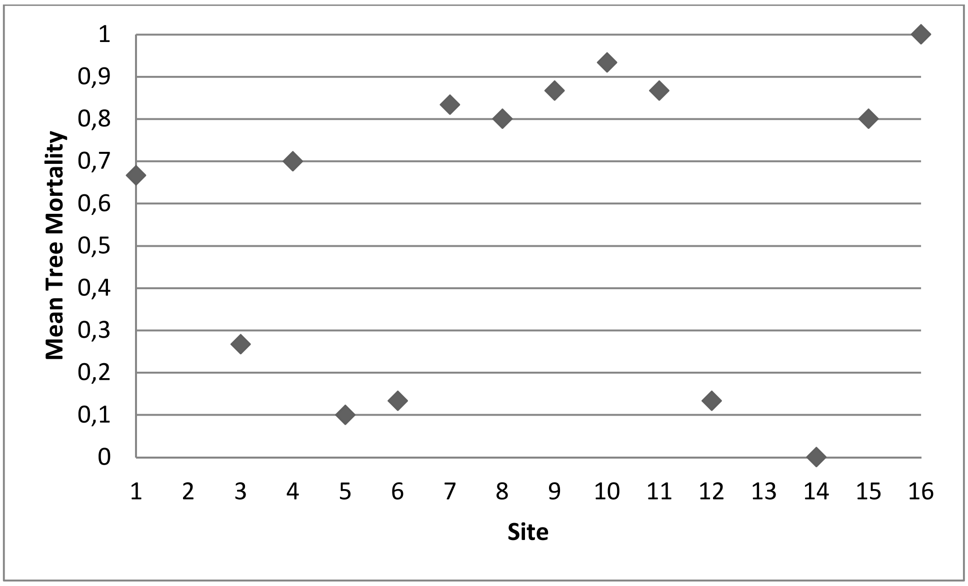

Figure 11. Mean tree mortality per site of trees measured for root exposure. Mortality was coded as 1 (Alive) or 0 (Dead). Note: some sites (2, 13) had no standing trees which is why some values are missing.

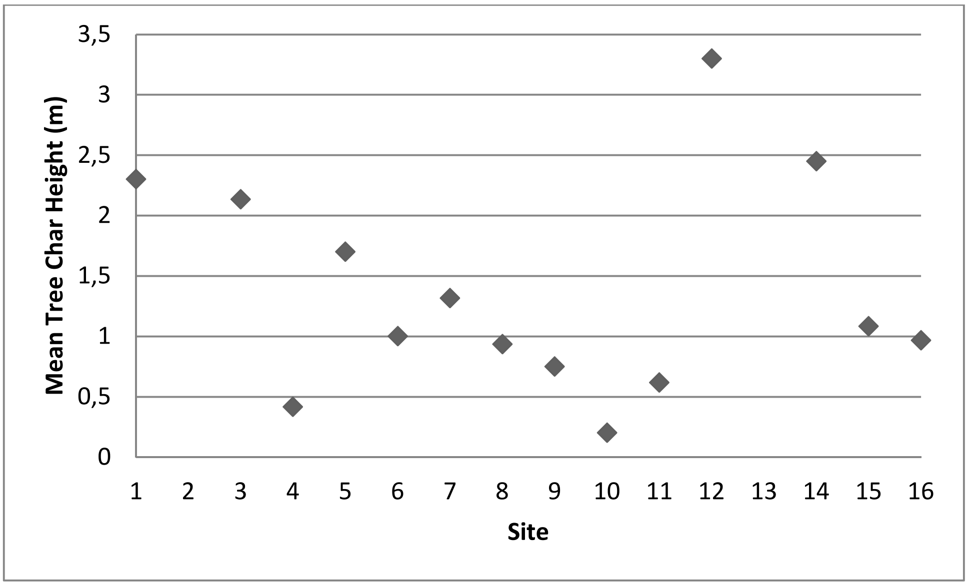

Figure 12. Mean tree char height per site of trees measured for root exposure. Note: some sites (2, 13) had no standing trees which is why some values are missing.

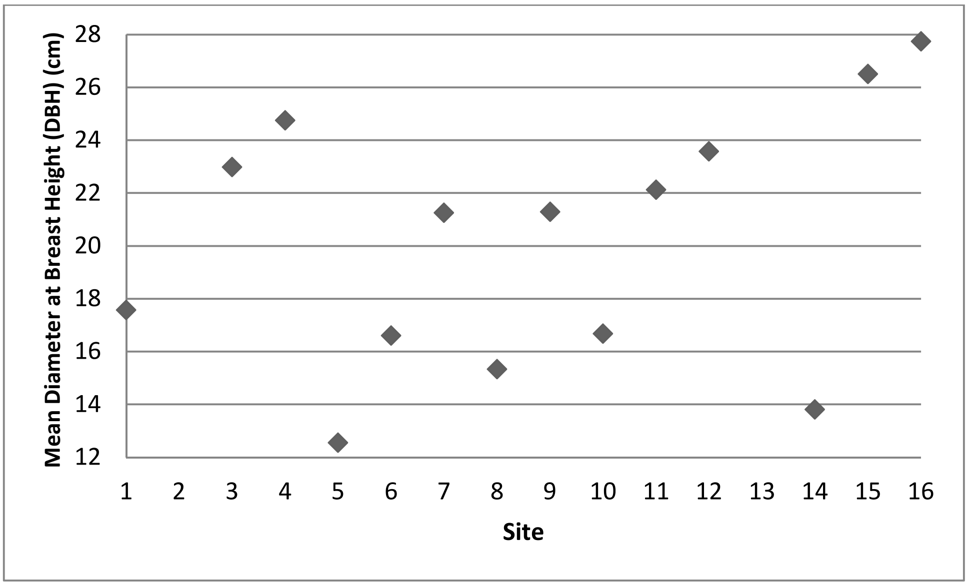

Figure 13. Mean diameter at breast height per site of trees measured for root exposure. Note: some sites (2, 13) had no standing trees which is why some values are missing.

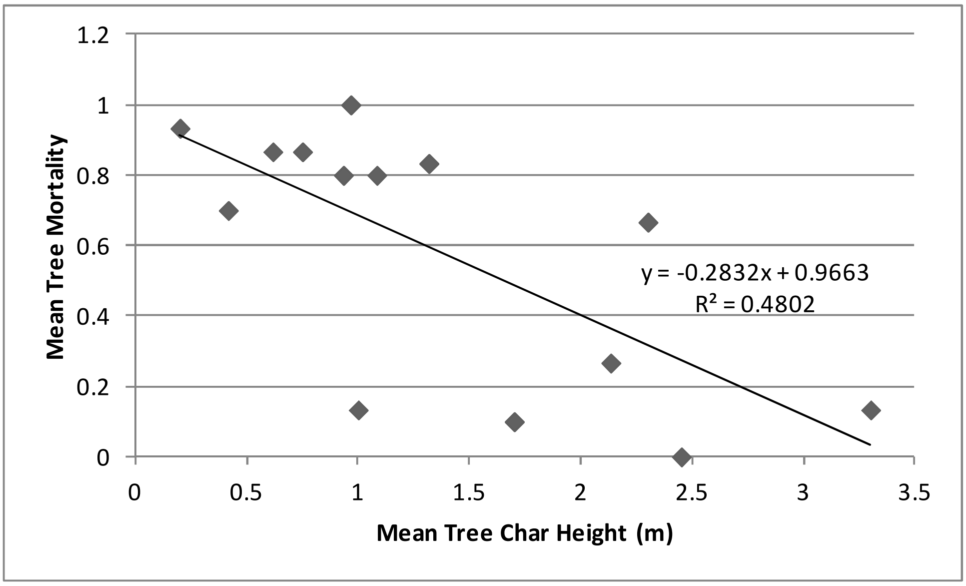

Figure 14. Mean tree mortality (0= 100% mortality, 1= 0%mortality) as a function of mean tree char height.

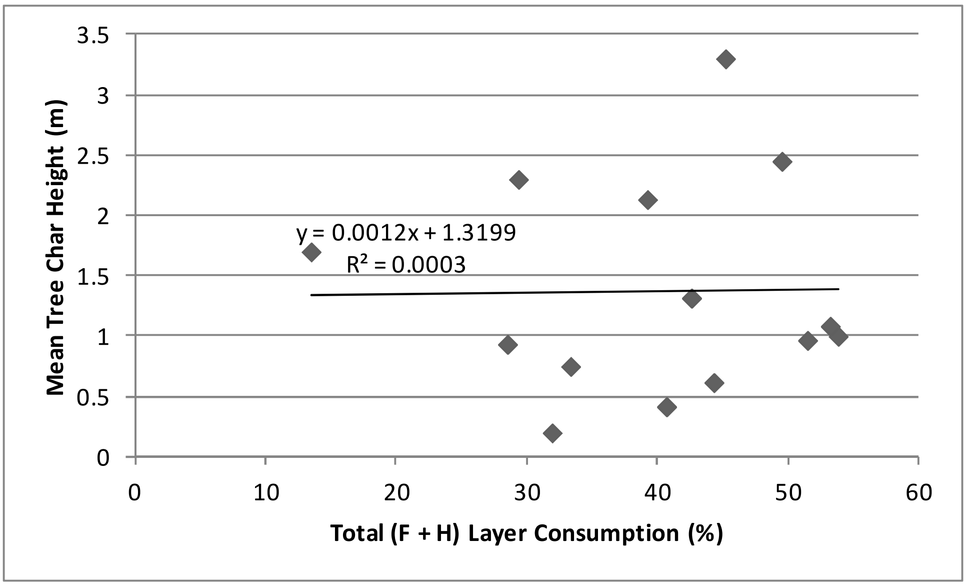

Figure 15. Correlation between total (fermentation and humus) organic layer consumption and the mean tree char height.

