Influence of forest mires on wildfire

A landscape analysis of the 2014 Västmanland forest fire

Andreas Souropetsis

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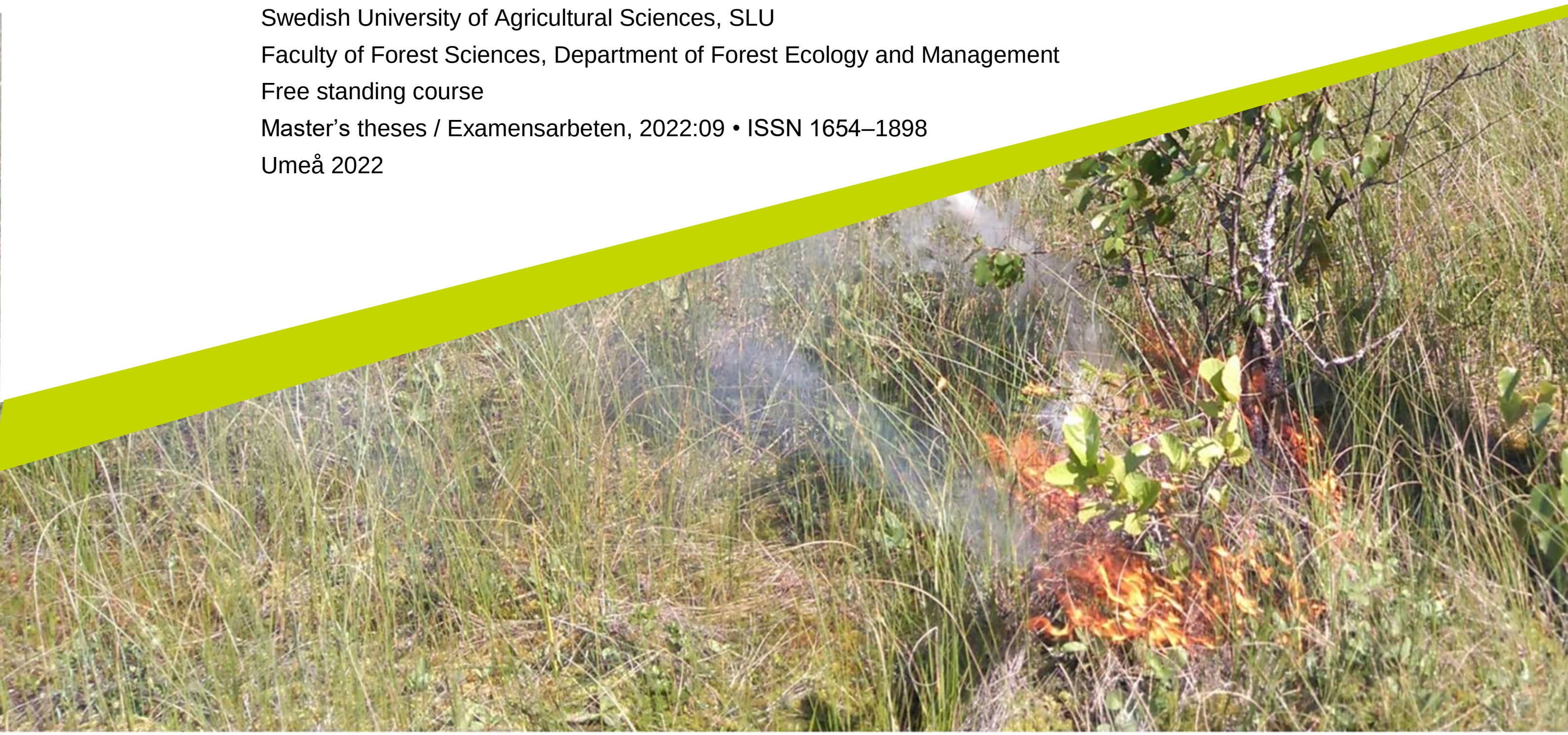

Influence of forest mires on wildfire. A landscape analysis of the 2014 Västmanland forest fire.

Souropetsis Andreas

Supervisor:	**Anders Granström, SLU, Department of Forest Ecology and Management**
Examiner:	Johnny Schimmel, SLU, Department of Forest Ecology and Management

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Swedish University of Agricultural Sciences
Faculty of Forest Sciences
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Abstract

Forest fire is a major natural disturbance that influence forest ecosystem structure and composition at both the stand and landscape level. In boreal Fennoscandia fire frequency has been very low over the last c.150 years due to effective fire suppression, although occasionally high-intensity fires escape initial attack and grow big. In the Swedish forest landscape mires of various types cover on average 15% of the land surface and are often relied upon as fire breaks during wildfire incidents. However, it is known that mires sometime actually burn, but so far there has not been any attempt to elucidate fuel characteristics of different type of mires and their potential as barriers or avenues for fire.

This study makes use of a large forest fire that occurred in the county of Västmanland in 2014 to investigate to what extent fire affect different mire types, and to analyse the fuel characteristics of each mire type.

The investigation focused on the three main mire types present in the area: Open mires (dominated by graminoids), shrub mires (dominated by dwarf-shrubs) and pine bogs (canopy of pine trees and dwarf-shrubs in the field layer). I used aerial photo interpretation of pre-fire and post-fire IRF photos to map mire types and the extent of non-burnt mire patches within the burnt area. Further, extensive field sampling was conducted both within and outside the burnt area: 77 sampling plots were surveyed by recording vegetation characteristics and estimating fire intensity. Also, live vegetation and litter was destructively sampled in unburnt mires to calculate fuel dry mass on an area basis.

Pine bogs has the highest surface fuel quantities of the mire types investigated and has the highest proportion of burnt area. Within the perimeter of the burnt area (13100 ha), almost 100% of the pine bog area burnt. Shrub mires with slightly lower fuel quantities burnt at 89,94% with the frequent present of smaller patches untouched by the fire. Open mires burned to a lower proportion (72,91%) than the other two types, particular in their edges. Presumably, the sphagnum mosses surface in their central parts was still wet despite the long drought, and that the graminoid litter was too sparse to carry the fire. Considering fire propagation at the landscape level, only the very large open mires were able to have an effect.

In order to predict the potential fire propagation in different mire types, additional fuel sampling and fire spread experiments would be needed. In comparison with closed forest, the surface vegetation of mires, and thus their fuel type, can more easily be mapped using remote sensing. Hopefully, detailed maps predicting fire spread potential of wetlands can be produced in the future, as a tool for operational fire suppression efforts.

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Abbreviations

SLU	Sveriges lantbruksuniversitet - Swedish University of Agricultural Sciences.
GIS	Geographic Information Systems
SMHI	Swedish Meteorological and Hydrological Institute - (Svenska)
MSB	Swedish Civil Contingencies Agency - (Svenska)
IRF	Aerial photos based on infrared radiation which is expressed in red colour
SFA	Swedish Forest Agency – Skogsstyrelse
NDVI	Normalized Difference Vegetation Index
TNDVI	Transformed Normalized Difference Vegetation Index
GPS	Global Positioning System
GSM	Global System for Mobile communications
ANOVA	Analysis Of Variance
CC	Canopy cover
VC	Vegetation cover

1. Introduction

1.1 Fire in Sweden – past and present

Forest fire is a major natural disturbance in many terrestrial ecosystems (Bond and Keeley, 2005; Pausas and Keeley, 2009), influencing their structure and composition by selectively killing organisms and altering their physical environment (Osborne, Kobziar and Inglett, 2013). Especially in the boreal region, forest fire is considered important for the integrity of various ecosystems (Granström, 2001; Girardin, et al., 2013).

With the entry of modern industrial forestry from the late 1800s and increasingly effective fire suppression, it dramatically decreased the frequency and extent of forest fires in Sweden (Granström, 2001; Granström and Niklasson, 2008; Drobyshev, Niklasson and Linderholm, 2012). However, on rare occasions forest fire escape early suppression efforts, and can, if weather is favourable in the days thereafter, burn large areas with high intensity. One of the largest wildfires over more than 100 years happened in the province of Västmanland in 2014, burning 13100 ha (Nilsson et al 2014; Gustafsson et al 2019).

Mires cover more than 15% of the Swedish land area (Malmer, 1965) constituting landscape elements that can potentially influence fire regimes. Mires would be expected to be barriers to fire spread because they constitute the wetter elements within forested areas, nonetheless palaeoecological studies often show evidence of past fires in various mire ecosystems (Sillasoo, Väliranta and Stiina, 2011). The role of mires during forest fires is however unclear as few studies have analysed their overall effect on forest fires in Sweden (Hellberg, Niklasson and Granström, 2004) or other boreal regions (Foster, 1983; Dansereau and Bergeron, 1993; Falk, et al., 2007).

1.2 Role of fire on forest and mire ecosystems

The ecological function of forest ecosystems can be affected by fire in various ways. Fire disturbs both plants and animal communities and affect soil nutrient conditions and soil structure (through the consumption of organic soil layers), (Bond and Keeley, 2005; Pausas and Keeley, 2009). Further, forest fire can release into the atmosphere massive amounts of carbon stored in the forest floor (Jacob, et al., 2010; Gonsamo, et al. 2017). At the same time, forest fire plays a crucial role in forest ecosystems. It regulates forest age structure, species composition and physiognomy, enhancing landscape spatial heterogeneity as well as controlling biochemical cycles (Sannikov and Goldammer, 1996; Rolstad, et al., 2017). Forest fire opens the forest canopy allowing regeneration of new individuals and creates the proper conditions for new species introduction, increasing biodiversity both above and below the forest floor. Also, fire disturbance on plants and soil release nutrients available for new growth (Esseen, et al., 1997; Wardle et al., 1998; Granström, 2001). Thus, fire is a vital part of forest ecosystems and in many ways important for creating the structural complexity that promotes biodiversity in boreal forests (Rolstad, et al., 2017).

Even if mires are wet ecosystems, they are potentially affected by forest fire depending on the fuel structure and their moisture conditions (Ronkainen, Väliranta and Tuittila, 2013). Fire disturbance on mires can, in the short term, influence the vegetation community, can lead to changes in the hydrological characteristics and lead to the release of massive amounts of CO_2 (Lukenbach, et al. 2015; Osborne, Kobziar and Inglett, 2013). In the long-term, fire can influence the ability of mires to accumulate carbon, but they only have a minor long-term influence on vegetation since the *sphagnum* mosses can recover rapidly after fire (Magnan et al., 2011).

1.2.1 Fire ecology

The fundamental factors influencing fire propagation are the fuel characteristics (mass, size distribution, horizontal and vertical structure, etc.), the fuel moisture content, the current weather conditions (wind direction and velocity) and the topography (terrain and landscape characteristics) (Bleken, Mysterud and Mysterud., 1997; Johnson and Miyanishi, 2001). These factors can determine if the fire can propagate at all and with what intensity and spread rate.

Complete combustion transforms fuel into primarily CO_2, minerals, and heat. Depending on the fuel characteristics, two types of combustion take place, flaming and smoldering. Flaming combustion is a rapid process that release large amount of energy per time unit, but it is dependent on a suitable fuel bed of well-dispersed and well aerated fuel elements (Saito, 2001). The propagation rate and fire intensity in flaming combustion can be very high but is heavily influenced by the fuel structure, and the fuel moisture content. The moisture of extinction, above which no fire spread is possible, is often as low as 25-30% on mass basis. Flaming combustion is most crucial for influencing forest tree canopies and the intensity of the fire will also determine resistance to control.

In smoldering on the other hand, a slowly progressing front of glowing combustion is preheating fuel and driving off water from the fuel, which is then consumed by the glowing front. Smoldering is the main combustion process in compact fuels such as humus or peat and can often proceed even at moisture content as high as 100% on mass basis. Propagation rate is however very slow and the process result in incomplete combustion with a high degree of smoke production and a high proportion of CO in the smoke (Ward, 2001). Smoldering can sometimes proceed for several days or even months. (Miyanishi, 2001).

After ignition, the flames start to spread, if the provided fuels are continuous enough, they move forward driven mainly by wind and slope. These parameters determine the shape of the fire. The different sections of the perimeter, burn with different rate of spread and intensity: (a) The head of the fire is the most rapidly advancing section, typically moving in the same direction as the wind. It has the highest intensity and rate of spread and for any particular fire event the fire behaviour in this section (rate of spread, flame length, flame depth etc.) is used to characterize it. (b) at the opposite end, back of the fire, fire is moving against the wind and is characterized by a very slow rate of spread and fire intensity. (c) Sections between the head and back are called flanks and are intermediate with respect to rate of spread and intensity.

Further, forest fire behaviour can be described according to what fuel strata are engaged: (a) Surface fire that burn the surface fuel and vegetation layer, even if a tree canopy is present. Intensities can vary greatly, with flames length from as little as 10 cm to several meters, (b) Crown fire, where the fire burn both surface fuels and fuels up in the tree canopy. Here intensity is always high, with flames length in the order of tens of meters, (c) Peat fire or ground fire, where the organic material beneath the surface smolders without the presence of visible flames. In a single fire event all three fire types can be present in combination and in different intensities causing different degree of impact to the vegetation and soil.

1.2.2 Fuel characteristics

At local scale, the spatial variation in fuel has a fundamental effect on fire behaviour by driving fire size, intensity, frequency, propagation and spread rate (Falk, et al, 2007; Loudermilk et al., 2012; Keane, 2016). Deeper understanding of the spatial heterogeneity of the fuel layer is crucial for fire behaviour predictions as well as for estimating the fires effect on the environment (Lavoie et al., 2010; Ottmar et al.; Loudermilk et al., 2012).

All the dead and living organic material which can be consumed under certain circumstances by fire, can be considered as fuel. Fuel is present in the forest ecosystems in different types, sizes, shapes etc., influencing the consumption processes during fire. To identify and categorize fuel, different parameters are used. Beside moisture content, various intrinsic properties are important such as heat content, quantity per unit area (kg/m^2), size and shape, compactness and arrangement (FDACS, 2014; Volokitina, 1996; Keane, 2016). In this study the fuel classification is based on the amount of dry biomass per area (kg/m^2), height (m) and coverage (%), as these are most frequently used in fire management (Keane, 2016), are easy to measure and can provide a basic fuel description.

Fuels are often divided into four main layers: the ground layer, the surface layer, the ladder layer, and the crown layer (Figure 1) (Lavoie, et al., 2010; Keane, 2016). The ground fuel consists of partly decomposed organic matter (humus or peat layers), derived from dead organic material (litter) and root system of the above-ground plants. Surface fuel consists of loose dead material on the soil surface such as leaves, needles, wood pieces, bark flakes, cones etc. Mosses and lichens of the bottom layer are also included as well as all field-layer vegetation (e.g. dwarf-shrubs, herbs, grasses, sedges, and tree seedlings). The ladder layer consists mainly of bushes, small trees below the canopy and dead branches below the canopy. The crown layer consists primarily of needles up in the canopy (Jenkins, 2008; Lavoie, et al., 2010; Keane, 2016).