FWI Values and Organic Layer Consumption

Using the data package provided by MSB and the GPS coordinates for the individual sites, values for the Duff Moisture Code, Drought Code, Build-Up Index, and overall Forest Fire Weather Index were determined for each site (Table 8). Values for the 11 x 11 kilometer cell that the site was contained in were used, due to the similarities of values of neighboring cells for that specific date and weather combination. Based on the numerical fire risk classifications for high and extreme fire risk (Table 1), these values were categorized as moderate, high, or extreme fire risk.

Table 8. DMC, DC, BUI and FWI values for all sites on the day of the fire event. Numbers with * represent values with a "high" fire risk. Numbers denoted with †* represent values with an "extreme" fire risk. Numbers neither in bold nor asterisk represent a moderate fire risk.

Site #	Site	DMC	DC	BUI	FWI
1	Norra Kvill	*37	169.3	*47.9	*18.9
2	Kalvaberget	*38.6	173.3	*49.6	15.1
3	Smedjevik A	*32.7	*271.4	*50.3	9.5
4	Smedjevik B	*32.7	*271.4	*50.3	9.5
5	Hammarby	†*73.2	*290.8	†*89.9	*30.7
6	Kalmar 11 A	26.4	*249.4	*41.7	*27.8
7	Kalmar 11 B	26.4	*249.4	*41.7	*27.8
8	Ekopark Hornsö 6	26.8	93.7	31.2	8.4
9	Ekopark Hornsö 7A	24.8	87.3	29	6
10	Ekopark Hornsö 7B	24.8	87.3	29	6
11	Ekopark Hornsö 8	26.1	88.7	30.1	8.1
12	Ekopark Hornsö 2	*38.2	*260.2	*55.9	*20.9
13	Hovmantorp A	†*104.1	250.7	†*104.1	†*40.4
14	Hovmantorp B	†*104.1	250.7	†*104.1	†*40.4
15	Fjällmossen	†*52.9	*243.5	*68.6	10.5
16	Vägershult	†*111.5	*259.2	†*111.4	†*46

Since the differences between transects of the same types (non-burned or burned) on the same sites were not significant, means were pooled together for sites with two transects before calculating the consumption. Since sites varied and had different pre-and-post-fire fermentation and humus depths, this consumption ratio was calculated as opposed to just using changes in mean thickness. Consumption for organic layer consumption of the fermentation, humus, and total organic layers was computed by the following equation:

$$C\ (\%) = \frac{|T_C - T_F|}{T_C}(100)$$

(2)

Where

C (%) = Consumption (%)

T_C = Thickness of Control Layer

T_F = Thickness of Fire Layer

This was computed for each consumption layer for each site using the mean layer thickness calculated (Table 9). Using these consumption percentages, a chart was created (Figure 16) to illustrate the various percentages of consumption for each organic layer across all sites.

Table 9. Consumption percentages for each layer by site.

Site #	Site	Fermentation Layer (%)	Humus Layer (%)	Total (F+H) Layer (%)
1	Norra Kvill	46.34	22.79	29.33
2	Kalvaberget	89.16	41.59	50.34
3	Smedjevik A	48.58	34.26	39.21
4	Smedjevik B	26.81	47.79	40.66
5	Hammarby	21.12	7.89	13.45
6	Kalmar 11 A	53.36	54.07	53.81
7	Kalmar 11 B	41.51	43.31	42.58
8	Ekopark Hornsö 6	44.68	13.68	28.49
9	Ekopark Hornsö 7 A	40.96	26.84	33.32
10	Ekopark Hornsö 7 B	42.80	24.75	31.91
11	Ekopark Hornsö 8	59.06	32.23	44.29
12	Ekopark Hornsö 2	49.16	41.95	45.19
13	Hovmantorp A	75.79	32.79	49.69
14	Hovmantorp B	71.11	25.65	49.50
15	Fjällmossen	71.78	44.71	53.20
16	Vägershult	75.56	37.69	51.46

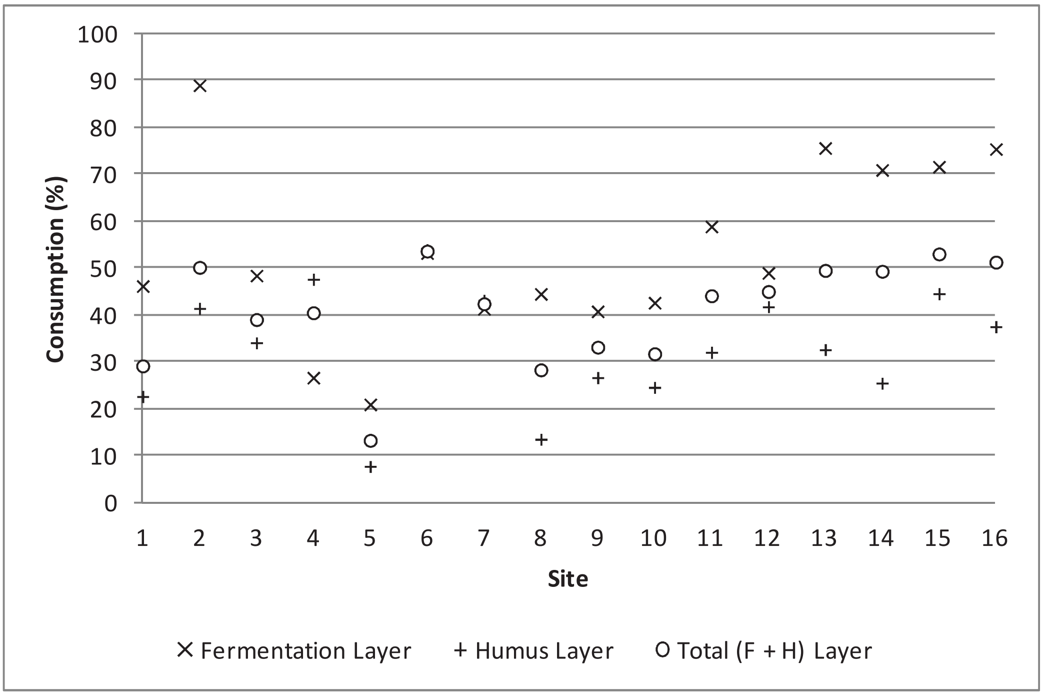

Figure 16. Overall consumption by site for all organic layers sampled.

Most fire sites in this study were prescribed burns, but some wildfires were measured. Therefore, it was necessary to determine the differences in consumption for these two types of sites. Site 13—Hovmantorp A, site 14—Hovmantorp B, and site 16—Vagershult were wildfire-caused events. The fermentation layer consumption for all of these sites was relatively high at 75.79%, 71.11% and 75.56% respectively. The humus layer consumption was relatively moderate at 32.79%, 25.65% and 37.69%. Total layer consumption for all of these sites was relatively high at 49.69%, 49.50% and 51.46%. Averaging across sites, prescribed burns consumed less of the fermentation layer than wildfires (48.87% and 74.16% respectively). Humus consumption was similar across prescribed burns and wildfires (33.53% and 32.04% respectively). Prescribed burns consumed less of the total (fermentation and humus) layer than wildfires (38.91% and 50.22% respectively). Figure 17 illustrates these differences.

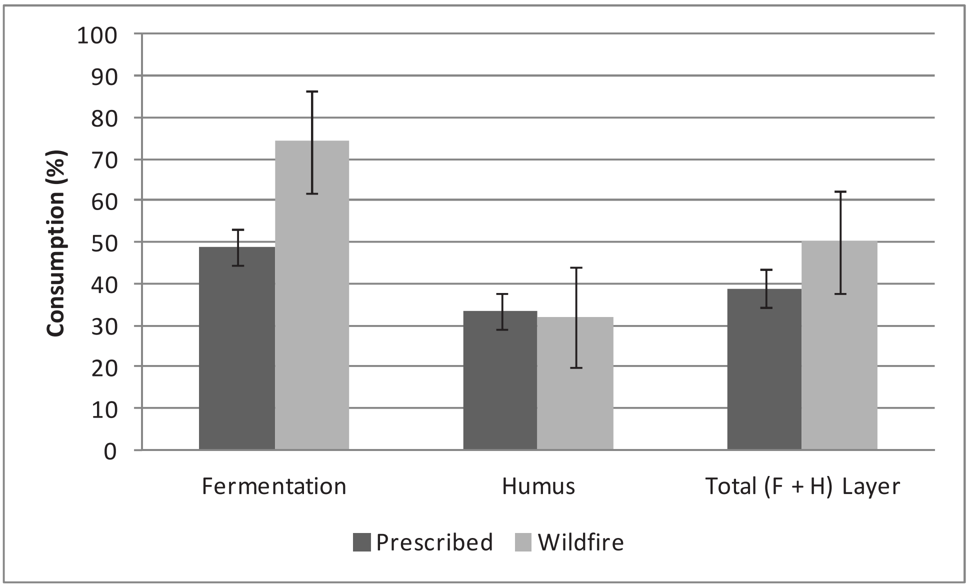

Figure 17. Overall consumption rates of organic layers during prescribed burn and wildfire-caused events.

Figure 18 shows the consumption of fermentation, humus, and total (fermentation and humus) organic layers for control and burn transects for each microtopography type averaged across all sites. Hollow microtopographies experienced the lowest consumption across all organic layers. Organic layers found on hummock microtopographies were consumed across all organic layer types more than hollows. Flat areas had less initial organic layer levels and were consumed more than hollows and hummocks. Slanted areas, existing on slopes, had the lowest initial organic layer thickness, but were consumed by fire events slightly less than those found on flat microtopographies.