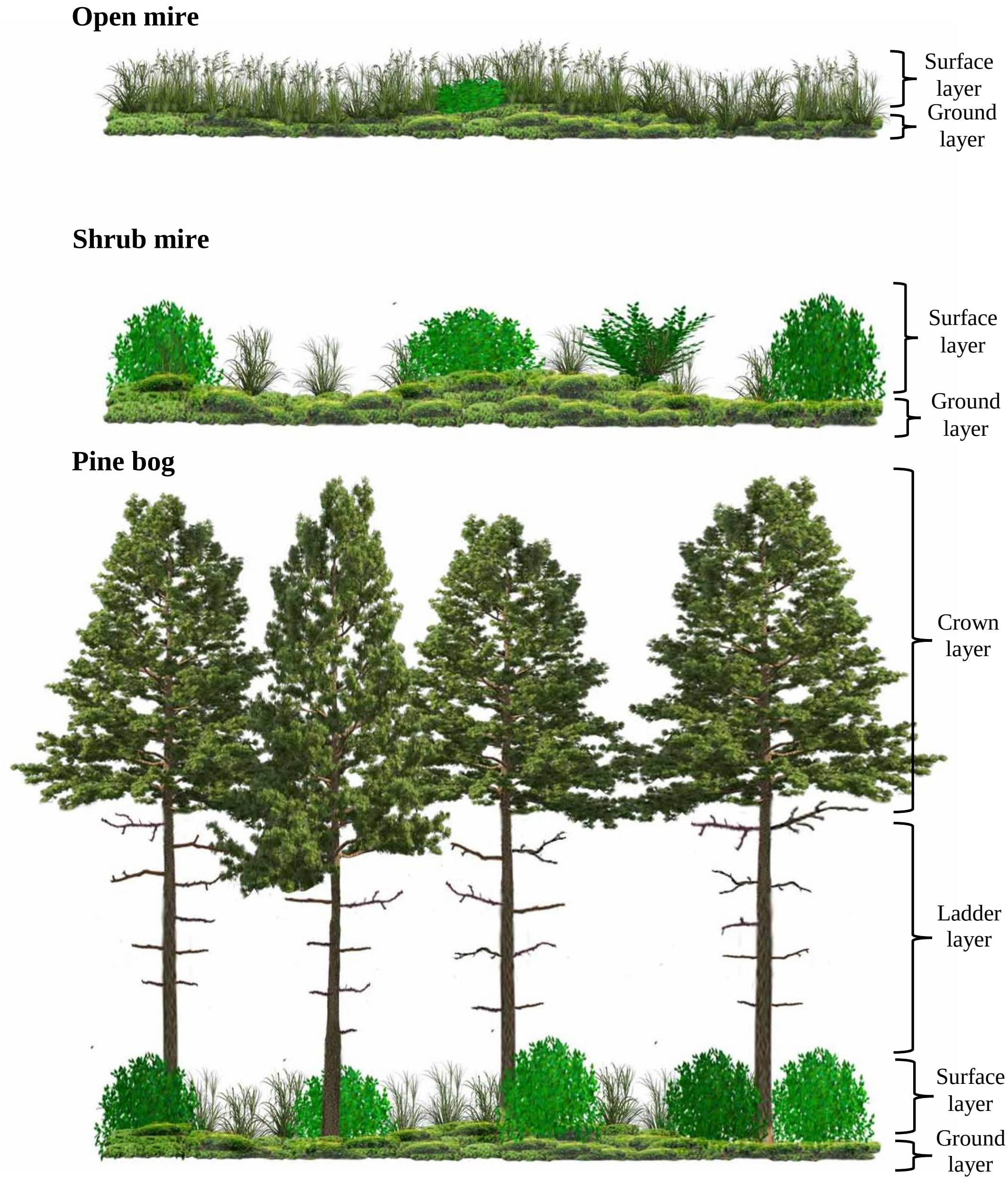


Figure 1: Graphical presentation of fuel structure for the tree main mire types. A) Open mires consist mainly of ground and surface fuels like mosses, graminoid litter and occasional small shrubs. B) Shrub mires have less graminoids, more dwarf-shrubs and occasional stunted pine trees. C) Pine bogs have dwarf-shrub dominated surface fuels, sparse ladder fuels and a relatively dense canopy of pine trees.

Meteorological conditions also have a significant role over both fuel and fire. Over the really long term, climate determines vegetation and thereby fuel composition, while on daily to weekly periods, weather controls the fuel moisture, ignition probability and fire spread, mediating effects on vegetation and fuel indirectly. At smaller timescales, of minutes to days, wind, relative humidity, temperature and precipitation affects ignition, fuel moisture and fire behaviour directly whereas vegetation creates the microclimatic conditions and indirectly affecting diurnal fuel moisture (Falk et. al., 2007).

The ability of fuel to ignite and burn depends mainly on its moisture content (%) and the supply of oxygen (O_2) to the reaction zone. The oxygen supply is rarely considered limiting except for compact fuels such as humus or peat. Instead, moisture content is the most important parameter for fire ignition and propagation. According to Schimmel and Granström (1997), the critical fuel moisture content for sustained fire propagation (moisture of extinction) for surface fuels in Swedish forest ecosystems is 20-25%. This moisture level can be reached after only a few precipitation-free days in typical upland forests. In mires, water levels are high and the surface will stay moist much longer. Often the mires surface is covered by *Sphagnum* mosses which can store much more water than upland mosses and also suck water from deeper layers to the surface.

Whereas dead fuels and mosses typically have a moisture of extinction in the range 20-25%, live vegetation elements such as needles, can often sustain fire at much higher moisture contents (Keane, 2016.). For example, a stand of *Calluna vulgaris* with an overall moisture content of 60% can readily carry fire independently of litter fuel below (Davies and Colin, 2011). The reason evergreen vegetation such as *Calluna vulgaris* can readily burn at moisture content as high as 100% when dead litter cannot, is thought depending on readily volatile organic compounds in their leaves (Keane, 2016). As a general rule, evergreen plants are more flammable than deciduous plants because of the lower moisture content in their leaves, often 100% vs 200-250%.

1.2.3 Mires and forest fires

Mire ecosystems cover approximately 10-15% of the total Swedish land area (Malmer, 1965; Tishkov A, 2010; MSB, 2015), and this landscape element can potentially influence the spatial distribution of fire. The unique characteristics of mires, particularly their high water-table and different vegetation compared to upland forest, can influence fire propagation rate and intensity level, or even act as barrier to fire (Hellberg, Niklasson and Granström; 2004, Tishkov; 2010).

At the local scale mires are not uniform landscape elements with identical characteristics, but dynamic mosaics of different fuel composition and different water regimes, like hummocky mires, pine bogs, grass or sedge dominated mires etc. (Ingvar, 1985, Ronkainen, Väliranta and Tuittila, 2013).

Furthermore, the ability of mires to influence fire propagation is related also to their size, as observed by Magnan, Levoie and Payette (2011) in a paleoecological study in Canada. In a long term, small mire (~ 2 ha) edges had burned with the same frequency as their central parts, but the central parts of bigger mires had burned less frequently than their edges.

Wetland drainage will permanently alter the water balances of mires and can increase the potential for fire (Sillasoo, Valiranta and Stiina, 2011), and also lead to deep burning in the peat layer, because of the lower water table.

1.2.4 Fire in a landscape perspective

Landscape elements such as lakes, wetlands, bare land, agriculture areas etc. can potentially alter fire propagation by forming fire breaks. The role of mires on fire propagation is not well researched, especially in Swedish landscapes. There are however several fire-history studies suggest that mires can disturb fire propagation by reducing fire intensity, or act as fuel breaks (Granström, 2001; Hellberg, Niklasson and Granström, 2004; Granström and Niklasson, 2008; Magnan et al., 2011; MSB, 2015).

1.3 The 2014 Västmanland fire

The fire started at around 13:15-13:20 on the 31st of July 2014, northeast of the village of "Seglingsberg" (567365 E, 6634228N – swereff99TM), within the boundaries of Surahammar municipality (MSB, 2015). The ignition was caused by mechanical scarification of a clear-cut area, due to sparks generated from either the track chains or from the scarifier teeth in contact with large stones. The machine operator spotted the fire within minutes at a size of 1,5 x 3m, but was not able to control it using a couple of fire extinguishers he had on the machine, and water in canisters. He reported the fire to SOS-Alarm at 13:29. By then already 20 x 30 m in size. According to an MSB report (Anonymous, 2015), the first firefight group reached the area at 14:20, one hour after the fire had started.

Warm and dry weather conditions had been prevalent during July, with relatively high temperatures and very little precipitation; less than 20 mm in all of July (MSB, 2015). Further, the Fire Risk Indices calculated by SMHI for the location was very high (FWI 29 on the day the fire started).

During the first day of the fire (31-07-2014), weather was partly cloudy with a temperature around 25 ^{o}C, a southwest wind (5-11 m/s) and relative humidity just below 40%. The fire spread rate over the first three hours was estimated at above 10 m/minute (Granström, unpublished), and in the evening the burnt area was 2,7 km long and maximum 1 km wide (Figure 2). On the second day the weather conditions were similar with a somewhat increased wind speed (6-12 m/s), which moved the head of the fire 2,5 km further to the northeast. On the third day (2nd of August) the temperature rose to 29 ^{o}C, and the relative humidity decreased to ~35%, with a 90-degree wind shift to a more southerly wind. Then, the left flank of the previous day became the fire front and expanded ~3,5 km to the north until midnight. The next day cooler conditions with slower wind speed resulted in a somewhat decreased fire spread towards northwest. On the 4th of August a high velocity southeast wind, which in some cases reached 17-19 m/s, and very low relative humidity (~25%), resulted in a crown fire with rate of spread over a three-hour period in the afternoon of 80 m/minute, expanding the burnt area 19 km towards northwest (~65% of the total burnt area). The next day the wind velocity decreased significantly, and relative humidity increased to 81 %, providing the opportunity for suppression crews to contain the fire perimeter (Figure 2). Thereafter, no expansion of the fire occurred, but extensive smoldering continued in humus and peat. Smoldering fire in peat was observed as late as 20th of September (Granström, unpublished).

Fire consequences included the death of one person, the damage or complete loss of 71 buildings, the evacuation of 1000 people and 1700 animals (cattle, horses and sheep) and thousands of people prepared for evacuation when the fire approached towns. Further, the fire affected around ~1.4 million m^3 of timber within the burnt area (MSB, 2015), although much of it was later salvage-logged. According to an estimate based on aerial photo interpretation after the fire 13100 ha had been affected by the fire of which 9576 ha where productive forest, 1485 ha non-productive forest, 1512 ha mires, 245 ha other land cover (e.g. roads, open fields) and 270 ha of open water areas (Nilsson et. al, 2014).

The burned area is owned by some 100 small-scale private owners and a handful of large forest companies and organizations (CAB 2014; Fire Protection Nerikes 2014; MSB 2015). In spring 2015, a nature reserve about half of the area (6500 ha) was bought by the state and turned into a nature reserve (Lidskog and Sjödin, 2016). In addition, 1500 ha owned by the company Sveaskog was declared an “Eco Park” and was left uncut.

1.4 Objectives

The main objective of this study is to investigate the role of mires on fire propagation, using the Västmanland fire of 2014 as a case study. The aim is to investigate how and to what extent different mire characteristics (size, shape, wetness, vegetation composition, position in the landscape, etc.), can influence forest fire. I wanted to answer the following questions:

1. To what extent did fire affect different mire types?
2. What are the fuel characteristics in each mire type?
3. Can fuel mass be predicted using cover and height?
4. How did mires of different type influence fire behaviour, at the local and landscape level?

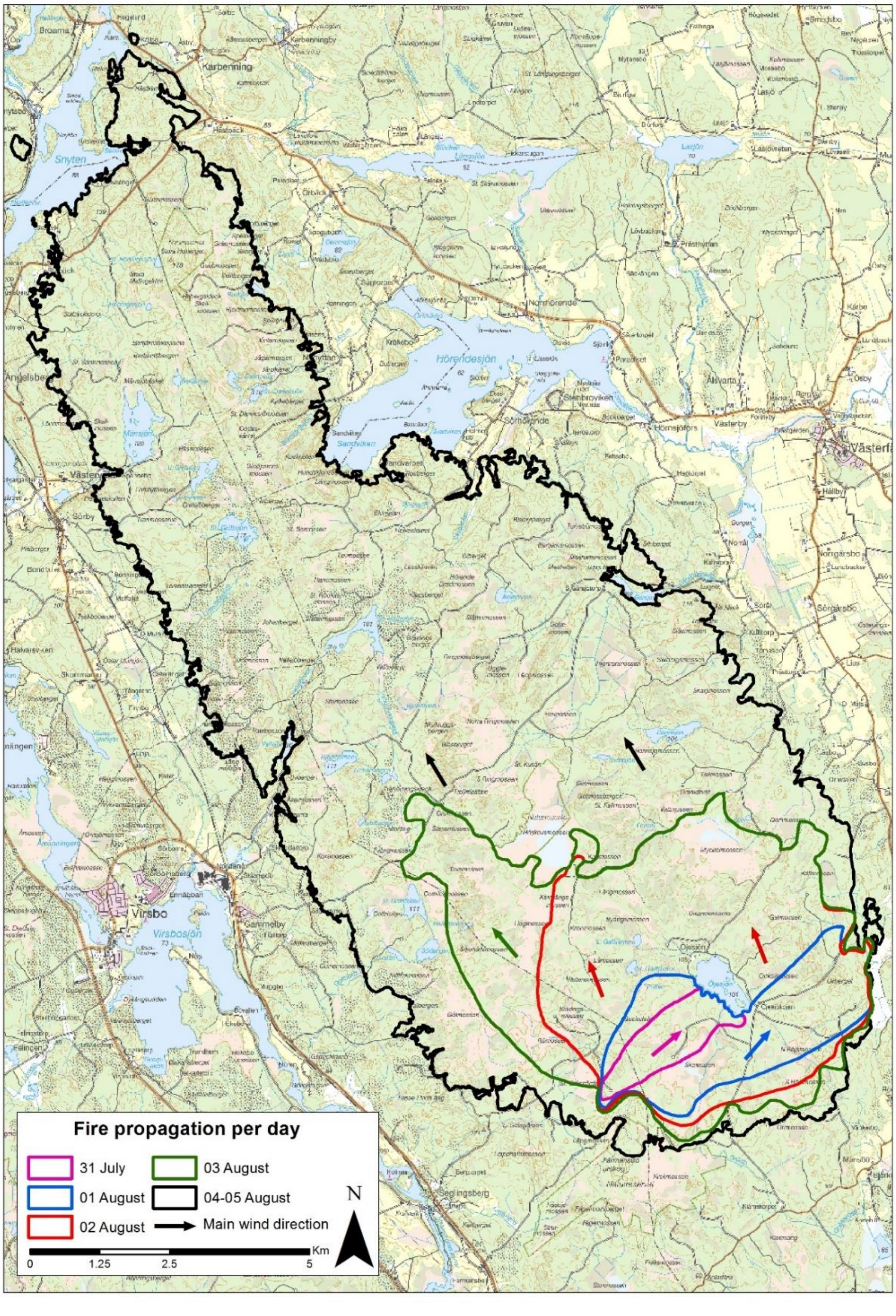


Figure 2: The total burnt area and daily progression of the Västmanlands fire (MSB, 2015).

2. Materials and Methods

The investigation was conducted both with field work and data analysis of remote sensing techniques. Field work involved inventories of different mire types both within and outside the burnt area. During fieldwork I sampled mire vegetation, estimated fire intensity, and sampled fuel to calculate dry mass per unit area. In total, 77 sampling plots were surveyed. Further, I used GIS and Remote Sensing analysis techniques to extract information from aerial photos.

2.1 Study area

The study area is located within Surahammar and Sala municipalities, in the province of Västmanland, 30 Km northwest of Västerås city. The field work was carried out from July to October 2015 and one day supplementary field work was done during August 2016. Although the whole burnt area was considered in the study, the main investigation was focused on the southern part of the burnt area, covering approximately 60 km^2. In the northern part of the burnt area, the extent of mires is limited because of the hillier terrain. Further, the northern part was affected by the high severity fire during the fifth day, limiting the potential role of different mire types or other barriers on fire propagation.

With an elevation of 85 – 130 m above sea level, the area is relatively flat, with the presence of numerous small hills. The elevation is gradually increasing from South to North, where the terrain is also hillier. The climate is characterized by mean temperatures of 13,6 ^oC during the summer period (June-July) and -1.9 ^oC during winter period (December-February), with an annual precipitation of approximately 570 mm, and summer being the wetter season (SMHI, 2016).

The primary land use in the area is forestry, covering approximately 73% of the area (based on data from the Swedish Forest Agency, 2014). The main species are Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). Further, the area is covered by 11% non-productive forest, 10% forest mires, 2% open water bodies and 2% by other land uses (SFA, 2014). The investigation area belongs to the Boreal-Nemoral vegetation zone (KSLA, 2017).

2.2 Experimental design

2.2.1 Preliminary investigation

I made a number of visits with my supervisor in the investigation area, during June and July 2015, to familiarize myself with the different mire types and mire vegetation species. The fire impact on different fuel types and landscape characteristics was investigated as well as a general assessment of fire intensity over the area was conducted.

2.2.2 Main inventory

The main inventory took place during August 2015 where I surveyed the three main mire types, both within the burnt and on nearby unburnt sites of the study area. A supplementary field sampling was done in September 2016, where additional fuel samples were collected.

The study focused on the three main mire types present in the investigation area, broadly categorized as open mires, shrub mires and pine bogs (Figure 3). As the investigation was using both field inventories and aerial photo interpretation, the three main mire types were chosen based to their main vegetation characteristics, possible to distinguish using aerial photos (Appendix II).