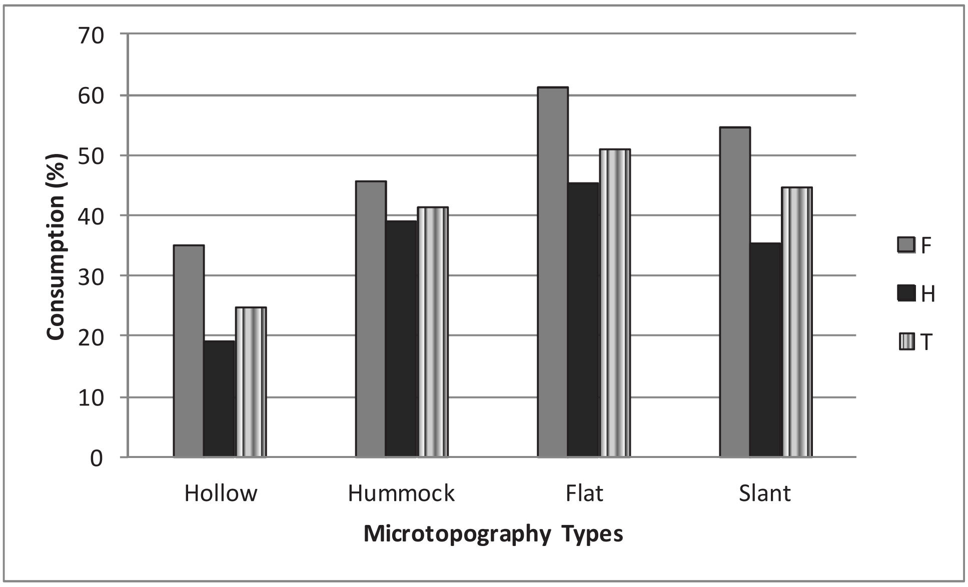

Figure 18. Consumption of organic layers averages across all sites by microtopography type.

The Forest Fire Weather Index (FWI) data specific to each site was compared to the data collected on the burn and non-burned sites. The primary focus of this analysis was to determine whether the moisture ranges believed to promote certain fire conditions, and represented by these numerical FWI values, are appropriate. In other studies, mean organic layer depth post-fire was compared to numerical FWI values, revealing a robust relationship (Amiro *et al.*, 2004; Goepfrich 2010). Since access to the sites prior to the burning events was not possible for this study, and data was collected from an adjacent non-burned control site, a consumption percentage was calculated rather than solely comparing mean organic layer thickness to the FWI values. This also helps to account for site variation.

The DMC risk rating for the day of the burn was related to the fermentation layer consumption on that day. Site 1—Norra Kvill experienced the highest fermentation layer consumption at 89.16% and had a DMC value of 37 for the day of the fire. This value is considered high risk. Site 14—Hovmantorp A had the second highest fermentation layer consumption at 75.79% with a DMC rating of 104.1, considered extreme risk danger. Site 16—Vägershult has the third highest fermentation layer consumption at 75.56% with a DMC rating of 111.5, extreme risk danger and the highest numerical DMC value across all of the sites.

The DC risk rating for the day of the burn was related to the humus layer consumption on that day. Site 5—Kalmar 11 A, has the highest humus layer consumption at 54.07% with a DC rating of 249.4, considered to be high. Site 4—Smedjevik B, has the second-highest humus layer consumption at 47.79% with a DC rating of 271.4, considered to be high. Site 15—Fjällmossen had the third-highest humus layer consumption at 44.71% with a DC rating of 243.5, considered to be high.

The DMC, DC, BUI, and FWI risk ratings for the day of the burn were related to the total organic layer consumption on that day. The highest total organic layer consumption was on site 6—Kalmar 11 A at 53.81%. This site had a DMC value of 26.4 (moderate), DC value of 249.4 (high), BUI value of 41.7 (high), and FWI value of 27.8 (high). The second-highest total organic layer consumption was on site 15—Fjällmossen at 53.20% and with a DMC value of 52.9 (extreme), DC value of 243.5 (high), BUI value of 68.6 (extreme), and FWI value of 10.5 (moderate). The third highest total organic layer consumption was on site 16—Vägershult at 51.46% and with a DMC value of 111.5 (extreme), DC value of 259.2 (high), BUI value of 111.4 (extreme), and FWI value of 46 (extreme).

Simple linear regression was employed to determine the correlation between these indices and the consumption rates of organic layers attributed to fire events. After evaluating initial data analysis across all variables (results not shown), the following relationships were deemed important: fermentation layer consumption as a function of DMC (Figure 19); humus layer consumption as a function of DC (Figure 20); total organic layer consumption as a function of DMC (Figure 19); total organic layer consumption as a function of DC (Figure 21); total organic layer consumption as a function of BUI (Figure 22); and total organic layer consumption as a function of FWI (Figure 23).

The R-square values were as follows: fermentation layer consumption as a function of DMC was 0.2113; humus layer consumption as a function of DC was 0.1303; total organic layer consumption as a function of DMC was 0.0608; total organic layer consumption as a function of DC was 0.0656; total organic layer consumption as a function of BUI was 0.0568; and total organic layer consumption as a function of FWI was 0.0837.

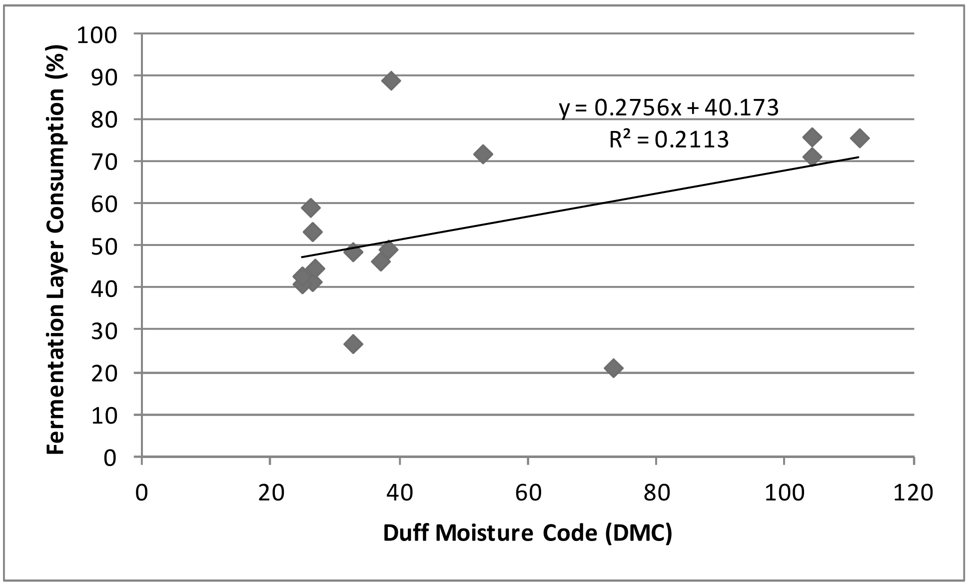

Figure 19. Fermentation layer consumption as a function of the DMC.

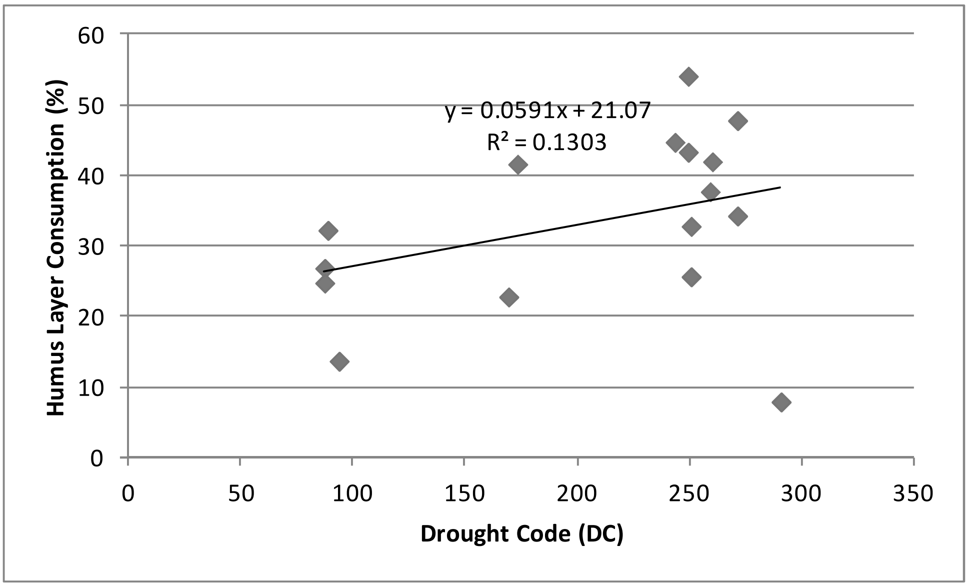

Figure 20. Humus layer consumption as a function of the DC.

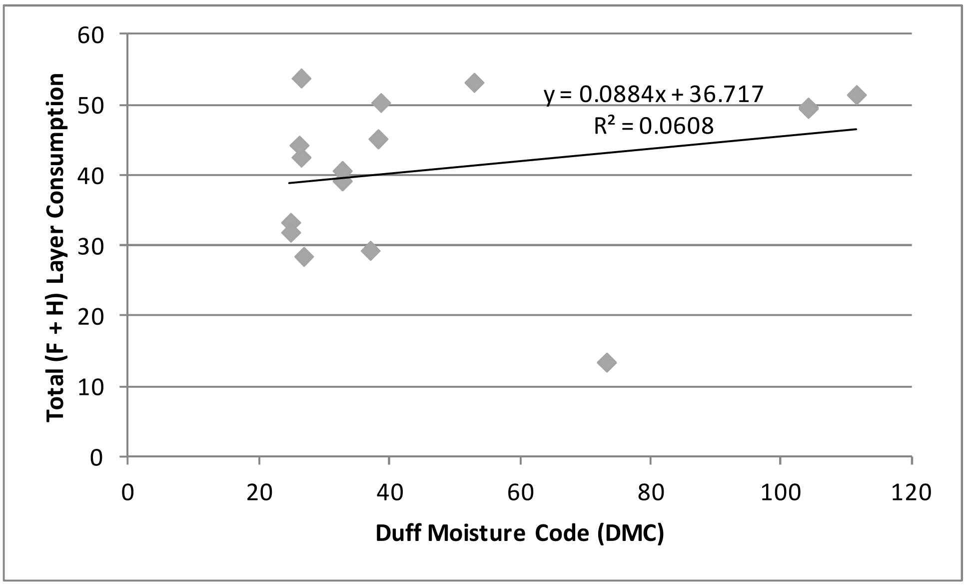

Figure 21. Total organic layer consumption as a function of the DMC.