- Open mires are dominated by graminoids, *sphagnum* mosses and herb vegetation with the rare presence of dwarf shrubs and small size trees. This group includes all subtypes of open mires, like graminoid dominated mires, reed dominated mires, hollow and hummocky mires, and mosses dominated mires. In open mire there are often areas with water at the surface.
- Shrub mires are covered by *sphagnum* mosses, dwarf shrubs (1-50 %), a small amount of graminoids, herbs and occasional small trees (< 1,5m). Shrub mires were divided into three subtypes based on vegetation cover, shrub mire with 30-50% vegetation coverage, 10-30% coverage and shrub mires with less than 10% coverage.
- In Pine bogs there is a near-continuous cover of pine trees (45-100 % canopy cover) with a field-layer of mainly dwarf shrubs and a minor component of graminoids and herbs. The bottom layer consists of *Sphagnum* mosses. Pine bogs were further divided into three subtypes based on canopy cover, high canopy coverage 70-100%, mean coverage 40-70% and sparse coverage 25-45%

Mire types vary in fuel characteristics, which can be expected to have an influence on forest fire behaviour (rate of spread, intensity etc.). Therefore, the aim of the field work was to investigate the vegetation structure, fuel composition and, when possible, to assess the intensity of fire within each mire type.

Figure 3: Representative photographs of the three main mire types: a) Open mires, b) Shrub mires, c) Pine bogs.

2.2.3 Field sampling

The first step was to identify and delineate the unburnt patches within the burnt area using post-fire IRF aerial photos interpreted in a digital photogrammetric workstation in stereo mode using the DAT/EM Summit Evolution and ArcMap software (Summit Evolution, 2012; ArcGIS, 2015). Thereafter the mire types and subtypes were identified and delineated using pre-fire IRF aerial photos, existing vegetation data sets (Lantmäteriet, 2015) and GIS analysis (ArcGIS, 2015).

After the burnt area and mire types had been delineated, I selected the field sampling plots using a random stratified sampling method, where the position of plots was selected randomly within each mire type, within both burnt and unburnt areas.

In the unburnt area the structure of mire vegetation-fuel was surveyed in total 17 circular 78,5 m^2 plots: 5 plots within Open and Shrub mires and 7 plots within Pine bogs. Within the burnt area 43 circular plots where surveyed: 15 plots within Pine bogs, 14 in Open mires and 14 in Shrub mires. Furthermore, destructive sampling of fuel on 1 m^2 plots was done in unburnt mire; 4 plots for each mire type, in total 12 plots (Table 1, Figure 4).

Table 1: Number of surveyed plots (78m^2) for each mire type in the unburnt area, the burnt area and the destructively plots.

	Unburnt plots	Burnt plots	Destructively plots
Open mire	5	14	4
Shrub mire	5	14	4
Pine bog	7	15	4
Total	**17**	**43**	**12**

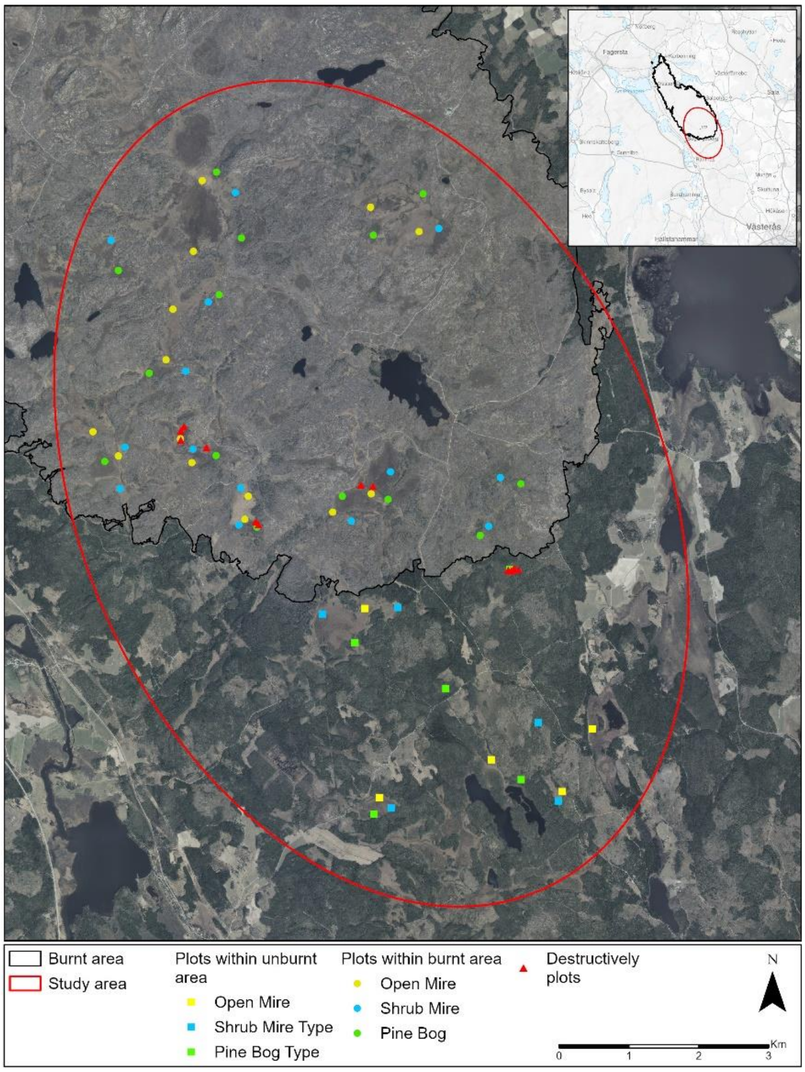


Figure 4: Position of sample plots within and outside of the Västmanland fire area

I conducted the sample plot inventory at two levels, the general plot level and the more detailed quadrat level within the plot (Figure 5). At the first level (plot level), in each plot I marked the centre with a red-coloured stick (≈ 1 m) and with the help of a 5 m string a circle was “drawn” and marked with a rope, to create the plot area (circle 5 m radius, i.e. ≈ 78,5 m^2). A more detailed species inventory was undertaken on three 1 m^2 quadrats within each plot. These quadrats where systematically placed at a distance of 2,5 m from the plot centre at 0°, 120° and 220° (Figure 5 and Figure 6) and marked with smaller red colour sticks (≈ 0.3 m). During the survey I recorded all information in field protocols (Appendix I) and photos were taken at fixed positions to capture conditions within the plot.

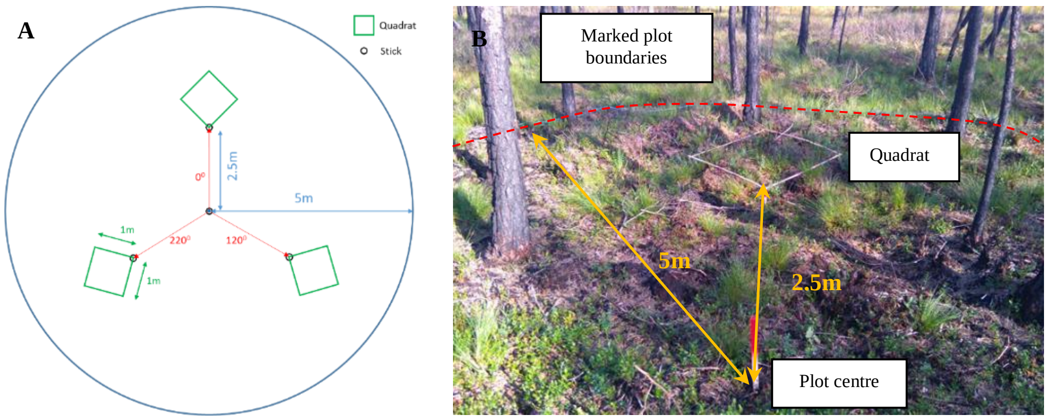


Figure 5: A) Graphical representation of the plot design; Circular 78 m^2 plot area (5m radius), and the three 1 m^2 quadrats (green) placed 2.5m from plot centre. B) Plot photograph from a plot in burnt pine bog, with the central pole, one of the 1m^2 quadrats and the circular plot boundary illustrated.

Within each plot, information regarding plot centre coordinates (GPS), survey date and time as well as the main mire type were noted (open mire, hummocky mire, shrub mire and pine bog). At the next step, the total cover of different broad vegetation classes (mosses, herbs, graminoids, shrubs, trees, and open water) where visually estimated (%) and afterwards a full vegetation species inventory was undertaken where all species were identified and their mean height (cm) and cover (%) was estimated. Furthermore, the cover and height of the two categories “live fuels” and “dead fuels” (e.g. graminoid litter, dead branches etc.) was estimated.

In the plots within the burnt areas, measurements were taken to indicate fire intensity and depth of burn (Figure 6). The proportion of the burnt ground and the average consumption depth of the moss/peat layer was visually estimated in each plot. If trees were present in the plot, stem-bark char height and crown scorch height were measured as proxies for fire intensity, using a hypsometer (Figure 7).

Figure 6: Example of 1m² quadrats. Both plots were within burned pine bog. The one to the left having abundant regrowth of Rubus chamaemorus, the one to the right instead having regrowth of mainly Eriophorum vaginatum.

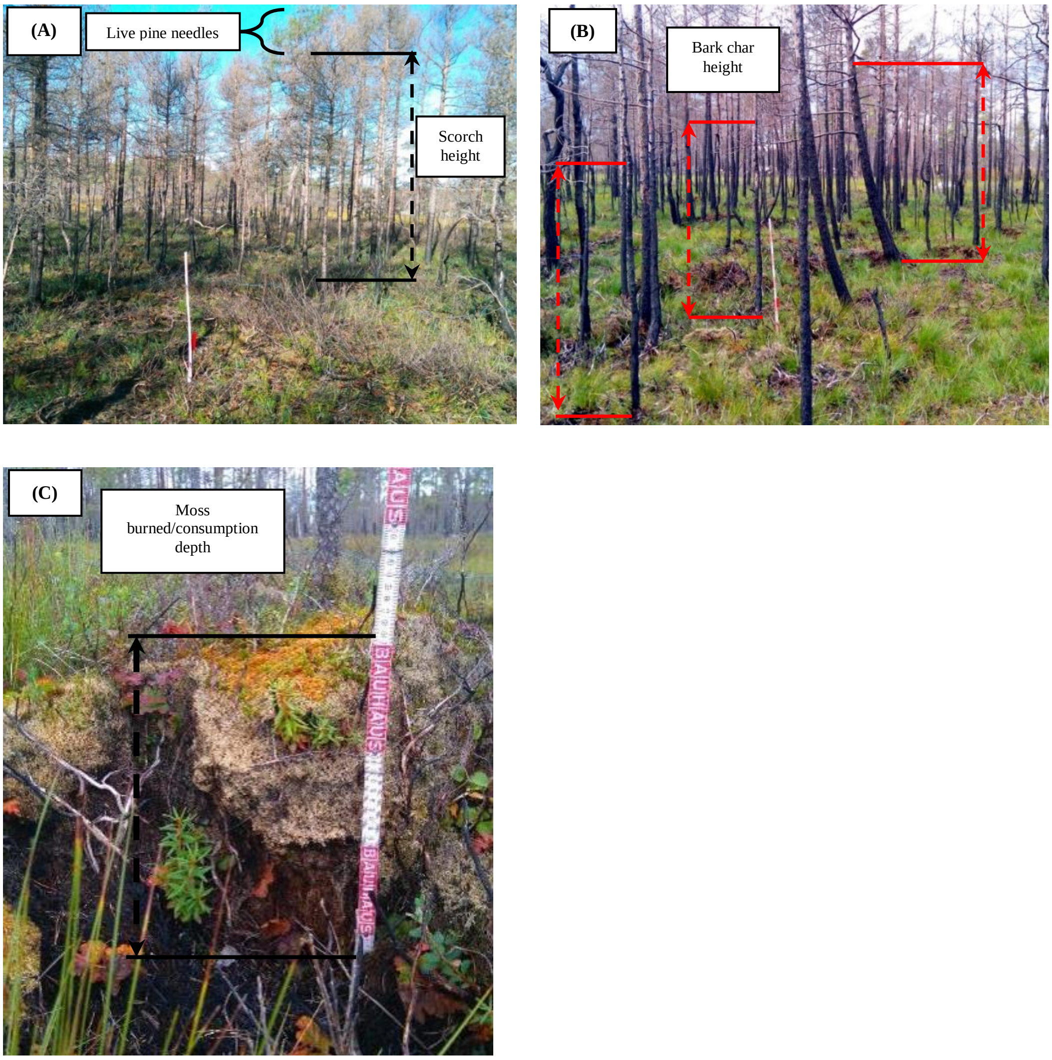


Figure 7: Measures of fire behaviour. A) Scorch height in the tree canopy resulting from heat kill of needles. B) Vertical measure of the highest charring on pine tree bark (Alexander and Cruz, 2012a; 2012b). C) Moss consumption depth.

The progressive experience gained in the field may influenced the vegetation cover estimation and lead to non-constant results. To investigate if there was any change in cover estimation over time, five randomly selected plots have been re-sampled, after all the samplings had been completed. These plots (Calibration plots) where 2 open mire plots, 2 shrub mire plots and 1 pine bog plot. The results indicate some small differences, can been explained by the experience gained and the vegetation growth during the two samplings, in some cases 1-month after. However, the differences were small and do not influence the overall data analysis (Figure 8).

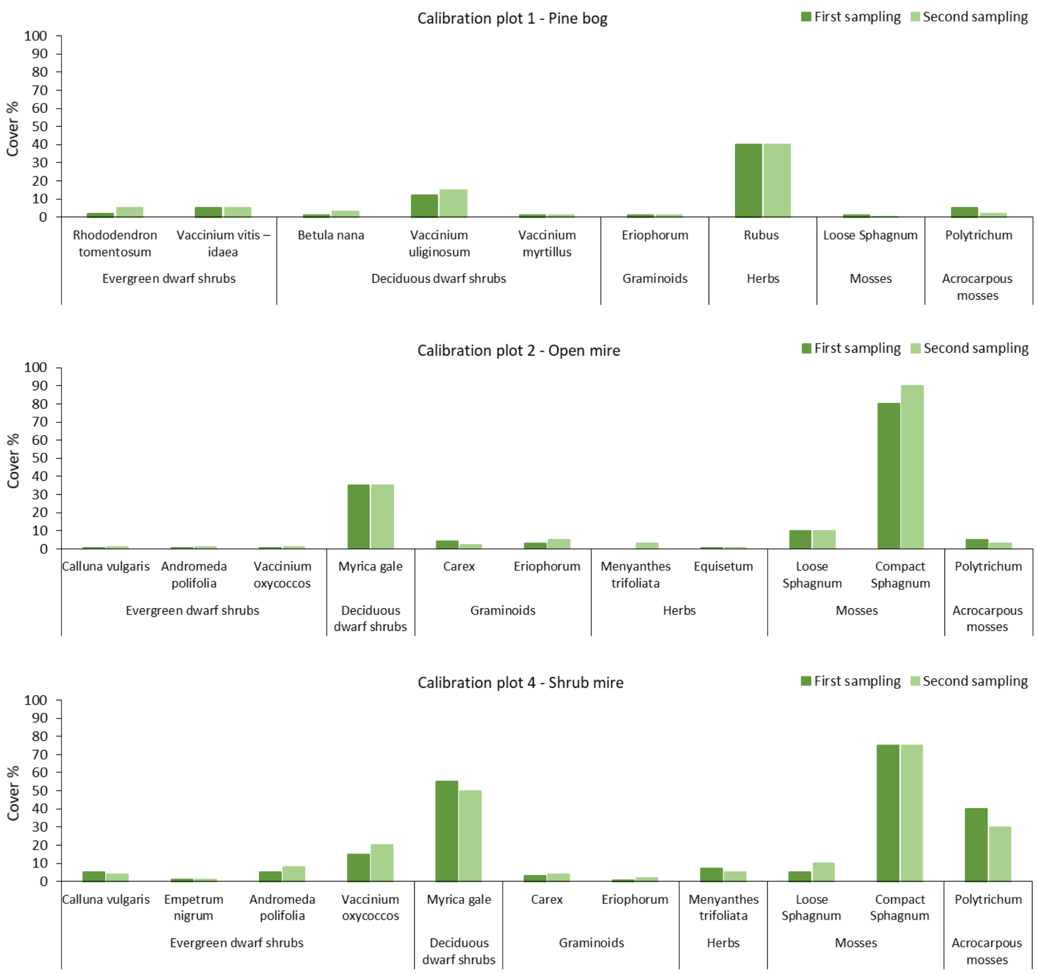


Figure 8: Results of two vegetation cover estimations on the same circular plots (≈ 78,5 m^2), taken one month apart. The dark green bars denote the first sampling and light green bars the second. Here presented three out of the five re-sampled plots.

2.2.4 Destructive fuel sampling

For the destructive fuel sampling, I randomly selected quadratic 1 m^2 plots within representative unburnt areas of open mires, shrub mires and pine bogs. In total 12 plots where sampled, 4 for each main mire type.

In each 1m^2 plot, an overview photo was taken, the height of all vascular plant species, mosses and litter was measured, and their respective cover was estimated. The depth of the loose upper part of the moss layer was measured by gently inserting a 2 cm-wide ruler vertically into the moss until reaching a more compact and more decomposed layer hard to penetrate layer.

Then I clipped all vegetation at the ground surface and sorted the material by species into separate plastic bags (Figure 9). For small-sized plant species (e.g. mosses, *Andromeda polifolia*, *Vaccinium oxycocc*os etc.) a smaller quadrat (40 x 40 cm or 20 x 20 cm) was used for sampling, placed at the centre of the 1 m^2 quadrat. Mosses have been taken down to the more compact layer. All samples were stored in a freezer until they were sent to the lab, where they were dried in a drying cabinet at 90 ^{o}C and weighed for dry mass.

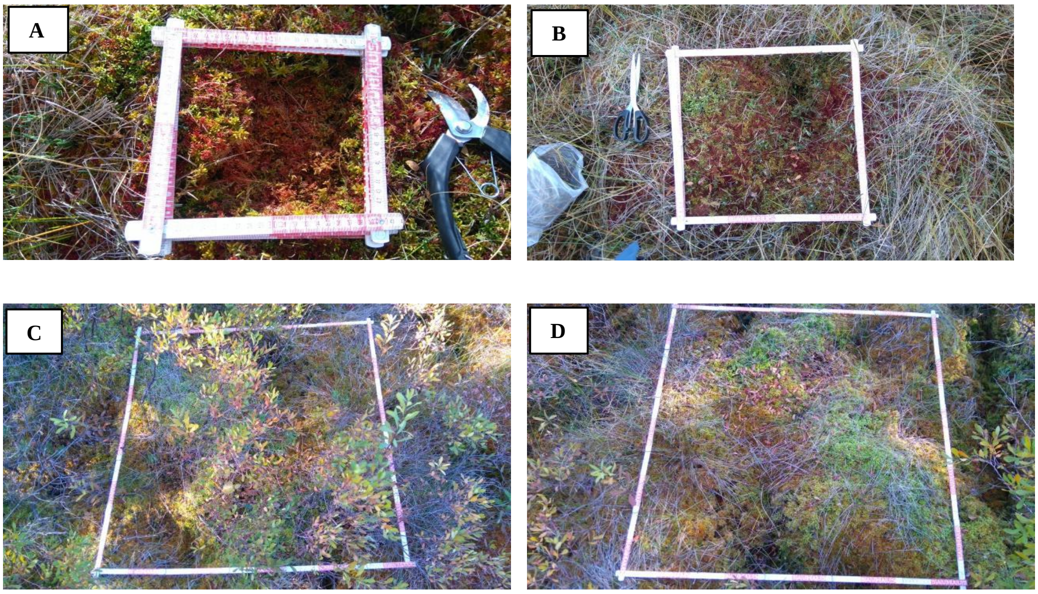


Figure 9: Fuel sampling during fieldwork on unburnt mire. (A) Moss sampling using a 20cm x 20cm quadrat; (B) Sampling of graminoids using a 40cm x 40cm quadrat; (C – D) Shrub sampling, before and after the clipping of shrub species within the full 1 m x 1m quadrat.

2.3 Delineation of unburnt mires

Unburnt area in mires, within the perimeter of the burnt area, were delineated using Summit Evolution software (Summit, 2012) and ArcMap (ArcGIS, 2015). Post-fire infrared (IRF) aerial photos were provided by the Swedish National Land Survey (Lantmäteriet, 2016). They were captured on the 16th of August 2014, eleven days after fire propagation had stopped.

An attempt was done to improve the speed of the delineation process using supervised classification (ENVI, 2015); however, the results were less accurate than with manual stereo interpretation. Also, vegetation indices were calculated, during the supervised classification, to improve the contrast between vegetated and non-vegetated areas. Several vegetation indices have been tested and compared visually, with Normalized Difference Vegetation Index (TNDVI) providing the best results. However, the performance was very poor, and the delineation of the unburnt mires was conducted manually with stereo interpretation in Summit (2012) software.

To test the accuracy of the delineation of unburned areas using aerial photo stereo interpretation, a number of unburnt patches were delineated in the field during May 2015. This was done using a high-accuracy GPS unit (TOPCON GRS-1, ~2cm accuracy). Several individual unburnt patches of open mires, shrub mires and pine bogs where delineated by walking with the GPS unit at the boundaries between burnt and unburnt vegetation. In most cases it was easy to determine the exact line between burnt and unburnt mire vegetation. Often, the top of the *Sphagnum* moss layer was consumed by the fire, but on occasion the moss layer was still intact close to the border of unburnt patches and then the presence of charred basal parts of sedge or other mire plants were used as reliable indicators of fire. The GPS trace was later compared to the results of the aerial photo delineation in ArcGIS.

2.4 Mire types mapping

Detailed mire type mapping was done within two separate areas, 100 hectares each (Figure 10). The two areas were selected to provide good representation of all mire types that occur within the burnt area. Both areas had been affected mainly by head fire and to a minor degree by flanking fire, meaning that they had been exposed to a high intensity fire. Further, in those areas no major fire suppression efforts had been undertaken, and I assume that the unburnt patches should primarily have been the result of unsuitable fuel conditions for fire to spread.

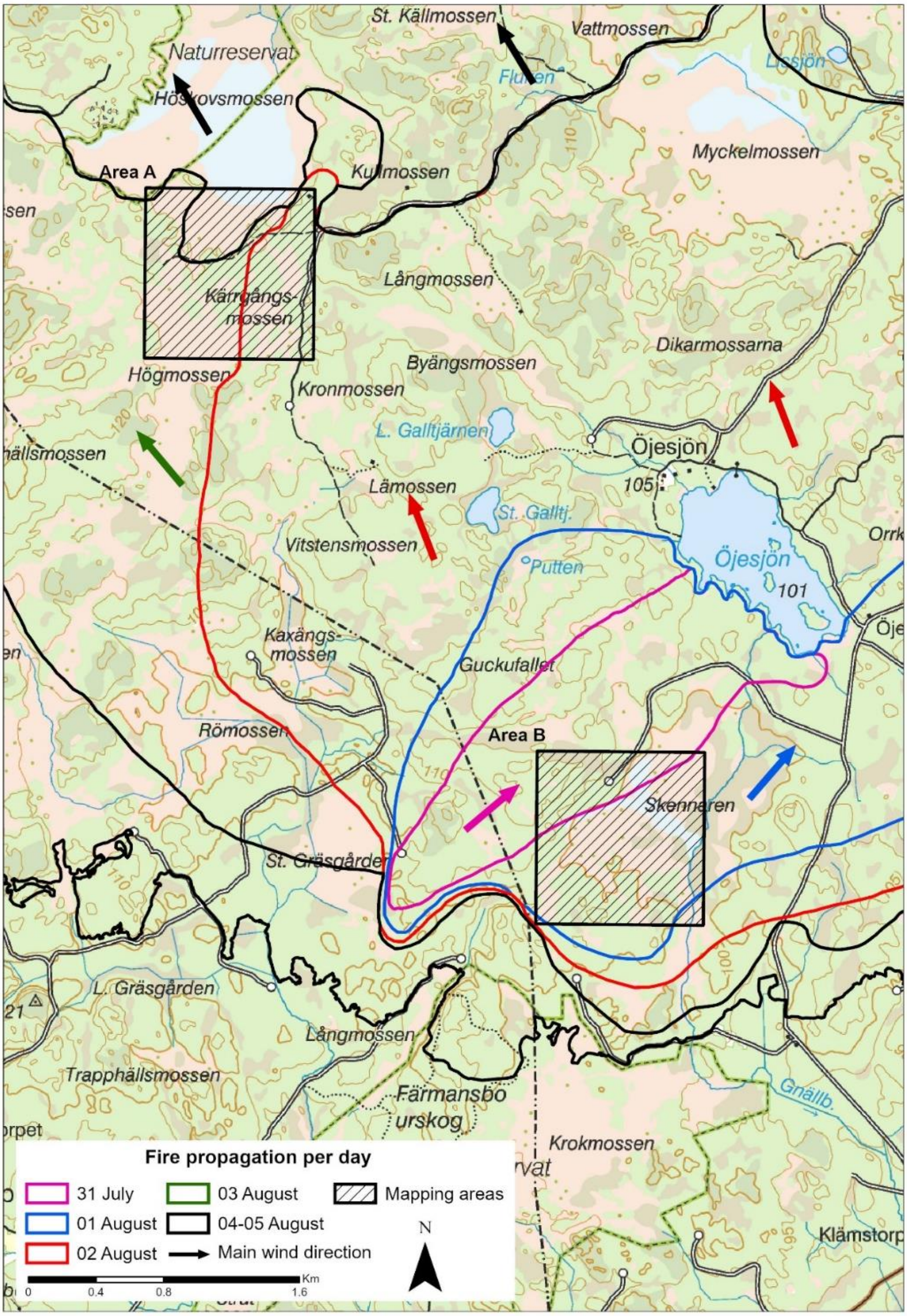


Figure 10: The two areas, each 100 ha, selected for detailed mapping of mire types and unburnt patches.

Mapping was based on stereo interpretation of post-fire aerial photos (IRF). Interpretation and classification were based on vegetation cover, vegetation type, colour and surface texture. Field information from the surveyed unburnt plots (mire type, vegetation structure and photos), pre-fire aerial photos from inside the burnt area and other information like land cover map (Naturtypkartering), vegetation maps (GSD-Vegetationsdata), terrain map (Terrängkartan), property maps (Fastighetskarta) also supported the interpretation. A vegetation-interpretation key (Appendix II) was created and used for easier and more systematic classification. Also, a calibration key was created (Appendix III) in which aerial and field photos from the same area were used, for easier and more consistent identification of mire types. In total, 11 mire classes were identified (3 for pine bogs, 3 for shrub mires type, 4 for open mires and 1 for very wet mires including open water surfaces within mires) (Table 2).

Table 2: Aerial photo interpretation classes.

Main class	Sub class	Information
Pine bog	Class(A)	70 – 100 % Canopy cover
	Class (B)	40 – 70 % Canopy cover
	Class (C)	25 – 40 % Canopy cover
Shrub Mire	Class (A)	30 – 50 % Shrub cover
	Class (B)	10 – 30 % Shrub cover
	Class (C)	< 10 % Shrub cover
Open Mire	Class (A)	Graminoids Type
	Class (B)	Phragmites Type
	Class (C)	Hummocky Type
	Class (D)	Moss – Graminoids
Wet Mire		Very wet mire – open water

2.5 Calculations and statistics

All the sampled data were visualized in charts in Microsoft Excel (Microsoft Office, 2010) to identify patterns before the statistical analysis. Data were checked if they fulfilled assumptions of normality, i.e. equal variances and normal distribution. This was done both graphically (histograms) and mathematically (Shapiro-Wilk's test and Lilliefors test), using R (2008) statistical software. Square root and logarithmic transformations were applied on the non-normal data, to comply with normal distribution, however transformation results were not satisfactory. The small size of samples leaded to use a non-parametric statistical analysis (ANOVA), as well as post-hoc tests. All analysis results were evaluated graphically by checking the assumptions of equal variances, normal distribution, independence, and fixed X-values of the residuals (Winder, 2015).

Fuel mass predictions using fuel cover and height was done using generalized linear models, as they can handle several exponential families, and non-normal distributions (Tack, 2015).

3. Results

3.1 Delineation of unburnt patches on mires

Visual comparisons of unburnt patches delineated using both high-precision GPS and post-fire IRF aerial photo interpretation indicates that the technique provide satisfactory results. At a very small scale, delineation lines differed, likely due to the limitations that the two methods have (Figure 11). As the GPS unit provides very accurate results (~2 cm accuracy), it has been considered as the ground truth “control lines” to evaluate the photo- interpretation. The evaluation was based on a GIS analysis where the mean distance of the two delineation methods was calculated using 10 cm intervals between each measurement along the line.

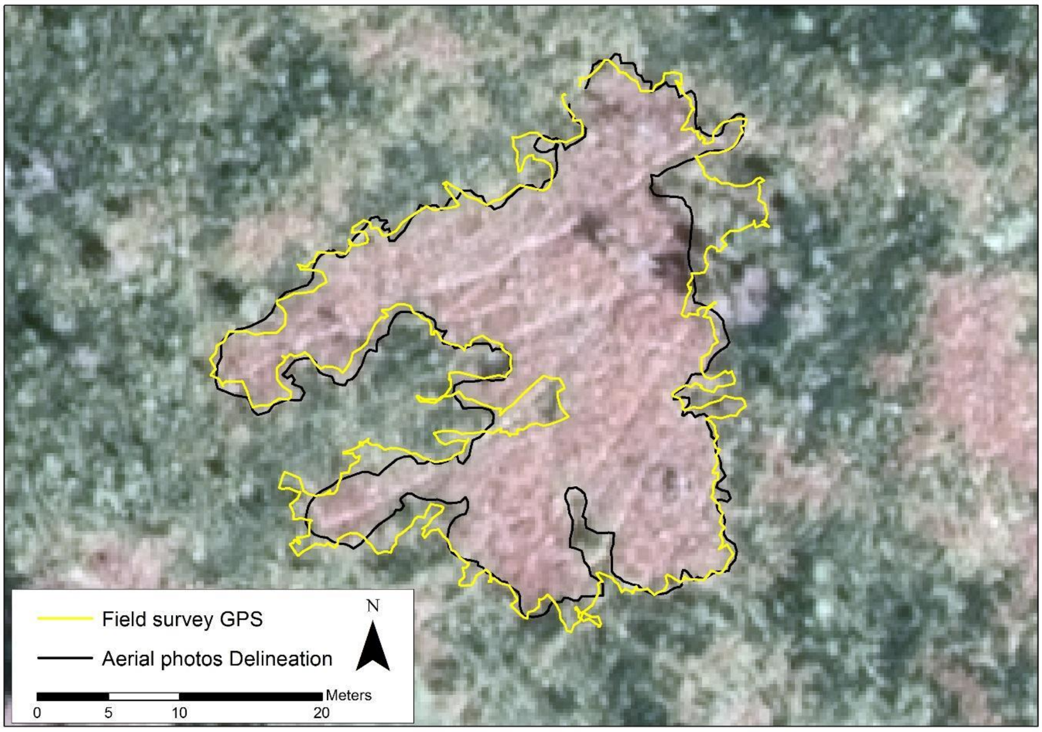


Figure 11: Visual comparison between the field survey (yellow trace) and aerial photo interpretation (black trace).

The mean difference between the two delineation methods was 0,23 m (Figure 12). However, the results show that photo interpretation was capable of delineating unburnt patches with sufficient precision.

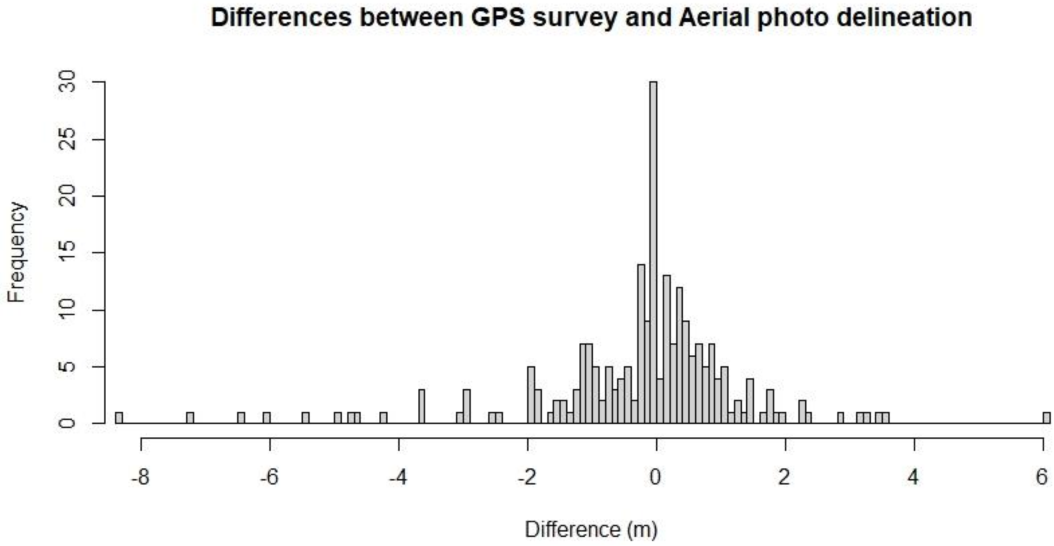


Figure 12: Histogram with the differences between Field survey (GPS) and Aerial photos interpretation (10cm intervals)

3.2 Mire-type mapping using aerial photo interpretation

In the two selected 100 ha areas (A and B), the main mire types were mapped using stereo interpretation of post-fire aerial photos. The results are presented in Figure 13, Figure 14 and Figure 15.