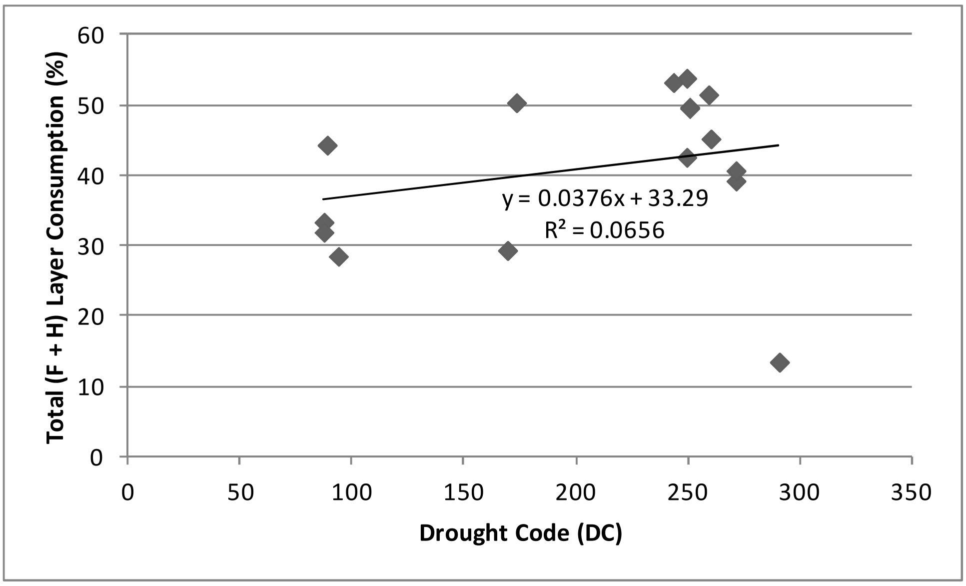

Figure 22. Total organic layer consumption as a function of the DC.

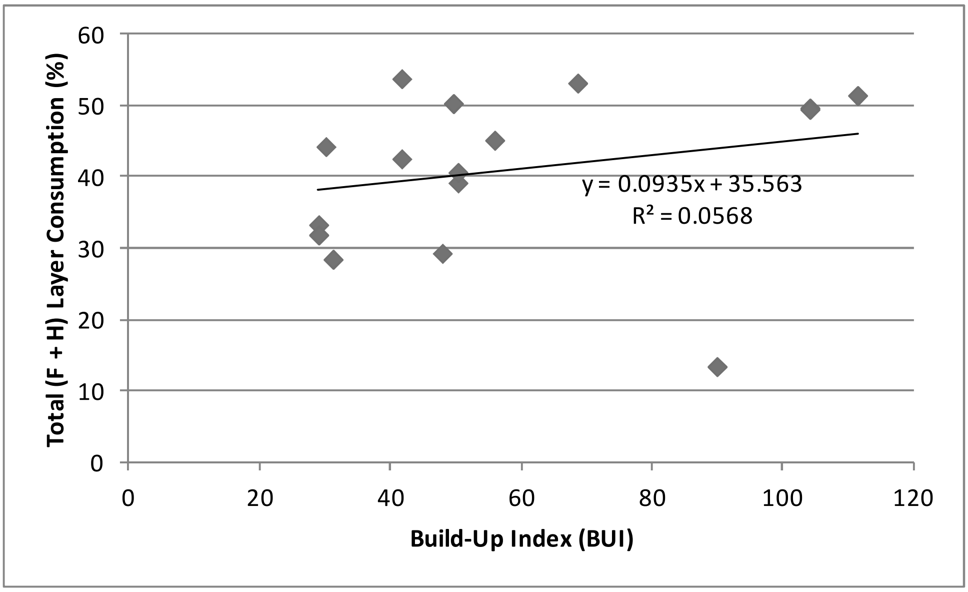

Figure 23. Total organic layer consumption as a function of the BUI.

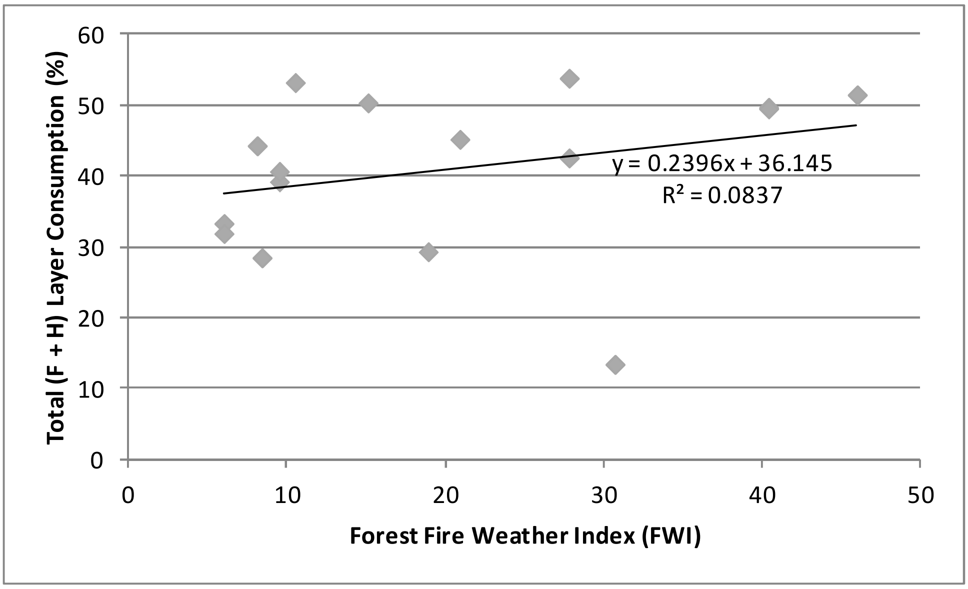

Figure 24. Total organic layer consumption as a function of the FWI.

Upon further inspection, it was discovered that site 5—Hammarby, had significantly lower consumption than the other sites. Hammarby had a 4-year interval between data collection and the fire event, the longest interval across all sites. The reaccumulation of the organic layer during the time may explain the lower consumption rates calculated. For fermentation, humus, and total layers, the consumption percentages were 21.1%, 7.8%, and 13.4% respectively. Therefore, this site was deemed an outlier, and while included in the overall data analysis, it was removed here to determine whether the correlations were stronger without inclusion of this site. The following relationships were compared, excluding the Hammarby site: fermentation layer consumption as a function of DMC (Figure 25); humus layer consumption as a function of DC (Figure 26); total organic layer consumption as a function of DMC (Figure 27); total organic layer consumption as a function of DC (Figure 28); total organic layer consumption as a function of BUI (Figure 29); and total organic layer consumption as a function of FWI (Figure 30).

The R-square values were as follows: fermentation layer consumption as a function of DMC was 0.4106 (up from 0.2113); humus layer consumption as a function of DC was 0.4195 (up from 0.1303); total organic layer consumption as a function of DMC was 0.2695 (up from 0.0608); total organic layer consumption as a function of DC was 0.3897 (up from 0.0656); total organic layer consumption as a function of BUI was 0.357 (up from 0.0568); and total organic layer consumption as a function of FWI was 0.3272 (up from 0.0837).

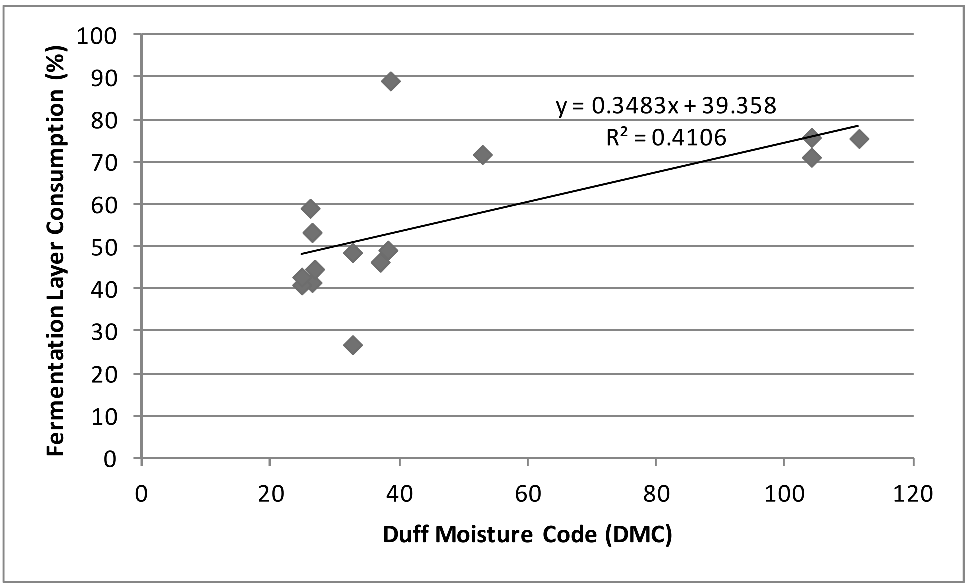

Figure 25. Fermentation layer consumption as a function of the DMC. In this case, site 5—Hammarby, was removed from the statistical analysis as an outlier due to the particularly low fermentation layer consumption rate calculated for this site.