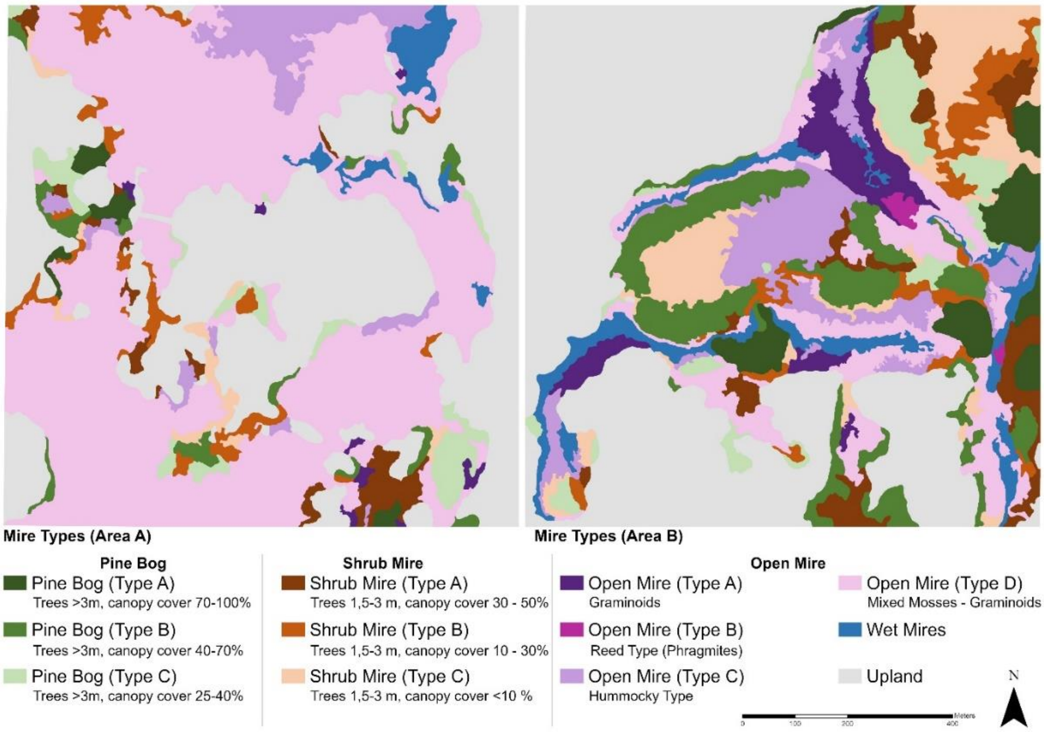
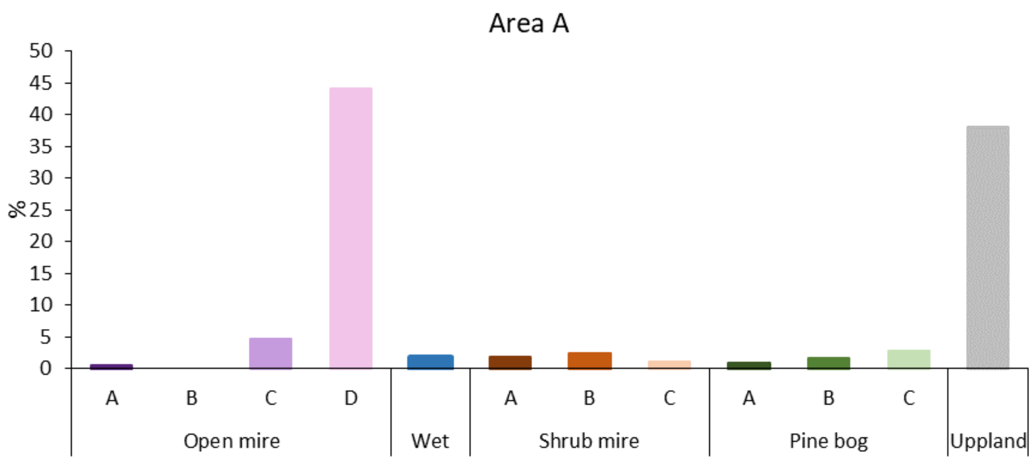


Figure 13: Distribution of the main mire types in areas A and B.



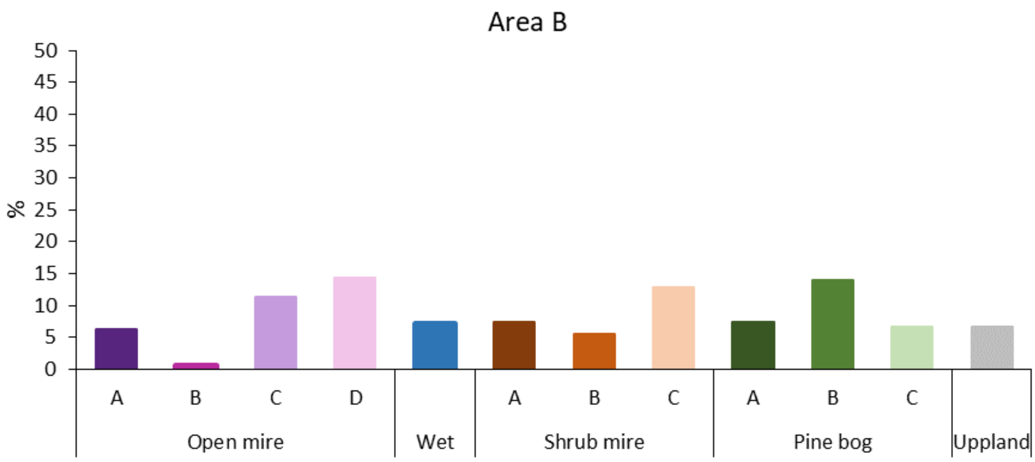


Figure 14: Proportion of mire types within areas A and B, based on interpretation of aerial photos taken before the fire.

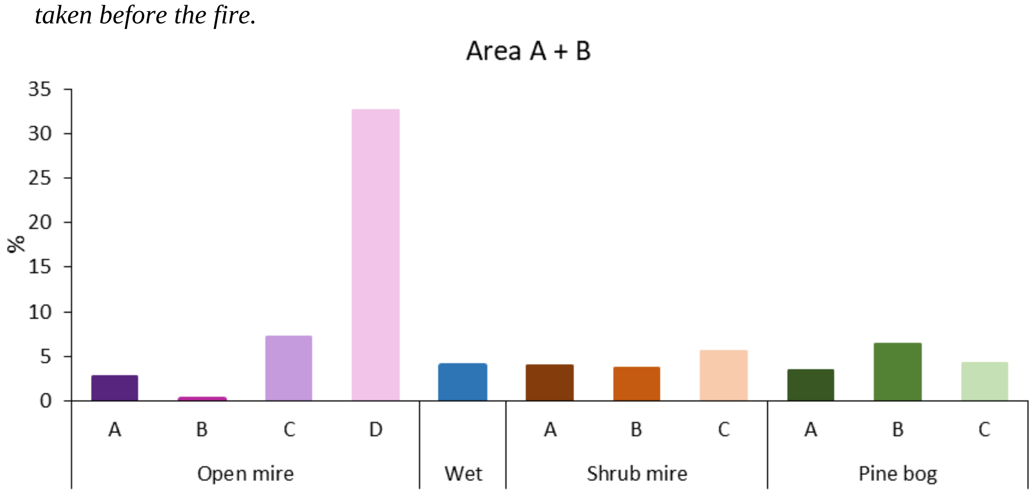


Figure 15: Percentage cover for each mire type out of total mires within the areas A and B combined.

3.3 Fuel classification

The different species as well as the dead litter (fuels) have been sorted into 3 main groups, further divided into 9 subgroups based on their assumed flammability characteristics (Table 3). The three groups cover the field layer fuels, the bottom layer fuels and the dead fuels. For all groups and subgroups fuel mass (kg), cover (%) and height (m) were measured or estimated.

Table 3: Main fuel components and their characteristics regarding fire perspective based on information by Anders Granström (personal communication 2017).

Fuel type	Vegetation type	Vegetation species – Fuel details	Characteristics
Field layer live fuels	Evergreen dwarf-shrubs	*Rhododendron tomentosum, Calluna vulgaris, Vaccinium vitis-idaea, Vaccinium oxycoccus, Empetrum nigrum, Andromeda polifolia. Seedlings of Pinus sylvestris <1m in height.*	Highly flammable live plants
	Deciduous dwarf- shrubs	*Betula nana, Myrica gale, Vaccinium uliginosum,Vaccinium myrtillus, Betula pendula (seedlings), Salix ssp. (seedlings), Populus ssp. (seedlings).*	Generally low flammability of live plants
	Graminoids	*Carex ssp., Carex leucocarpa, Carex lasiocarpa, Molinia caerulea,. Eriophorum ssp., Eriophorum vaginatum, Phragmites australis.*	Variable flammability of live plants. All produce highly flammable litter
	Herbs	*Menyanthes trifoliata, Viola ssp., Comarum palustre, Drosera ssp., Epilobium angustifolium, Rubus chamaemorus. Equisetum ssp*	Nonflammable mesophytic herbs. Litter non-persistent
Bottom layer fuels	*Loose Sphagnum*	*Sphagnum section cuspidata*	Low bulk density. Flammable if dry
	Compact Sphagnum	*Sphagnum section acutifolia (mainly Sphagnum fuscum).*	High bulk density. Less flammable even if dry
	Pleurocarpous mosses	*Pleurozium schreberi, Hylocomium splendens.*	Flammable
	Acrocarpous mosses	*Dicranum undulatum, Polytrichum juniperinum, Polytrichum strictum, Polytrichum commune. Marchantia polymorpha*	Less flammable
	Lichens	*Cladonia rangiferina, Cladonia arbuscula, Cladonia stellaris.*	Highly flammable
Dead Fuels		*All dead organic material on the mire surface (leaves, twigs, branches)*	Highly flammable

3.4 Cover and height of different fuel categories in the three mire types

Fuel composition varies substantially between mire types (Figure 16). In open mires, live graminoids and graminoid litter with some evergreen dwarf shrubs, mainly low-grown *Calluna vulgaris*, dominated the cover of field layer. In both shrub mires and pine bogs, evergreen dwarf shrubs were instead completely dominant, although the species differed between types: Primarily *Calluna vulgaris* in shrub mires and the taller *Rhododendron* in pine bogs. In pine bogs there was also a substantial herb component, in the form of low-grown *Rubus chamaemorus*, which also occurred as a minor component in shrub mires.

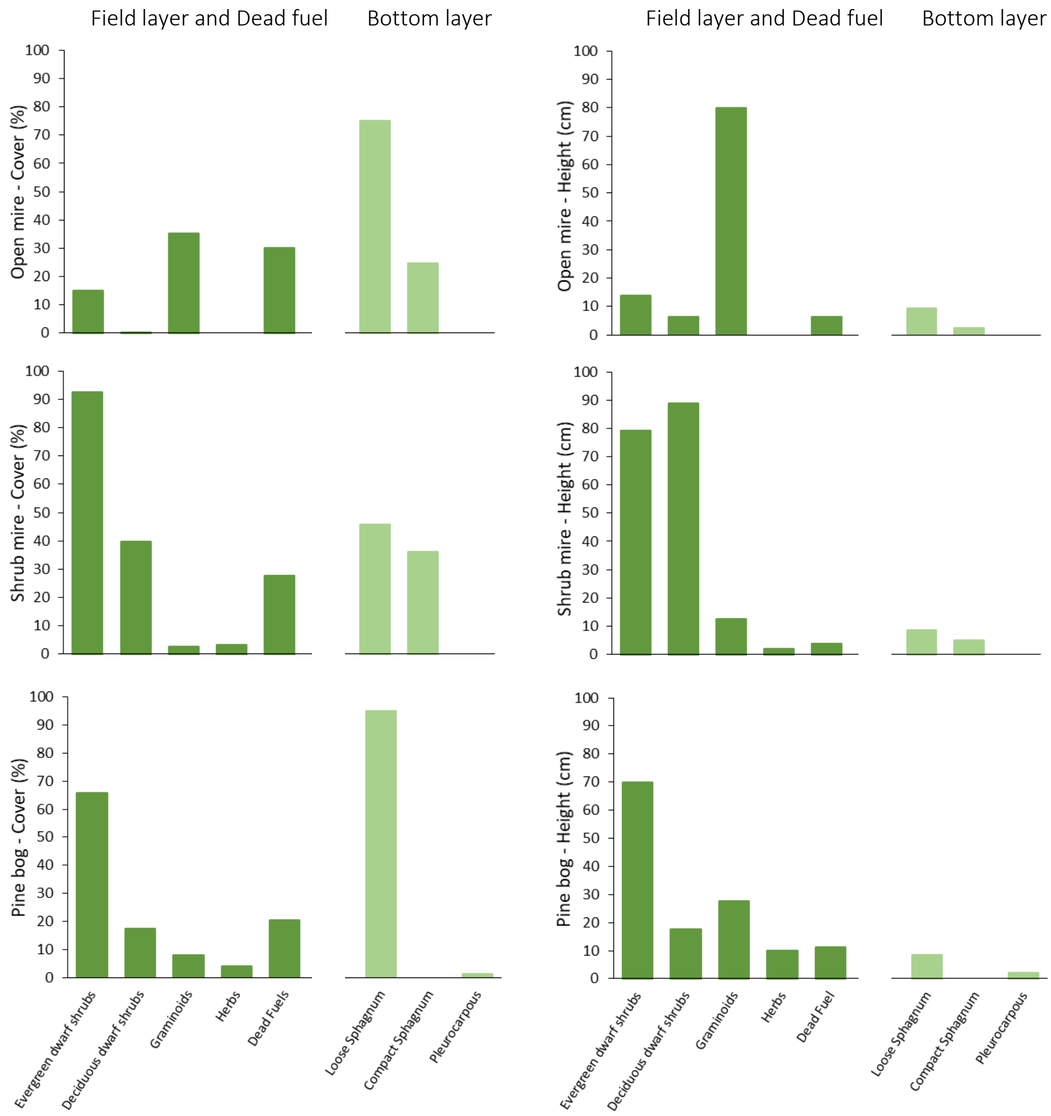


Figure 16: Cover (%) and height (cm) of the main fuel components in each Mire type.

In the bottom-layer mosses had a nearly complete cover but there were large differences in the moss categories between mire types. In pine bogs, loose *Sphagnum* species dominated completely but in shrub mires compact *Sphagnum* species had a cover nearly on par with loose *Sphagnum* species. In open mires loose *Sphagnum* had a cover c 3 times that of compact *Sphagnum*. The depth to which loose *Sphagnum* was penetrated during measurements was c 10 cm in all mire types (Figure 16). Beside *Sphagnum* species there was also a small component of *Pleurocarpous* mosses, *Acrocarpous* mosses and reindeer lichens, primarily in the pine bog type. The summed cover of the more flammable fuel elements generated from vascular plants (i.e. excluding live herbs) was more than double in pine bogs and shrub mires compared to open mires. Cover of flammable bottom-layer species on the other hand (excluding compact *Sphagnum* and *Polytrichum* spp.) was nearly complete in both open mires and pine bogs, but only about half in shrub mires (Figure 17).

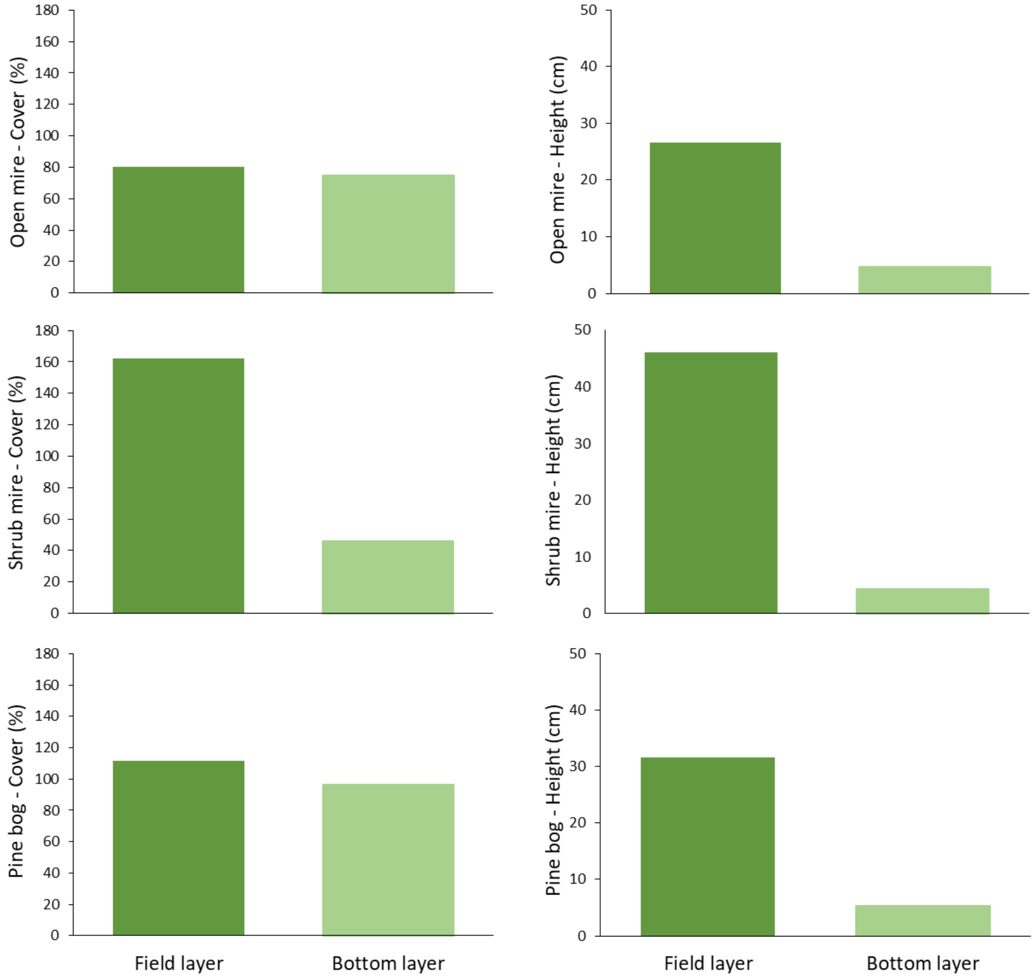


Figure 17: Potentially flammable fuel cover (%) and mean height (cm) of the field and bottom layer. Less flammable fuels like herbs, compact mosses and acrocarpous mosses are not presented in these figures.

3.5 Fuel mass

Pine bogs have the larger fuel mass, over 2 times the fuel mass on shrub and open mires (Figure 18). In all mire types, bottom layers provide a significant amount of fuel mass, especially the loose *Sphagnum* layer and the presence of *Pleurocarpus* mosses in pine bogs. Both in pine bogs and open mires, bottom layer provides larger fuel mass than the above ground fuels where in shrub mires above ground fuels have a slightly larger fuel mass.

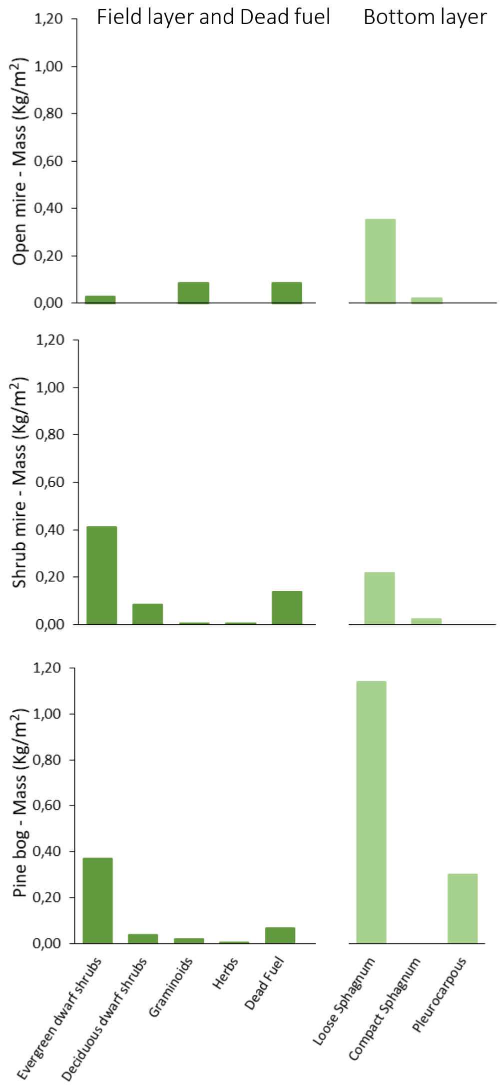


Figure 18: Mass (Kg/m²) of the main fuel components in each mire type.

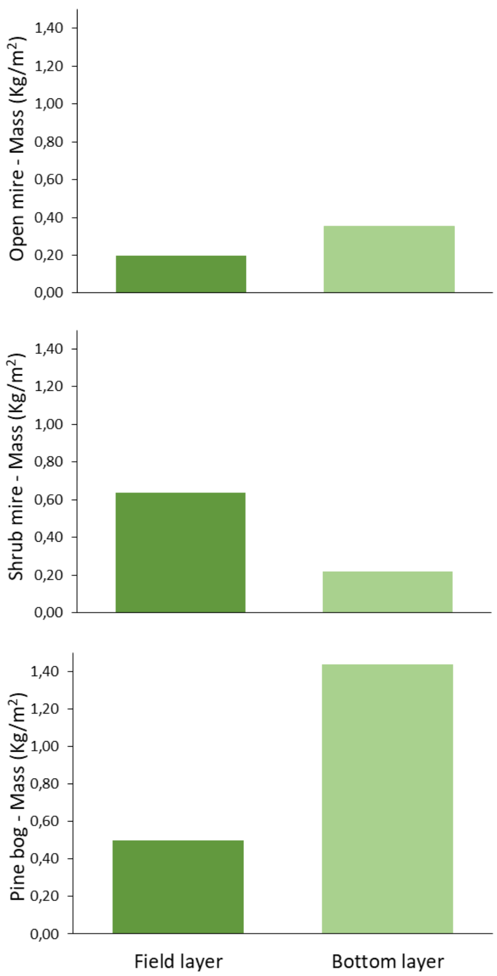


Figure 19: Potentially flammable fuels mass (Kg/m²) of the above ground and bottom layer. Less flammable fuels like herbs, compact mosses and acrocarpous mosses are not presented in these figures.

Above ground fuel in pine bogs mainly consist of evergreen dwarf shrubs, like *Rhododendron* and smaller amounts of *Calluna vulgaris* and *Vaccinium vitis idaea*, as well as dead fuel. In shrub mires, evergreen dwarf shrubs are the dominant fuel component with *Rhododendron* and *Calluna vulgaris* and high amount of dead fuel, higher among the other mire types. *Graminoid* layer, mostly consist by *Eriophorum spp.* and dead fuel (graminoid litter) are the main fuel components of the above ground layer in the open mires, with smaller amount of *Calluna vulgaris* dwarf shrubs. In open mires where the *Phragmites australis* is dominant the fuel mass of graminoids layer is almost 5 times higher, than those covered by *Eriophorum spp.*

3.6 Fuel mass models

Fuel mass models for different fuel components were constructed, based on cover and height, using generalized linear model analysis where mass was the response variable and cover and height the explanatory variables. The analysis did not consider mire types separately because of the small sample size, but plot data from all mire types were included. Linear relations were calculated for the total fuel mass and for the different fuel components separately (*Table 4*).

Table 4: Fuel mass prediction using generalized linear relations, with fuel cover and height. The analysis considers all fuel types (total fuel) and the fuel that components have sufficient sample size. Pleurocarpus mosses, acrocarpous mosses and lichens were not included in the analysis because of small samples size.

Main fuel components		**p**	**F**	**Generalized Linear relation**
Total fuel	mass ~ cover	0,001	18,71	Total fuel mass = 0,002xTotal fuel cover + 0,017xTotal fuel height
	mass ~ height	0,5	0,485	
Evergreen dwarf shrubs	mass ~ cover	0	61,49	Evergreen dwarf shrub mass = -0,003xEvergreen dwarf shrub cover + 0,006xEvergreen dwarf shrub height
	mass ~ height	0,239	1,565	
Deciduous dwarf shrubs	mass ~ cover	0,001	716,8	Deciduous dwarf shrubs mass = 0,0025xDeciduous dwarf shrub cover - 0,0001xDeciduous dwarf shrub height
	mass ~ height	0,549	0,508	
Graminoids	mass ~ cover	0	162,1	Graminoids mass = 0,0016xGraminoids cover + 0,0002xGraminoids height
	mass ~ height	0,217	1,844	
Herbs	mass ~ cover	0,05	160,4	Herbs mass = 0,001xHerbs cover - 0.0001xHerbs height
	mass ~ height	0,287	4,489	
Loose Sphagnum	mass ~ cover	0,009	13,93	Loose Sphagnum mass = 0,009xLoose Sphagnum cover - 0.006xLoose Sphagnum height
	mass ~ height	0,911	0,011	
Compact Sphagnum	mass ~ cover	0	0	Compact Sphagnum mass = 0,0008xCompact Sphagnum cover - 0,0001xCompact Sphagnum height
	mass ~ height	0	0	
Dead fuels	mass ~ cover	0,0003	27,821	Dead fuels mass = 0,003xDead fuels cover + 0,001xDead fuels height
	mass ~ height	0,721	0,134	

3.7 Burnt proportion in the local and landscape level

Comparing the local scale inventory (plot level) and the landscape level (aerial photo interpretation in areas A and B), the proportion of the area burnt was relatively similar (Figure 20 and Figure 21). For open mires the burnt area was somewhat higher within the plots than at the landscape level (95% vs. 73%). For shrub mires the reverse was true (72% vs. 90%). For pine bogs, the proportion of area burnt was equally high within the plots and at the landscape level (100% vs. 96%).

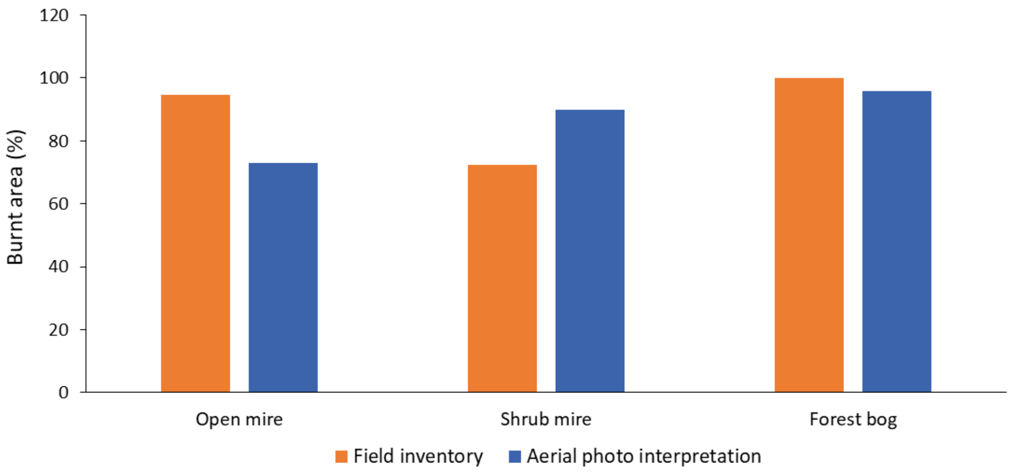


Figure 20: Local (field plots) and landscape level (aerial photo interpretation) burnt area in each mire type.

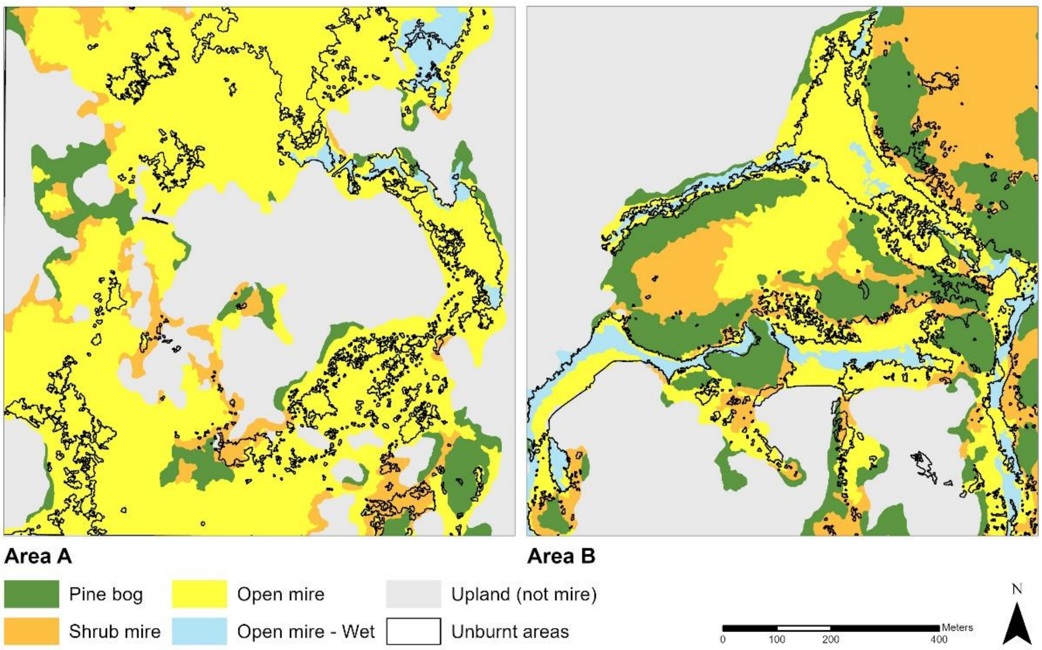


Figure 21: Unburnt patches within the two 100 ha areas and the main mire types from aerial photos interpretation.

Further, the results of the more detailed aerial photo interpretation of mire sub-categories showed differences in proportion of area burnt only between the Open mire sub-types. Here only 27% of the Graminoid type burned, vs. 81% for the Moss-Graminoid type, 61% for the *Phragmites* type and 55% for the Hummocky type. Of the areas classified as wet 32% burnt (Figure 22).

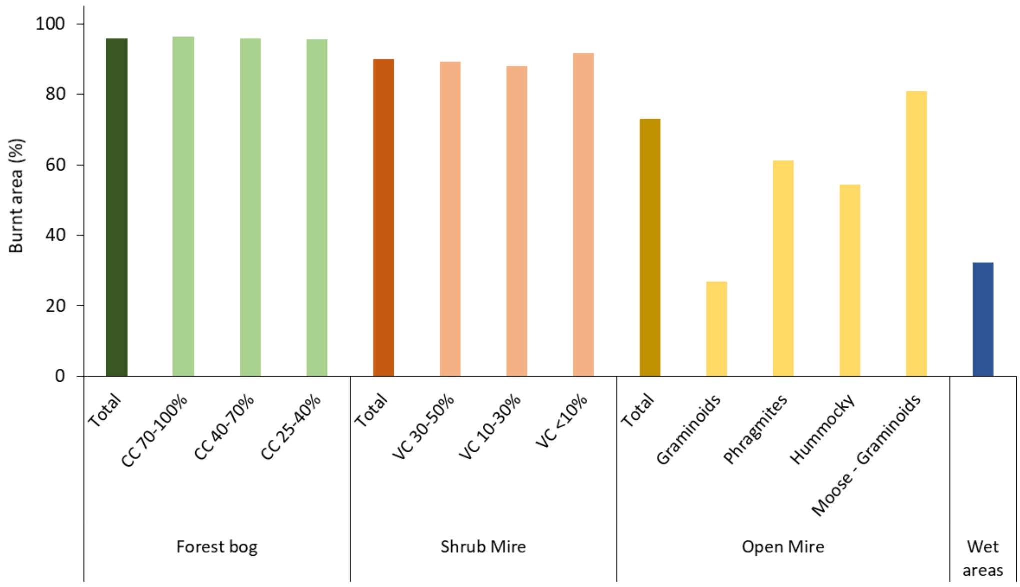


Figure 22: Proportion of burnt area of each mire type sub-category within the two investigation areas combined. Data from the aerial photo interpretation (Canopy Cover – CC, Vegetation Cover – VC).

Considering the impact of mires on fire propagation, the analysis indicates that wet open mires, under the right conditions, have the potential to reduce fire propagation end even stop fire. Within the two areas (Figure 23), I identified three big-enough unburned mire areas, which should have acted as barriers to the fire. Those areas are oriented vertical to the main direction of fire propagation and are long enough (530m - 350m) to influence fire spread.