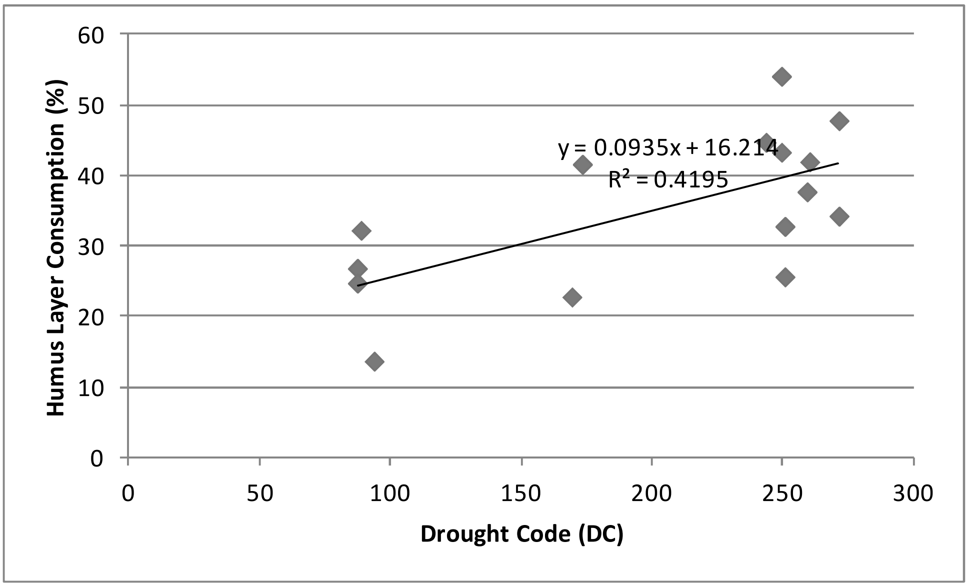

Figure 26. Humus layer consumption as a function of the DC. In this case, site 5—Hammarby, was removed from the statistical analysis as an outlier due to the particularly low humus layer consumption rate calculated for this site.

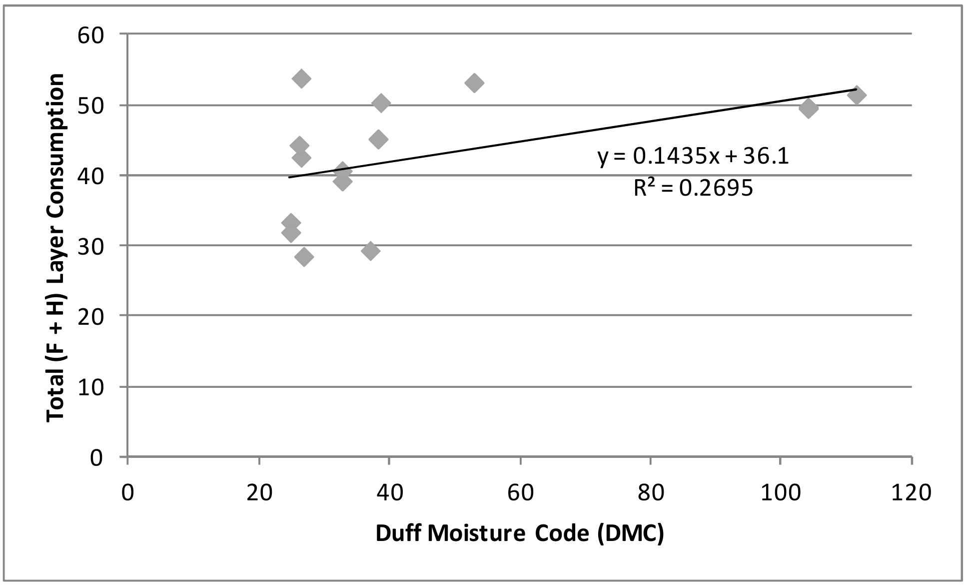

Figure 27. Total organic layer consumption as a function of the DMC. In this case, site 5—Hammarby, was removed from the statistical analysis as an outlier due to the particularly low total layer consumption rate calculated for this site.

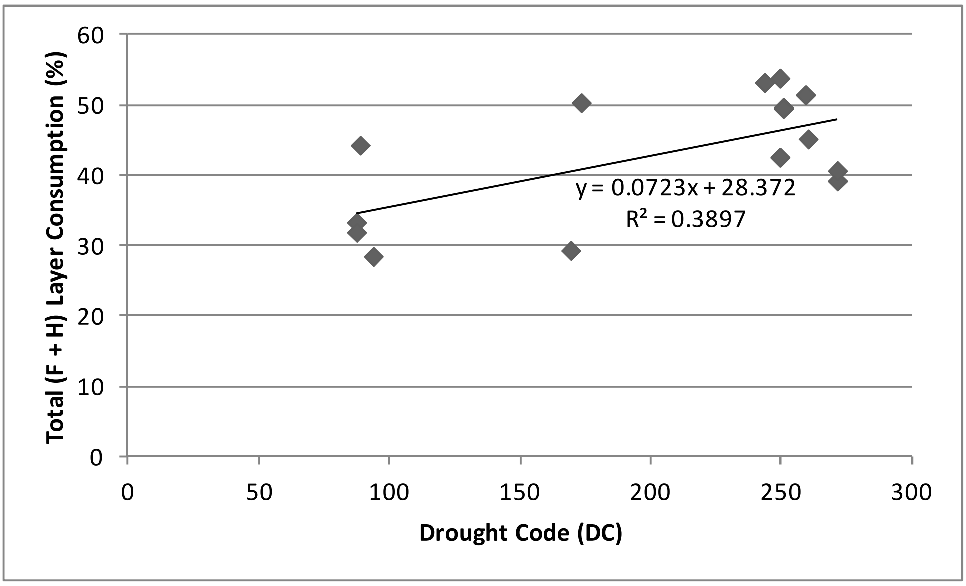

Figure 28. Total organic layer consumption as a function of the DC. In this case, site 5—Hammarby, was removed from the statistical analysis as an outlier due to the particularly low total layer consumption rate calculated for this site.

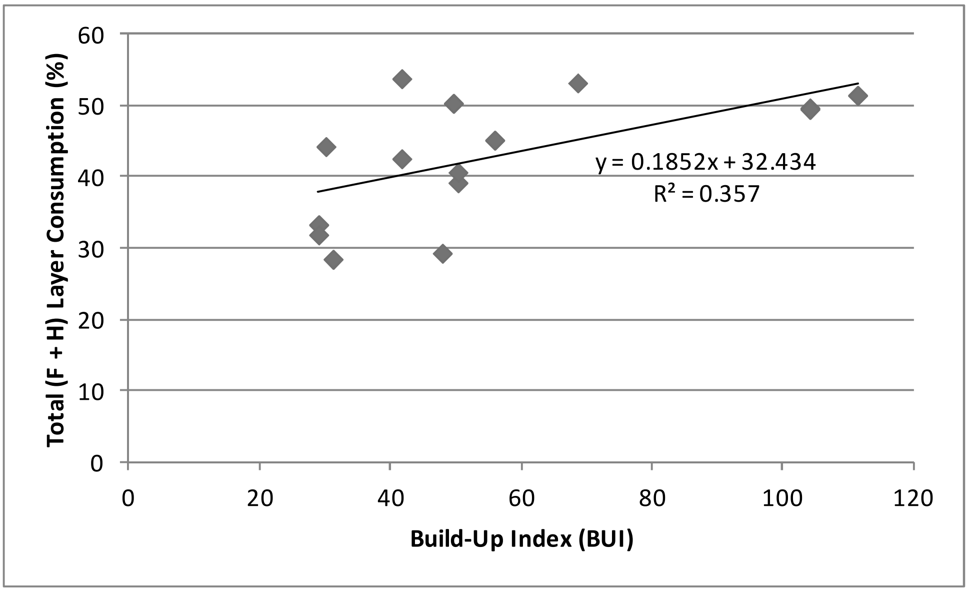

Figure 29. Total organic layer consumption as a function of the BUI. In this case, site 5—Hammarby, was removed from the statistical analysis as an outlier due to the particularly low total layer consumption rate calculated for this site.

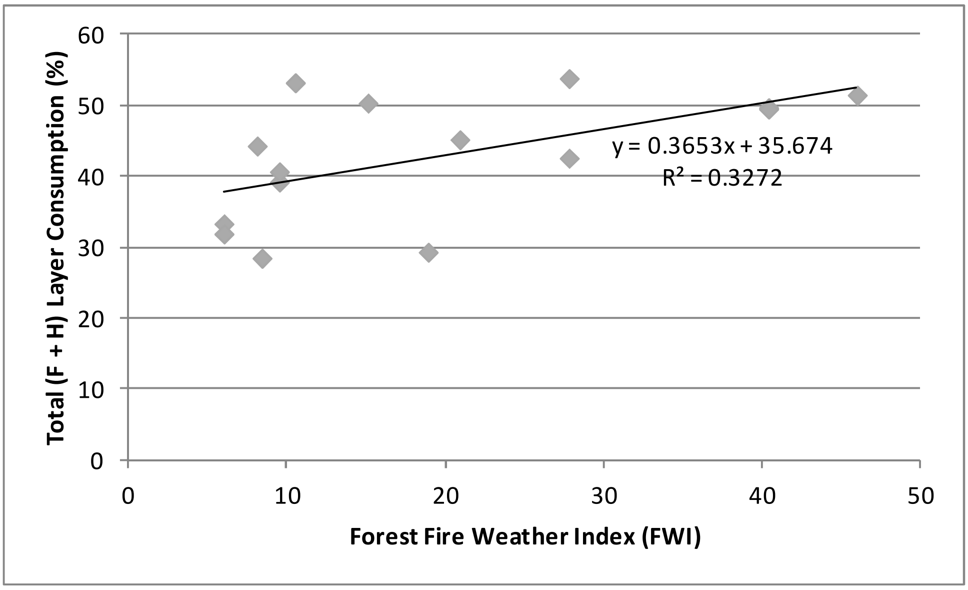

Figure 30. Total organic layer consumption as a function of the FWI. In this case, site 5—Hammarby, was removed from the statistical analysis as an outlier due to the particularly low total layer consumption rate calculated for this site.

DISCUSSION

Fermentation and Humus Measurements

The site and transect type variables were significant across fermentation, humus, and total organic layer depths. Significance of the site variable could be attributed to variation across sites. Appendices I and II present individual site characteristics. There were varying lengths in time since the fire event. The longest was site 5—Hammarby, being burned four years prior (June 2007) to the time of data collection for this study (June 2011). Other sites were burned anywhere from three years to just one year prior to data collection, but all were burned in the months on May, June, or July. Sites also varied in stand density and forest management treatments (thinning, clearcutting), as well as in the dominant tree species. All of these factors can explain the significance of the site variable found in this study.