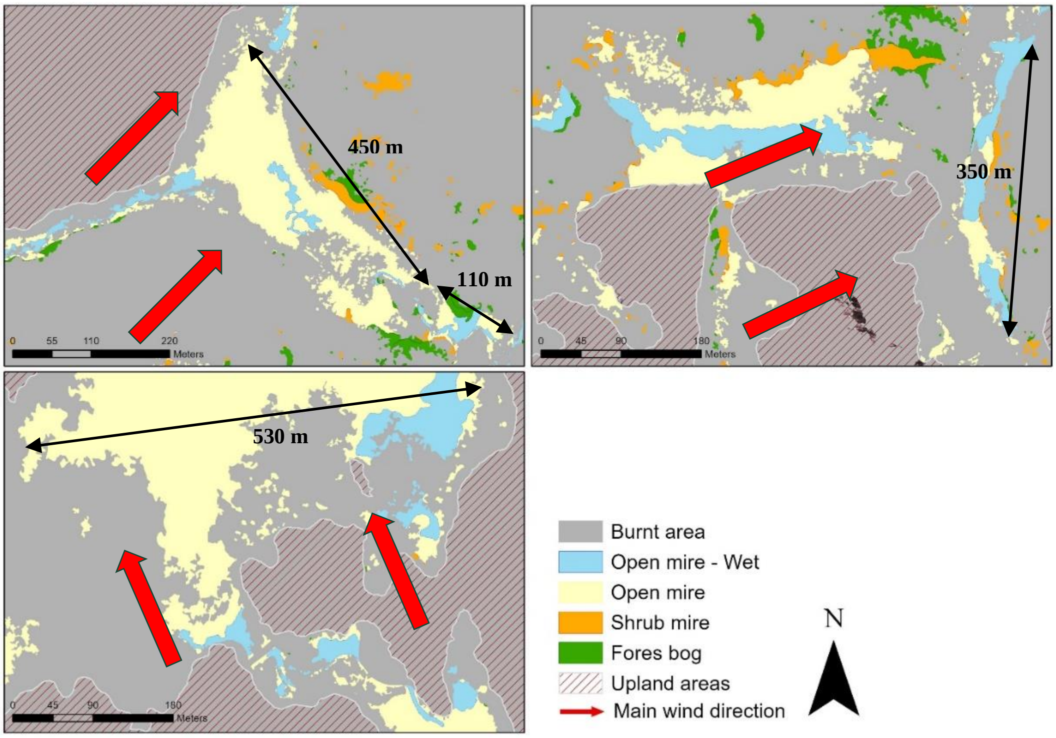


Figure 23: Examples of unburnt mires stretching up to 530m perpendicular to forest fire propagation. With red arrows the fire propagation.

3.8 Fire intensity

In pine bogs there were strong evidence of high-density fire where almost all the area has been burnt and the fuels have been consumed in their biggest extent (Figure 24). Also have been observed high Skorch-height up to 8-9 m indicating long flames.

Figure 24: Evidence of high severity fire in pine bog where vegetation has been burned entirely. Bottom layer fuels have been consumed down to the water table, where field layer vegetation has been consumed almost totally, some bigger size shrub branches didn't consumed by fire.

Fire intensity in shrub mires was lower than in pine bog and an amount of fuels has not been burned or consumed by fire (Figure 25). Even in areas where fire passed, shrub leaves where often killed but not consumed by the flames, especially the higher parts of *Myrica gale* leaves (Figure 26), indicating a generally lower fire intensity here than in pine bog.

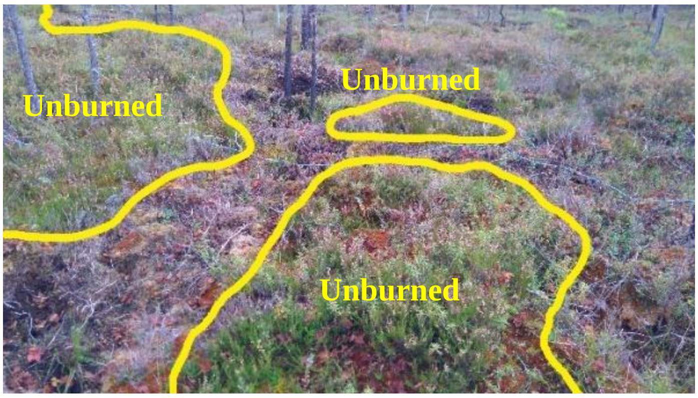


Figure 25: Unburned patches within shrub mire. This plot was burned 25%. Calluna shrubs on compact mosses and areas with more wet conditions have not been affected by the fire.

Figure 26: Totally burned (100%) Shrub mire dominated by Myrica gale. Myrica gale leaves have been killed by the fire but leaves on the higher parts have not consumed.

During the field survey, I observed that many larger-sized fuels in open mires, such as shrubs, have not been affected by the fire, even when it passed beneath or nearby them. On most occasions, the moss layer was burned only in their upper layer and in many cases was untouched by the fire. That shows the presence of low intensity fire as well as short length flames. Also, wetter parts of open mire have not been affected by the fire even though they had similar fuel structure and composition as the nearby burnt areas.

4. Discussion

The study of the different mire types shows that mires in Fennoscandia can burn under certain conditions and the fuel characteristics have an important role on fire intensity. Previous studies in Fennoscandia (Hellberg, Niklasson and Granström, 2004) and other boreal forest regions (Magnan, Lavoie, Payette, 2011; Sillasoo, Valiranta and Stiina, 2011; Osborne, Kobziar and Inglett, 2013) show that mires have been burnt in the past. Also, studies on recent forest fire events show that fire can propagate over and burnt the mires (Ronkainen, Väliranta and Tuittila, 2013; Hederskog, 2018), however there is not clear discussion about the role of fuels in each mire type.

4.1 Effect of mires on fire at the local level

The results show a significant relation between mire type and proportion of burnt area. Virtually all available areas of pine bogs within the fire perimeter had burnt whereas there were frequent unburnt areas of open mire. This can be explained by differences in both fuel structure and resistance to drying.

In pine bogs the bottom layer is typically composed of *Pleurocarpous* mosses on hummocks and loose *Sphagnum* mosses in between, both of which are highly flammable when dry. Pine bogs tend to raise 20-50 cm above the dominant water table, with a well aerated moss layer (Rydin, Sjors and Lofroth, 1999) creating dryer conditions compared to other mire types. Above the moss/litter layer, there is a well-developed canopy of mostly evergreen dwarf-shrubs, *Vaccinium vitis-idea*, *Calluna vulgaris* and *Rhododendron spp*. These cover nearly 65% of 211% total fuel cover. As soon as the litter/moss layer is dry-enough to burn the evergreen dwarf-shrubs will contribute greatly to fire intensity. Possibly, dense canopies of flammable dwarf-shrubs might carry fire even without support from bottom layer. This is frequently observed in pure *Calluna vulgaris* fuel beds in Scotland (Matt and Colin, 2011), but has not been investigated in pine bog of our type.

Even though long length flames were observed, there was not any evidence of crown fire, and that is because the pine bog typically has a mono-layered tree canopy and lacks understory trees that can act as ladder fuels and promote crown fire.

Shrub mires high amount of highly flammable evergreen dwarf shrubs and dead litter (75% of fuel mass), as well as the presence of the flammable deciduous dwarf shrubs (5%), provide good conditions for fire to burn and propagate. Shrub mires burned almost totally (89,94%) in landscape level, however during field survey I noticed numerous small unburnt patches.

To that mosaic of burnt and unburnt patches, the moss layer has an important role because of its ability to absorb and sustain high amounts of water. Loose *Sphagnum* mosses have been burnt in their largest extent but not consumed during fire, helping fire propagation in the adjacent fuels. Further, the presence of high amount of compact *Sphagnum* mosses in shrub mires, makes it more difficult for fire to propagate, as this moss type is less flammable even if it is dry enough (Granström, personal observation).

Another parameter that may explain the high amount of small unburnt patches, are the firefighting efforts in the area. As those efforts are not well documented, there is a possibility those patches are present because of water droppings from helicopters or ground units' firefighting activity. As mentioned by Granström (2015), from his personal experience during the fire event, helicopters had concentrated their firefighting efforts in open areas like shrub and open mires.

Higher water table in open mires dictates the fuel composition, mostly by graminoids, mosses, dead fuel and small amount of dwarf shrubs. Graminoids and dead fuel, mostly dead graminoids, represented 23% of fuel mass and cover almost 50% of open mires. Fire can spread very fast in graminoid litter (Granström and Niklasson, 2008), however this fine fuel type produces low energy flames, which can be "vulnerable" to high moisture content fuels or very wet areas.

In open mires the loose *Sphagnum* moss layer has a key role, constituting 59% of the fuel mass with a cover of almost 75%. As mentioned, *Sphagnum* mosses can burn if they are dry enough, creating low intensity flames that can carry fire over the landscape. Considering that open mires tends to have a higher groundwater table, than the other two mire types with frequent presence of open water areas, and the fact that mosses can absorb huge amounts of water (Rydin, Sjors and Lofroth, 1999), even after prolonged droughts, fire ignitions and propagation becomes more difficult (Hellberg, Niklasson and Granström, 2004). Those wet conditions and the low-intensity fire produced, can explain the extensive presence of large unburnt areas within open mire.

4.2 Effect of mires on fire at the landscape level

The burnt patterns, identified from aerial photo interpretation, indicate that particular large open mires can constrain fire propagation and, if the conditions are suitable, even to stop it. The dynamics that act to constrain fire are not easy to deduce retrospectively, without direct observation at the event, as it depends on many variables such as fuel conditions (fuel type, spatial distribution, moisture content) and environmental conditions (humidity, wind etc.). However, in comparison with the other mire types, open mires often hava only a sparse fuel layer of standing graminoid litter above the *Sphagnum* and the moisture content of the *Sphagnum* cover is often higher, compared to the other mire types (Malmer, 1965;

Kellner, 2003). The fact that vegetation density in open mires tends to decrease from mire edge to the central parts (Rydin, Sjors and Lofroth, 1999; Kelner, 2003; Magnan et al., 2011) in consort with increasing wetness, can explain why the margins of open mires are often burned but not their central parts.

The Västmanland fire developed into the largest in Sweden in over one hundred years, with all the conditions in favour for fire to expand rapidly and with high intensity. The fire occurred after a long drought period and with very high fire danger indices, over the five days of active fire propagation. Even under those extreme conditions many unburnt patches were present in the area, some over 500m long (Figure 27). Most of those patches observed within open mires and wet areas, as those identified by aerial photo interpretation. It is noticeable that the unburnt patches over the wet areas were as high as 68%, indicating the significance of local fuel conditions for fire propagation.

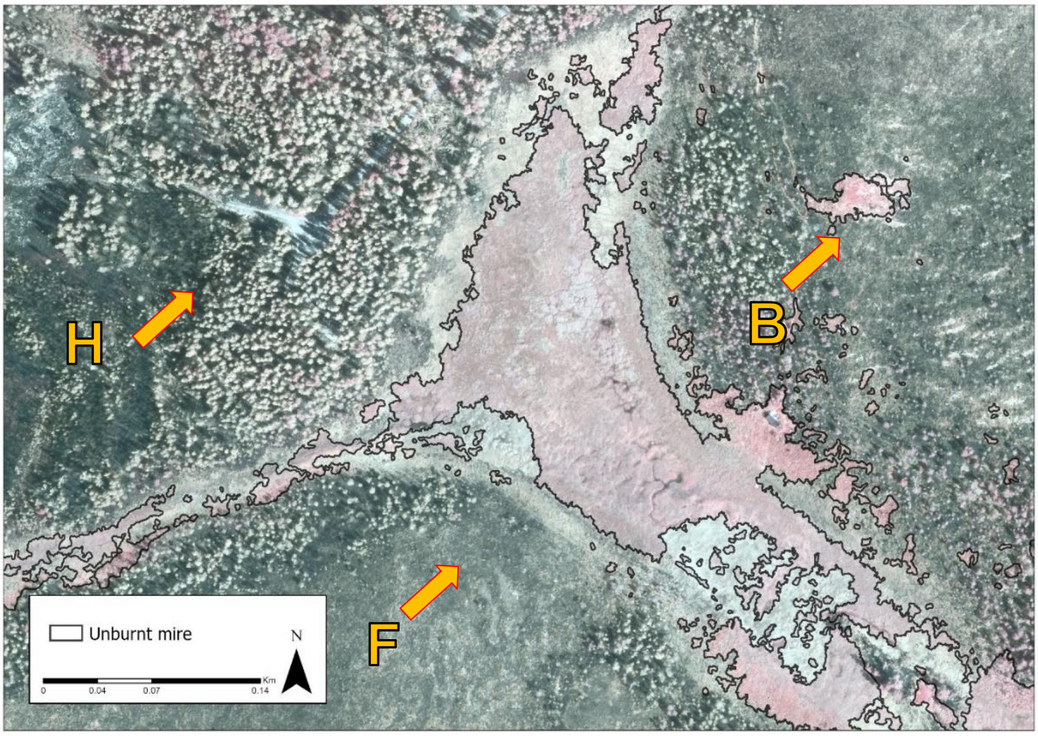


Figure 27: A contiguous unburned area within an open mire, inside area B, delineated with a tracer line. Orange arrows indicate the wind direction when the respective areas burnt, which happened in the order H, F and B. H denote an upland section where a narrow head of the fire moved shortly after ignition, partly as a crown fire. F denote section burned by a flank fire. B denote a section where the fire was moving against the wind, i.e. backing, after having moved into the mire north of the non-flammable open mire. Wind direction was the same throughout, indicated by the arrows.

The other two mire types did not seem to have any significant restrictive role on fire propagation, especially pine bogs, where there were hardly any unburnt patches. Within shrub mires, numerous unburnt patches are present, but due to their small size and scattered spatial distribution, they did not influence fire propagation.

As mentioned, fuel moisture content threshold for fire ignition in moss is 25% (Schimmel and Granström, 1997), and within the central part of large open wet areas this moisture content appears not to have been reached even in this extreme drought. When the moss layer is permanently moist enough it creates an unfavourable fuel bet for fire (Hellberg, Niklasson and Granström, 2004). From the analysis, it is clear that wet areas have the potential to restrict fire propagation and act as total barriers.

4.3 Challenges in delineation of burnt mires

The high-precision GPS tracing of fire margins in the field provided ground-truthing to the aerial photo interpretation and show its capacity to define burnt vs unburnt mire vegetation.

The aerial photo-interpretation technique provides several advantages compared to field surveys, not least that the interpretation of large areas can be done in short amount of time.

When the top of the *Sphagnum* has been heat-killed, it made it visible on the IR-photos, and it was easy to distinguish live/active vegetation from dead. Even more contrast was given when the top of the *Sphagnum* layer was dry-enough to burn, which gave a charred mire surface. Further, the high-resolution aerial photos make it possible to accurately delineate the burnt/unburnt boundary irregularities, because of the more landscape perspective they provide, including enclaves (unburnt refugial patches within the burnt area) and exclaves (burnt patches outside the burnt area, resulting from spot fires that extinguished themselves). Additionally, the aerial photo interpretation in stereo mode (3D) makes it possible to identify and map the different vegetation layers such as graminoids, mosses, shrubs and trees, and even identify burnt surfaces under sparse tree canopies.

In some cases where the fire impact was very small, making even ground observations difficult, particularly in situations when only a sparse standing graminoid litter had burnt without even damaging the *Sphagnum* below, burnt margins where not clear enough on aerial photos, made it more difficult to map burnt boundaries with high accuracy.

To speed up the process and make it easier to map burnt areas, a technique for automated analysis of aerial photos was tested, namely supervised classification. This attempt gave unacceptably poor results. The poor performance was apparently due to the high spatial resolution of the aerial photos (25 cm), where minor details like shadows or differences in brightness levels on the leaves and the ground surface, lead to misclassifications. Further, the tree canopy shadows over the terrain and the presence of unburned tree canopies over the burnt surfaces significantly influenced the classification results. An attempt to decrease the spatial resolution did not provide acceptable results and led to a dramatically decreased delineation accuracy.

Also, in combination to supervised classification, I calculated vegetation indices (NDVI, TNDVI) to increase the contrast between vegetated (unburnt) and non-vegetated (burnt) areas. The results were not accurate enough with a lot of miss classifications and further those calculations decreased the spatial resolution of the aerial photos, further decreasing the delineation accuracy.

Because of the above-mentioned limitations, automated techniques were rejected early on, and the investigation was conducted using manual interpretation.

More comprehensive remote sensing analysis, combining different methods and additional data sets, (e.g. Lidar, background maps, etc.), may improve automated classification results and accelerate the delineation process. However, as this was not the main aim of my study, I had not investigated the matter in more detail.