After accounting for site, transect type was significant across thickness of fermentation, humus, and total organic layers. Inherently, this study centralizes on the fact that some organic layer is generally consumed during fire events. Thus, an adjacent control transect should have thicker fermentation and humus layers than a fire transect type.

Microtopography was found to be significant across depths of fermentation, humus, and total organic layers after accounting for site and transect type. The possible microtopographic classification values were: hummock, hollow, slant, or flat. Previous studies have given merit to geographic and topographical features in promoting or inhibiting organic layer consumption, bolstering the argument for including these characteristics into the FWI in the future (Tanskanen and Venalainen, 2008). One of the main aspects of the influences of microtopography on organic layer consumption is the promotion of soil moisture. Organic layers found on a slant (slope) would be more readily drained of water, and those on a flat surface should exhibit consumption uninfluenced by microtopography. Hollows, being dipped in formation, collect water. The moisture level of soils influence the ability for these soils to burn (Robichaud *et al.,*, 2004), as exhibited in general during this study.

After accounting for site, transect type, and microtopography, vegetation (species type) and height of vegetation were both significant across fermentation, humus, and total (fermentation and humus) organic layer measurements. In the case of vegetation, heather (*Calluna* spp.) and fireweed (*Epilobium* spp.) respond to fire events and are found in greater prevalence on a burn transect versus a control transect. Fire events consume vegetation, especially mosses and lichens, further encouraging divergent species on a control transect as opposed to a fire transect. Varying microtopographies create different moisture regimes and build-ups of the organic layer, some of which will be best suited for some vegetation types over others. Vegetation that is left undisturbed will continue to grow, allowing for higher possible heights of vegetation on the control transects. Also attributing to this, different vegetation species have different height potentials.

Soil spatial variability along transects has been noted as significant in other studies focused on land management. In these studies, spatial variability was determined both along transects and at varying depths (Butcher *et al.,* 1991). Butcher *et al.* (1991) collected measurements at every 1 meter mark, at 30 and 60 centimeter depths along a 100 meter transect. This study employed similar transect lengths and measurement points, but the depths sampled were not as deep in this research. Due to the differences in scale of the depths at which thickness is being measured, the same soil spatial variability should not be expected. In this study variability along transects was not significant in terms of the thickness of the fermentation, humus, and total (fermentation and humus) organic layers after accounting for site, transect type and microtopography. Variations between sites and the influence of microtopography may have altered identifying typical transect autocorrelation patterns in this research.

Root Exposure Measurements

Root exposure is attributed to long smoldering fires consuming the organic layer around the base of the trees, therein exposing the roots. Trends were noted for root exposure, mean tree mortality, mean tree char height, and mean diameter at breast height in association with the calculated organic layer consumption.

Mean root exposure was most severe on site 15—Fjällmossen. Fjällmossen experienced relatively high fermentation (71.78%) and humus (44.71%) consumption rates. Total consumption at this site was the second-highest across sites at 53.20%.

Root exposure was lowest on site 8—Ekopark Hornsö 6 and this site experienced moderate fermentation (44.68%) consumption and relatively low humus (13.68%) consumption. Total consumption at this site was the third-lowest at 28.49%. Root exposure on these study sites was an indication of smoldering fire events and of the relative amount of fermentation, humus, and total (fermentation and humus) consumption.

Tree mortality was highest on site 14—Hovmantorp B. Hovmantorp B experienced relatively high fermentation consumption (71.11%), but humus consumption was relatively low (25.65%). Total (fermentation and humus) consumption at Hovmantorp B was high at 49.50%. Tree mortality was lowest on site 16—Vägershult, although it experienced a high fermentation layer consumption rate (75.56%) and a moderate humus layer consumption rate (37.69%). The total (fermentation and humus) consumption was high at 51.46%. Both Hovmantorp B and Vägershult were burn sites caused by wildfire events. More trees remained after the wildfire to sample at Hovmantorp B than at Vägershult, potentially skewing these tree mortality results. However, when the graphs of mortality and root exposure are compared, mortality is generally higher on sites with a higher root exposure amount.

Mean char height was highest on site 12—Ekopark Hornsö 2. Consumption of both fermentation (49.16%) and humus (41.95%) layers was relatively moderate for site 12—Ekopark Hornsö 2. This site also experienced high mortality. Trends between char height and mortality were apparent. Figure 14 revealed an R-square value of 0.4802, indicating that as the char heights on the stem of trees increased, mortality also increased. There was also a trend between root exposure and mortality. However, as could probably be expected, char heights and root exposure did not exhibit a strong relationship with each other. Higher char heights and greater root exposure are generally evidences of two potentially different fire behaviors unrelated to one another. Root exposure is evidence of a smoldering fire, while high char height is evidence of an intense and hot fire with available fuel for combustion. While these phenomena can occur during the same fire, in the event of these sites, that trend was not noted. Furthermore, Figure 15 exhibited an R-square value of 0.0003 for the relationship between total organic layer consumption and mean tree char height. This suggests that a fire event consuming a large amount of the organic layer does not necessarily have to be very hot and intense, as evidenced by higher char heights.

Mean diameter at breast height (DBH) was highest on site 16—Vagershult. Mean DBH should not really be an indicator of organic layer consumption, and was not found to be so in the case of these sites. However, higher DBH indicates an older stand and may insinuate a longer period of organic layer build-up.

FWI Values and Organic Layer Consumption

Site 5—Hammarby had experienced the longest amount of time since the fire event. As previously mentioned, this site was burned four years prior (June 2007) to the time of data collection for this study (June 2011). Due to this fact and the low consumption amounts across all organic layer types in this study, Hammarby was removed from this data analysis. When excluding this site, an argument can be made that some FWI fuel moisture codes and numerical risk ratings can moderately predict the relative level of fermentation, humus, and total (fermentation and humus) organic layer consumptions when coupled with knowledge of other site characteristics. On a dry site where wildfire risk is high, more consumption is expected. On the three wildfire sites (site 13—Hovmantorp A, site 14—Hovmantorp B, and site 16—Vägershult), fermentation layer consumption was among the highest, while humus layer consumption was moderate in comparison to prescribed burn sites. Total (fermentation and humus) organic layer consumption was high for all wildfire sites in relation to prescribed burned sites. Including site characteristics such as these in fire management can only strengthen the efficacy of the FWI as a predictive tool in southern Sweden.

In this study, when the DMC rating for a site was extreme or high, consumption of the fermentation layer on this site was also relatively high. The R-square value of fermentation layer consumption as a function of DMC was 0.4106 when not including site 5—Hammarby. DMC is a relatively good predictor of relative fermentation layer consumption. Smoldering fires, as evidenced by the presence of root exposure, also occurred at times when DMC codes were high and fermentation layers were consumed.

When the DC rating for a site was high, consumption of the humus layer on this site was also relatively high. There were no DC values at any site above 300, the threshold over which DC values are considered to represent extreme fire risk. The R-square value of humus consumption as a function of DC was 0.4195 when not including site 5—Hammarby. DC is a good predictor of relative humus layer consumption. While root exposure was generally high when DC values were higher, and higher humus layer consumption was seen as a result; this study had no sites with DC values in the extreme fire risk category. If a forest planner was interested in producing a smoldering fire, they may want to plan a burn on a day with an extreme DC rating if complete consumption of the humus layer was the goal of the prescribed fire. However, managers should be cautioned as extreme DC ratings are generally coupled with other extreme FWI ratings and climatic conditions which could make a prescribed fire difficult to control, especially afterwards in the smoldering period.

Goeprfrich (2010) compared total organic layer burn depths during fire events to the DMC. This study found that ignition occurring under extreme drought situations were coupled with a high DMC value and increased organic layer consumption (Goepfrich, 2010). In the current study, total (fermentation and humus together) layer consumption was regressed as a function of DMC, DC, and BUI. When considering fermentation and humus total consumption as a function of DMC, the relationship was not as strong as when considering total consumption as a function of DC or BUI. The R-square value of total organic layer consumption as a function of DMC was 0.2695, of DC was 0.3897, and of BUI was 0.357, when not including site 5—Hammarby.

DMC ratings ranged from moderate to high on the sites experiencing the highest total consumption. However, since DMC is reflective of the fire risk based upon moisture of organic layers at a fairly shallow depth, a single rain event can greatly alter the combustibility of those superficial fuels. Additionally, in the case of the Goepfrich (2010) study, data was collected at consistent site types, which may explain the strength of the DMC to predict total organic layer in that study but not in this one.

Here, DC and BUI seem to give a more complete account of total organic layer consumption. DC ratings were all high for the sites experiencing highest total consumption. Since DC is reflective of the fire risk based upon the moisture of deeper organic layers, it would take more than a single rain event to greatly increase the moisture of these soils and decrease the numerical fuel moisture code. Since BUI is derived from the numerical ratings from DMC and DC, this relationship is in line with the trends seen with DMC and the fermentation layer and DC and the humus layer. Very high and extreme fire risk ratings for BUI were partnered with the highest total organic layer consumption rates observed. As with the suggestions for forest managers for DC and humus layer consumption, if a smoldering fire is the management goal, selecting a day for a prescribed burn with a high or extreme DC or BUI would be the suggestion. However, planning a burn during a time when mid-and-deep level organic layers are almost entirely void of moisture could most certainly have deleterious consequences and caution should be used. This is one of the reasons why prescribed burns are not planned on extreme fire risk days because they are very difficult to control.

The fermentation and humus (total) consumption was also regressed as a function of the FWI. When considering fermentation and humus consumption as a function of the FWI, the relationship becomes less clear. FWI is composed of numerical ratings from the BUI, which derives values from the DMC and DC. However, FWI also takes into account the Fine Fuel Moisture Code (FFMC), wind, and the Initial Spread Index (ISI) (CWFIS, 2009). ISI and FFMC were not within the scope of this study. Therefore, the correlation between FWI and total organic layer consumption was not as strong as those correlations exhibited between DMC and fermentation consumption and DC and humus consumption. The R-square value of total organic layer consumption as a function of FWI was 0.3272 when not including site 5—Hammarby. The R-square value of 0.3272 for FWI was close to the R-square values for DC at 0.3897 and BUI at 0.357. However, FWI takes into account other factors, as mentioned previously. These disparities were noted in the comparisons of FWI ratings and total organic layer consumption. Therefore, while it can be used as an indicator of fermentation and humus consumption, BUI and DC would give a clearer and more accurate picture for these specific events.

Based upon the results of this study, the Canadian FWI is effective as a fire risk rating system in southern Sweden and applicable for predicting the fermentation and humus consumption of soil organic layers with fairly accurate precision. The addition of more weather stations and fuel moisture code collection areas across Sweden would be helpful in decreasing the size of the cell from 11 x 11 kilometers. In this way, FWI values would be interpolated over a smaller area, hopefully increasing the accuracy of the numerical ratings. Addition of other site characteristics to the system would further enhance the strength of the FWI ratings.

Future Research

Since knowledge gaps persist about organic layer consumption in southern Sweden fire ecology, this study should be replicated across the region by forest managers. Furthermore, reproduction of this study would allow for better attempts at organic layer consumption for specific ecological benefits. Using the DMC and DC fuel moisture codes and the BUI numerical fire risk index, along with specific site characteristics, forest managers introducing smoldering ground fires for seed germination or increased fermentation and humus consumption could possibly maximize desired root exposure and tree mortality.

The methodology for this project was developed to be quick and efficient, while also providing valuable data. To replicate this study, on a non-burned site a transect would be marked off at each end with rebar or another fire resistant marker. The transect measurement procedure employed in this research would be carried out and then the site would be burned. After the consumption process completed, the site would be re-measured along the exact same transect. This would give the truest picture of the actual consumption occurring in the fermentation and humus layers due to fire events. The litter layer could also be measured along with the other organic layers to increase the study variables and enhance analysis.

Additionally, forest managers and modelers with an intimate knowledge of forest fire weather indices should investigate the development of a forest fire weather index specifically developed for Sweden, if not solely for southern Swedish conditions. This would give forest managers and fuels planners a more complete picture, rather than extrapolating an index developed for Canada. Site characteristics should be considered as an addition to any future forest fire weather index for this region.

CONCLUSIONS

The Canadian Forest Fire Weather Index (FWI) numerical fire risk ratings focused upon in this study were useful indicators for relative amounts of fermentation and humus organic layer consumption attributed to fire events in southern Sweden. In particular, the fermentation layer consumption was a function of the Duff Moisture Code (DMC), the humus layer consumption was a function of the Drought Code (DC), and the total (fermentation and humus) layer consumption was a function of the Build-Up Index (BUI) and Drought Code (DC). Trends were clear, but variation was large enough in consumption that it is hard to predict a precise consumption goal. Furthermore, post-fire weather conditions may have an additional influence on the consumption of organic layers by influencing smoldering combustion.

Where root exposure and tree mortality was found on sites, the fermentation layer and humus layer consumption rates were relatively high. Additionally, the DMC and DC fuel moisture codes were classified as high or extreme. Microtopography and vegetation site characteristics were significant factors for both the thickness and the amount of consumption of these organic layers. In particular, grouping knowledge of vegetative species types and topography at a potential burn site can be beneficial to understanding the site-specific attributes that inhibit or increase the capability of organic layers to combust. The strength of the FWI numerical codes and index values (specifically the DMC, DC, and BUI) for predicting fermentation and humus organic layer combustion should only increase when considering these characteristics.

Methodology utilized in this study could be replicated in potential new fire research in southern Sweden. Future studies should involve reproduction of studies similar to this one at a larger number of sites to increase the ability to more closely identify trends. Further measurements and studies across the region will reinforce and enhance the use of the FWI and potentially encourage the development of a southern Sweden forest fire weather index.

LITERATURE CITED

Acuna, M. A., Palma, C. D., Cui, W., Martell, D. L., and Weintraub, A. (2010). Integrated spatial fire and forest management planning. *Canadian Journal of Forest Research, 40,* 2370-2383.

Amiro, B. D., Logan, K. A., Wotton, B. M., Flannigan, M. D., Todd, J. B., Stocks, B. J., and Martell, D. L. (2004). Fire weather index system components for large fires in the Canadian boreal forest. *International Journal of Wildland Fire, 13*(4), 391–400.

Angelstam, P. and Kuuluvainen, T. (2004). Boreal forest disturbance regimes, successional dynamics and landscape structures – a European perspective. Ecological Bulletins, 51: 117–136.

Bartsch, A., Balzter, H., and George, C. (2009). The influence of regional surface soil moisture anomalies on forest fires in Siberia observed from satellites. Environmental Research Letters, 4: 9 pp.

Bouchard, M. and Pothier, D. (2011). Long-term influence of fire and harvesting on boreal forest age structure and forest composition in eastern Quebec. Forest Ecology and Management, 261: 811-820.

Boucher, Y. and Grondin, P. (2012). Impact of logging and natural stand-replacing disturbances on high-elevation boreal landscape dynamics (1950-2005) in eastern Canada. Forest Ecology and Management, 263: 229-239.

Brose, P. H. (2010). Long-term effects of single prescribed fires on hardwood regeneration in oak shelterwood stands. Forest Ecology and Management, 260: 1516-1524.

Butcher, B., Aina, P. O., Azari, A. S., and Nielsen, D. R. (1991). Soil spatial variability along transects. Soil Technology, 4: 297-314.

Byram, G. M. (1959). Combustion of forest fuels. In K.P. Davis (Ed.), Forest fire: control and use (61-89). New York: McGraw-Hill.

Canadian Wildland Fire Information System (CWFIS). (2009). Background Information: Canadian Forest Fire Weather Index (FWI) System. Retrieved from http://cwfis.cfs.nrcan.gc.ca/background/summary/fwi

Esseen, P. A., Ehnström, B., Ericson, L., and Sjöberg, K. (1997). Boreal forests. Ecological Bulletins 46: 16-47.

Forestry Department of the Food and Agriculture Organization of the United Nations (FAO). (2010). Global Forest Resources Assessments 2010 Country Report—Sweden. Rome, Italy: The Forest Resources Assessment Programme (FRA).

Goepfrich, A. (2010). Do climatic conditions at the time of fire alter post-fire growth of Scots pine (Pinus sylvestris)? (Doctoral dissertation). Bangor University, Bangor, Wales.

Granström, A. (2001). Fire management for biodiversity in the European boreal forest. Scandinavian Journal of Forest Research: 16: 62-69.

Granström, A., and Niklasson, M. (2008). Potentials and limitations for human control over historic fire regimes in the boreal forest. Phil. Trans. R. Soc. B, 363: 2353-2358.

Hille, M. and den Ouden, J. (2005). Fuel load, humus consumption and humus moisture dynamics in Central European Scots pine stands. International Journal of Wildland Fire 14(2): 153–159.

Hille, M. G. and Stephens, S. L. (2005). Mixed Conifer Forest Duff Consumption during Prescribed Fires: Tree Crown Impacts. Forest Science, (51)5, 417-424.

International Forest Fire News (IFFN). (1998). Forest Fire and Fire Management in Sweden. (A. Granström, Ed.). No. 18: 75-77.

International Forest Fire News (IFFN). (2004). Fire in Sweden—History, Research, Prescribed Burning, and Forest Certification. (M. Niklasson & A. Granström, Eds.). No. 30: 80-83.

Johnstone, J. F. and Chapin III, F. S. (2006). Effects of Soil Burn Severity on Post-Fire Tree Recruitment in Boreal Forest. Ecosystems, 9: 14-31.

Keane, R. E. and Karau, E. (2010). Evaluating the ecological benefits of wildfire by integrating fire and ecosystem simulation models. Ecological Modelling, 221: 1162-1172.

Larjavaara, M., Kuuluvainen, T., and Rita, H. (2005). Spatial distribution of lightning-ignited forest fires in Finland. Forest Ecology and Management, 208: 177-188.

Lecomte, N., Simard, M., Fenton, N., and Bergeron, Y. (2006). Fire Severity and Long-term Ecosystem Biomass Dynamics in Coniferous Boreal Forests of Eastern Canada. Ecosystems, 9: 1215-1230.

Miyanishi, K. (2001). Duff Consumption. In E. A. Johnson & K. Miyanishi (Eds.), Forest Fires: Behavior and Ecological Effects (437-475). San Diego, CA: Academic Press.

National Climatic Data Center. (1990). Climate normals 1961-1990 by WMO Region Association (RA) [RA-VI [Europe]: Sweden]. Retrieved from http://www.ncdc.noaa.gov/oa/wdc/index.php?name=climateoftheworld

Nesmith, J. C. B, Caprio, A. C., Pfaff, A. H., McGinnis, T. W., and Keeley, J. E. (2011). A comparison of effects from prescribed fires and wildfires managed for resource objectives in Sequoia and Kings Canyon National Parks. Forestry Ecology and Management, 261: 1275-1282.

Niklasson, M. and Drakenberg, B. (2001). A 600-year tree-ring fire history from Norra Kvills National Park, southern Sweden: implications for conservation strategies in the hemiboreal zone. Biological Conservation, 101: 63-71

Niklasson, M. and Granström, A. (2000). Numbers and sizes of fires: Long term trends in a Swedish boreal landscape. Ecology, 81, 1496-1499.

Otway, S. G., Bork, E. W., Anderson, K. R., and Alexander, M. E. (2007). Predicting sustained smouldering combustion in trembling aspen duff in Elk Island National Park, Canada. International Journal of Wildland Fire, 16(6), 690–701.

Rein, G., Cleaver, N., Ashton, C., Pironi, P., and Torero, J. L. (2008). The severity of smouldering peat fires and damage to the forest soil. CATENA, 74(3), 304-309.

Risberg, L. and Granström, A. (2009). The effect of timing of forest fire on phenology and seed production in the fire-dependent herbs Geranium bohemicium and G. lanuginosum in Sweden. Fire Ecology and Management, 257, 1725-1731.

Robichaud, P. R., Gasvoda, D. S., Hungerford, R. D., Bilskie, J., Ashmun, L. E., and Reardon, J. (2004). Measuring duff moisture content in the field using a portable meter sensitive to dielectric permittivity. International Journal of Wildland Fire, 13(3), 343–353.

Robichaud, P.R. and Miller, S.M. (2000). Spatial interpolation and simulation of post-burn duff thickness after prescribed fire. International Journal of Wildland Fire 9(2) 137-143.

SAS Institute Inc., SAS® 9.2 Enhanced Logging Facilities, Cary, NC: SAS Institute Inc., 2008.

Schimmel, J. and Granström, A. (1996). Fire severity and vegetation response in the Boreal Swedish forest. Ecology, 77(5), 1436-1450.

Soil Survey Staff. (1999). Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd edition. Natural Resources Conservation Service. U.S. Department of Agriculture Handbook 436.

Stocks, B. J., Lawson, B. D., Alexander, M. E., Van Wagner, C. E., McAlpine, R. S., Lynham, T. J., and Dubé, D. E. (1989). Canadian forest fire danger rating system: an overview. The Forestry Chronicle 65: 450-457.

Swedish Meteorological and Hydrological Institute (SMHI). (2011). Canadian Forest Fire Weather Index Values for Sweden [FWI 2007-2010]. Retrieved from http://www.smhi.se

Tanskanen, H. and Venäläinen, A. (2008). The relationship between fire activity and fire weather indices at different stages of the growing season in Finland. Boreal Environment Research, 13: 285-302

Tanskanen, H., Venäläinen, A., Puttonen, P., and Granström, A. (2005). Impact of stand structure on surface fire ignition potential in Picea abies and Pinus sylvestris forests in southern Finland. Canadian Journal of Forest Research, 35: 410-420.

Van Wagner, C. E. (1987). Development and structure of the Canadian Forest Fire Weather Index. Canadian Forest Service Forestry Technical Report 35.

Van Wagner, C. E. and Pickett, T. L. (1985). Equations and FORTRAN program for the Canadian Forest Fire Weather Index System. Canadian Forest Service, Ottawa, ON. Forestry Technical Report 33.

Varner, J. M., Putz, F. E., O'Brien, J. J., Hiers, J. K., Mitchell, J. M., and Gordon, D. R. (2009). Post-fire tree stress and growth following smoldering duff fires. Forest Ecology and Management, 258: 2467-2474.

Wallenius, T. H., Kauhanen, H., Herva, H., and Pennanen, J. (2010). Long fire cycle in northern boreal Pinus forests in Finnish Lapland. Canadian Journal of Forest Research, 40: 2027-2035.

Wein, R. W., Wein, R. W., and Maclean, D. A. (1983). Fire behaviour and ecological effects in organic terrain. The Role of Fire in Northern Circumpolar Ecosystems. John Wiley & Sons

Wotton, B. M., Stocks, B. J., and Martell, D. L. (2005). An index for tracking sheltered forest floor moisture within the Canadian Forest Fire Weather Index System. International Journal of Wildland Fire, 14(2), 169–182.

Zackrisson, O. (1977). Influence of forest fires on the North Swedish boreal forest. Oikos, 29: 22-32.

APPENDICES

Appendix I: Site characteristics I

Site #	Site	Administrator	Coordinates (WGS 84)	Burn Date	Time Since Burn When Measured (Years)	Type of Fire
1	Norra Kvill	Sveaskog	57.75188, 15.59234	29-Jun-10	1	Prescribed
2	Kalvaberget	Skogssällskapet	56.78623, 12.85967	4-Jul-10	1	Prescribed
3	Smedjevik A	Länsstyrelsen Kalmar	56.89506, 15.86288	1-Jul-10	1	Prescribed
4	Smedjevik B	Länsstyrelsen Kalmar	56.89506, 15.86288	1-Jul-10	1	Prescribed
5	Hammarby	Sveaskog	56.90110, 15.30903	13-Jun-07	4	Prescribed
6	Kalmar 11 A	Private	56.606568, 15.890108	24-Jun-09	2	Prescribed
7	Kalmar 11 B	Private	56.606568, 15.890108	24-Jun-09	2	Prescribed
8	Ekopark Hornsö 6	Sveaskog	57.007009, 16.096991	6-May-08	3	Prescribed
9	Ekopark Hornsö 7 A	Sveaskog	57.049011, 16.08222	6-May-08	3	Prescribed
10	Ekopark Hornsö 7 B	Sveaskog	57.049011, 16.08222	6-May-08	3	Prescribed
11	Ekopark Hornsö 8	Sveaskog	56.976542, 16.098770	6-May-08	3	Prescribed
12	Ekopark Hornsö 2	Sveaskog	56.970567, 16.071966	29-May-10	1	Prescribed
13	Hovmantorp A	Sveaskog	56.78873, 15.16456	7-Jun-08	3	Wildfire
14	Hovmantorp B	Sveaskog	56.78873, 15.16456	7-Jun-08	3	Wildfire
15	Fjällmossen	Naturvårdsverket	56.697350, 16.538395	1-Jul-10	1	Prescribed
16	Vägershult	Länsstyrelsen Växjö	56.93829, 15.35812	8-Jun-10	1	Wildfire

Appendix II: Site characteristics II

Site #	Site	Forest Stand Type	Treatment	Trees Per Hectare (TPH)
1	Norra Kvill	Pine-dominated	Thinned	350-400
2	Kalvaberget	-	Clearcut	-
3	Smedjevik A	Pine; Birch	Thinned	200-250
4	Smedjevik B	Spruce; Birch	-	600-650
5	Hammarby	Pine-dominated	-	600-650
6	Kalmar 11 A	Pine-dominated	Clearcut; Some trees left	50-100
7	Kalmar 11 B	Pine-dominated	-	100-150
8	Ekopark Hornsö 6	Pine; Birch	Thinned	550-600
9	Ekopark Hornsö 7 A	Mixed: Pine; Oak; Birch	Thinned	200-250
10	Ekopark Hornsö 7 B	Birch	-	200-250
11	Ekopark Hornsö 8	Mixed: Pine; Oak; Birch; Aspen	-	150-200
12	Ekopark Hornsö 2	Pine; Birch	Thinned	200-250
13	Hovmantorp A	-	Clearcut	-
14	Hovmantorp B	Mixed: Pine; Spruce; Birch	-	600-750
15	Fjällmossen	Pine-dominated	Thinned	200-250
16	Vägershult	Pine-dominated	Clearcut; Some trees left	20-50

Appendix III: Trees commonly found on field sites.

Common Name	Latin Name
Scots pine	Pinus sylvestris L.
Norway spruce	Picea abies (L.) Karst.
Birch	Betula spp.
Oak	Quercus spp.
Aspen	Populus tremula L.

Appendix IV: Understory vegetative species commonly found on sites.

Geranium species noted are generally found on sites post-fire and specifically require smoldering burns within the soil layers to germinate (Risberg and Granström, 2009).

Common Name	Latin Name
Geranium	Geranium spp.
Heather	Calluna sp.
Bracken Fern	Pteridium sp.
Raspberry	Rubus spp.
Fireweed	Epilobium angustifolium
Lignonberry	Vaccinium vitis-idaea
Blueberry	Vaccinium spp.
Grasses	Calamagrostis arundinacea
	Deschampsia flexuosa
Feather Mosses	Pleurozium schreberi
	Hylocomium splendens
Lichen	Cladonia spp.

Appendix V: Data collection sheet for sampling along transects.

Site (#)	Site (Name)	Transect (Type)	Transect (#)	Location (m)	F (cm)	H (cm)	Total (cm)	Topography	Vegetation (Species)	Vegetation Ht (cm)	Notes

Appendix VI: Data collection sheet for root exposure sampling.

Site (#)	Site (Name)	Tree (#)	Mortality Code (0,1)	Root Exposure Class (0,1,2)	DBH (cm)	Char Ht (m)	Species	Notes

Appendix VII: Definition of variables in raw data set.

Sampling along transects:

Site (#) = Number of site. There were 16 sites so values range from 1-16.

Site (Name) = Name of site.

Transect (Type) = Fire (transect on burned site) or Control (transect on unburned site)

Transect (#) = Number of transect.

Location = Location of the measurement on the transect. Each transect was 50 meters in length with a measurement taken at each meter mark, so values range from 1-50.

F = Fermentation Layer measurement, taken in centimeters (cm).

H = Humus Layer measurement, taken in centimeters (cm).

Total = Total Layer measure (F+H), taken in centimeters (cm).

Topography = Microtopography in the area where measurement taken. Topography was taken at each measurement location, yielding 50 topography results per transect.

Vegetation (Species) = Species of vegetation. Vegetation measurements were taken at each location applicable (when vegetation present).

Vegetation Ht = Height of vegetation. Vegetation height measurements were taken at each location applicable (when vegetation present).

Notes = Anything additional, pertinent, or interesting.

Root exposure sampling:

Site (#) = Number of site. There were 16 sites so values could range from 1-16, although root exposures were not noted on every site.

Site (Name) = Name of site.

Tree (#) = The number of the tree sampled. 30 trees were sampled per site, and in some cases 15 due to the small size of the site.

Mortality Code = Alive (A) or Dead (D). Given for each tree sampled for root exposure. Later coded at 0 for Dead and 1 for Alive for statistical analysis purposes.

Root Exposure Class = Amount of root exposure on a tree, ranked 0-2.

0=None; Almost no root exposure. Relatively no burnout present.

1=Some; Approximately 50% of root exposure. Burnout present, but duff/humus consumption only apparent on approximately half of the tree base.

2=All; Close to100% of root exposure Burnout present on entire tree; all roots exposed.

DBH = Diameter at Breast Height, measured in centimeters.

Char Ht = Char Height on the stem of the tree, measured in meters.

Species = Species of the tree measured.

Notes = Anything additional, pertinent, or interesting.