From the early stages of this study, the use of satellite images for mapping the burnt area has not been consider as an appropriate method. Even though the use of satellite images is a common method to map burnt areas from the early 1980s, their spatial resolution is still high enough (5-500m) (Chuvieco et al., 2019) and is not possible to capture in detail the burnt patterns, at least in the scale of this project. Also, two-dimension (2D) environment of high-resolution satellite imagery, make it difficult or even impossible to map the vegetation structure compared with the stereo aerial photos interpretation.

As mentioned, the high-precision GPS unit had some limitations that influenced delineation results. The strength of GPS and GSM signals were frequently unstable, occasionally decreasing the accuracy of positioning by several meters. Sometimes the signals altogether disappeared for a sufficient length of time to make it impossible to survey (Figure 28). Further, it was challenging to walk with the GPS antenna in a truly vertical position above the winding burn-boundaries, and involuntary movements influenced the accuracy of the survey somewhat.

The field survey was conducted one year after the fire event, when some of the evidence of fire had started to erode. This time delay was another factor that influenced the speed of the field survey. The aerial photos were captured only 11 days after the fire event and should have been optimally timed for distinguishing burned surfaces from unburnt ones.

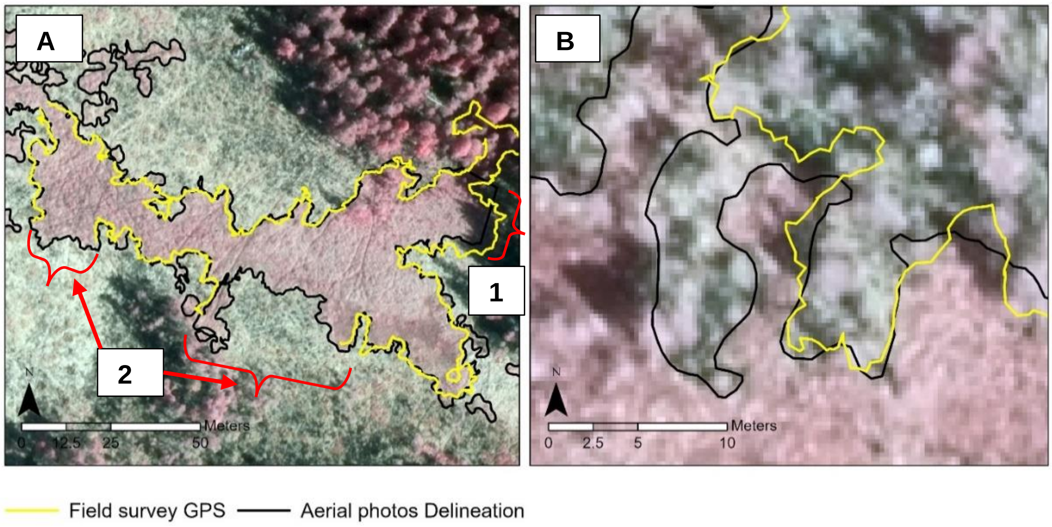


Figure 28: Delineation of the border between burnt and unburnt mire through field survey with a high-precision GPS unit (yellow tracer) and aerial photo delineation (black). A) At the section marked (1) the limitations of aerial photo interpretation under dense tree canopies with ground shadows is visible; at the sections marked (2) the GPS unit lost connection, resulting in missing data. B) Enclaves and exclaves were more difficult to identify and survey in the field than by photo-interpretation.

With aerial photo-interpretation, it is difficult or impossible to assess fire behaviour variables such as intensity and depth of burn. For that reason, field inventories are needed to capture details that can support interpretation of fire behaviour. Another limitation with aerial photos interpretation in mires is the occasional presence of dense tree canopies where the trees or their shadows obscures the surface. Nevertheless, such areas were few and did not influence the overall delineation results much, as the tree canopies in pine bog tend to be sparse, providing good visibility of the surface.

4.4 Fuel mass predictions

Detailed knowledge of the structure of mire fuels in terms of mass, cover and height and surface to volume ratio is critical for modelling fire potential. Destructive fuel sampling, followed by lab processing (drying, weighing) is time consuming. The use of indirect techniques to estimate fuel mass using easily measured fuel characteristics such as cover and height, can provide critical fuel mass information fast and at a low cost.

The poor fit of the regression functions is likely explained by the clustering of deferent species into a few groups of samples, resulting large variation on mass measurements. The structure differences between the several species fuel biomass components, like leaves and branches, can provide a diverse amount of mass per given area and that can explain these irregularities, especially when the analysis is focused on individual species. Because of that limitation, it was not able to investigate further and in more detail fuel mass relation to cover end height, for each mire type and each fuel component.

Nevertheless, as this is the first attempt at quantifying mire fuels the data can provide some indication regarding structure and mass in different mire types. To get more solid data further field sampling is required.

5. Conclusions

I investigated the role of three commonly occurring forest mire types on fire distribution, both at the local and at the landscape level, using the Västmanland fire of 2014 as a case study. As this may be the first study in Sweden directly investigating the role of mire fuels for fire distribution, there is little supporting information in the published literature. Fuel characteristics differed between the mire types and can explain some of the variation in fire distribution and behaviour. During the field inventory it was possible to identify how fuel structure and composition can influence fire behaviour at the local scale, providing key knowledge for understanding burnt / unburnt (fire refugia) patterns at the landscape level. Considering the landscape level, it became clear that large open mires with higher moisture content in the *Sphagnum* layer, relatively sparse litter fuels and especially the presence of areas classified as very wet, have the capacity to stop fire propagation even during a severe drought, as was the case in 2014. Shrub mires and pine bogs can influence fire intensity, but they do not stop fire propagation.

To better understand the relation between cover and height of various plants and the resulting fuel mass, more extensive fuel sampling is needed. The small amount of destructive samples used, provide a general outline of the fuel characteristics, but it was impossible to obtain good predictive regression models between cover/height and fuel mass. Further investigation is needed, with more fuel samples to get a more comprehensive understanding of fuel characteristics and more accurate fuel predictions. Eventually, a comprehensive “fire-typing” of Swedish mire types might be possible to construct, adding mires to the preliminary national fuel map that was released in 2019. This would greatly benefit fire suppression efforts during severe wildfires.

The results show that aerial photo interpretation is a very reliable and fast method to evaluate burnt areas at the landscape level and can be used to assess the role of fire over different mire types. It is likely that remote sensing techniques using change detection in satellite imagery can provide reasonably accurate results in less amount of time (Chuvieco et al., 2019), when considering big fire events (mega-fires). A key factor is that most mires have no or relatively open tree canopies, making it possible to determine both the pre-fire vegetation type and the spatial fire-patterns in detail.

A good understanding of fuel conditions in mires will help predict forest fire propagation in boreal landscapes more accurately. Given the high degree of structural variation in mires, analyses have to be done over the different mire types and subtypes. Further, climate change will likely influence species composition and moisture dynamics in mire ecosystems in the future (Drobyshev, Niklasson and

Linderholm, 2012; Drobyshev, et al., 2014, Flannigan, et al. 2009, Lidskog and Sjödin, 2016) and the consequences for flammability must be investigated further.

References

Alexander E. Martin and Crus G. Miquel, 2012(a). Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height. International *Journal of Wildland Fire*.21, pp. 95-113. (http://dx.doi.org/10.1071/WF11001).

Alexander E. Martin and Crus G. Miquel, 2012(b). Graphical aids for visualizing Byram's fireline intensity in relation to flame length and crown scorch height. *The Forestry chronicle*. 88(2), pp. 185-190

Backeus lngvar, 1985. Aboveground production and growth dynamics of vascular bog plants in Central Sweden. Ph.D. Uppsala University.

Bleken Erik, Mysterud Ivar and Mysterud Iver, eds., 1997. Forest fire and environmental management – a technical report on forest fires as an ecological factor. Oslo: Contracted Report. Directorate for Fire & Explosion Prevention and Department of Biology, University of Oslo. 266 pp.

Bond William and Keeley Jon, 2005. Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. TRENDS in Ecology and Evolution. 20(7), pp. 387-394

Chuvieco Emilio, Mouillot Florent, Guido R. van der Werf, San MigueldJesús, Tanase Mihai, Koutsias Nikos, García Mariano, Yebra Marta, Padilla Marc, Gitas Ioannis, Heil Angelika, Hawbaker J.Todd, Giglio Louis , 2019. Historical background and current developments for mapping burned area from satellite Earth observation. Remote Sensing of Environment 225, pp. 45–64.

Dansereau Pierre-Rene and Bergeron Yves, 1992. Fire history in the southern boreal forest of northwest Quebec. Canadian Journal of Forest Research. 23, pp. 25-32.

Davies Matt and Legg Colin, 2011. Fuel moisture thresholds in the flammability of Calluna vulgaris. Fire Technology.47, pp. 421-436. (doi: 10.1007/s10694-010-0162-0)

Drobyshev Igor, Granstrom Anders, Linderholm W. Hans, Hellberg Erik, Bergeron Yves and Mats Niklasson, 2014. Multi-century reconstruction of fire activity in Northern European boreal forest suggests differences in regional fire regimes and their sensitivity to climate. Journal of Ecology, 102, pp. 738–748. doi: 10.1111/1365-2745.12235.

Drobyshev Igor, Niklassona Mats, Linderholm W. Hans, 2012. Forest fire activity in Sweden: Climatic controls and geographical patterns in 20th century. Agricultural and Forest Meteorology, 154-155, pp. 174-186. doi:10.1016/j.agrformet.2011.11.002.

Esseen Per-Anders, Ehnström Bengt, Ericson Lars and Sjöberg Kjell, 1997. Boreal Ecosystems and Landscapes: Structures, Processes and Conservation of Biodiversity. Ecological Bulletins, 46, pp. 16-47

Falk A. Donald, Miller Carol, McKenzie Donald and Black E. Anne, 2007. Cross-Scale Analysis of Fire Regimes. Ecosystems, 10, pp. 809-823. doi: 10.1007/s10021-007-9070-7.

Flannigan Mike, Stocks Brian, Turetsky Merritt and Wotton Mike, 2009. Impacts of climate change on fire activity and fire management in the circumboreal forest. Global Change Biology. 15, pp. 549–560.

Florida Department of Agriculture and Consumer Services (FDACS), 2014. *Fire Behavior* [online] Available at: www.freshfromflorida.com/content/download/39685/866712/PFT_Chapter_07_Fire_ Behavior. pdf [Accessed 15 February 2017]

Foster R. David, 1983. The history and pattern of fire in the boreal forest of southeastern Labrador. Canadian Journal of Botany. 61, pp. 2459-2471

Girardin P. Martin, Ali A. Adam, Carcaillet Christopher, Gauthier Sylvie, Hély Christelle, Le Goff Héloïse, Terrier Aurélie, Bergeron Yves, 2013. Fire in managed forests of eastern Canada: Risks and options. Forest Ecology and Management, 294, pp. 238-249. doi:10.1016/j.foreco.2012.07.005.

Granström Anders, 1993. Spatial and Temporal Variation in Lightning Ignitions in Sweden. Journal of Vegetation Science. 4(6), pp. 737-744.

Granström Anders, 2001. Fire management for biodiversity in the European boreal forest. Scandinavian Journal of Forest Research. 3, pp. 62-69.

Granström Anders and Niklasson Mats, 2008. Potentials and limitations for human control over historic fire regimes in the boreal forest. Philosophical Transactions of the Royal Society B. 363, pp. 2353-2358. doi:10.1098/rstb.2007.2205.

Gonsamo, A., J. M. Chen, S. J. Colombo, M. T. Ter-Mikaelian, and J. Chen, 2017. Global change induced biomass growth offsets carbon released via increased forest fire and respiration of the central Canadian boreal forest. Journal of Geophysical Research: Biogeosciences, 122, 1275–1293, (doi:10.1002/2016JG003627).

Gustafsson Lena, Berglind Mårten, Granström Anders, Grelle Achim, Isacsson Gunnar, Kjellander Petter, Larsson Sören, Lindh Magnus, Pettersson B. Lars, Strengbom Joachim, Stridh Bengt, Sävström Tom, Thor Göran, Wikars Lars-Ove and Mikusiński Grzegorz, 2019, Rapid ecological response and intensified knowledge accumulation following a north European mega-fire. Scandinavian Journal of Forest Research. 34(4), pp. 234–253. (doi: 10.1080/02827581.2019.1603323)

Hederskog Martin, 2018, Är uteblivna bränder i skogslandskapet en bidragande orsak till igenväxning av myrmarker?, Master Thesis, Sveriges Lantbruksuniversitet, Umeå.

Hellberg Erik, Niklasson Mats and Granström Anders, 2004. Influence of landscape structure on patterns of forest fires in boreal forest landscapes in Sweden. Canadian Journal of Forest Research. 34, pp. 332–338.

Jacob, D. J., Crawford, J. H., Maring, H., Clarke, A. D., Dibb, J. E., Emmons, L. K., Ferrare, R. A., Hostetler, C. A., Russell, P. B., Singh, H. B., Thompson, A. M., Shaw, G. E., McCauley, E., Pederson, J. R., and Fisher, J. A., 2010. The Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) mission: design, execution, and first results, Atmos. Chem. Atmospheric Chemistry and Physics 10, 5191–5212.

Jenkins Michael, 2008. *Wildland Fire Management and Planning*. WILD4520 - Wildland Fire Management and Planning. Utah State University. Available at: http://ocw.usu.edu/Forest__Range__and_Wildlife_Sciences/Wildland_Fire_Management_and_Planning/Schedule.html [Accessed 06 June 2016]

Johnson Edward and Miyanishi Kiyoko 2001. Strengthening fire ecology's roots. In: Johnson Edward and Miyanishi Kiyoko ed. Forest fires – Behavior and ecological effects. USA: Academic Press, pp. 1-9.

Keane E. Robert, 2016. Spatiotemporal Variability of Wildland Fuels in US Northern Rocky Mountain Forests. Forests. 7, 129.

Kellner Erik, 2003, Wetlands – different types, their properties and functions TR-04-08. SKB. Available at: https://www.skb.com/publication/21624 [Accessed 06 February 2021]

Kungl. Skogs- och Lantbruksakademien (KSLA), 2017. *Forest and Forestry in Sweden*. [pdf] Available at: < http://www.ksla.se/wp-content/uploads/2015/08/Forests-and-Forestry-in-Sweden_2015.pdf> [Accessed 17 January 2017].

Lavoie N., Alexander M.E., and Macdonald S.E. 2010. Photo guide for quantitatively assessing the characteristics of forest fuels in a jack pine – black spruce chronosequence in the Northwest Territories. [pdf] Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, AB. Available at: < http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/31785.pdf> [Accessed 15 March 2017]

Lidskog Rolf and Sjödin Daniel, 2016. Extreme events and climate change: the post disaster dynamics of forest fires and forest storms in Sweden. Scandinavian Journal of Forest Research. 31(2), pp. 148-155. (doi:10.1080/02827581.2015.1113308).

Lukenbach C. M., Devito J. K., Kettridge N., Petrone M. R. and Waddington M. J., 2015. Hydrogeological controls on post-fire moss recovery in peatlands. Journal of Hydrology. 530, pp. 405–418. (doi: dx.doi.org/10.1016/j.jhydrol.2015.09.075).

Loudermilk E. Louise, O'Brien J. Joseph, Mitchell J. Robert, Cropper P. Wendell, Jr, Hiers J. Kevin, Grunwald Sabine, Grego John and Fernandez-Diaz C.Juan., 2012. Linking complex forest fuel structure and fire behavior at fine scales. International Journal of Wildland Fire, 21, pp. 882–893.

Magnan Gabriel, Lavoie Martin, Payette Serge, 2011. Impact of fire on long-term vegetation dynamics of ombrotrophic peatlands in northwestern Québec, Canada. Quaternary Research. 77 (2012), pp. 110-121.

Malmer Nils, 1965. The Southern Mires. In: The Swedish Phytogeographical Society, ed. 1965. The plant cover of Sweden. Uppsala: The Swedish Phytogeographical Society. pp. 150-158.

Miyanishi Kiyoko 2001. Duff Consumbtion. In: Johnson Edward and Miyanishi Kiyoko ed. Forest fires – Behavior and ecological effects. USA: Academic Press, pp. 437-475.

Myndigheten för samhällsskydd och beredskap (MSB), 2015. Obsärvatorsrapport Skogsbranden i Västmanland 2014.(ISBN: 978-91-7383-527-5)

Niklasson Mats and Granström Anders, 2000. Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape. Ecology. 81(6), 1484-1499

Niklasson Mats and Granström Anders, 2004. Fire in Sweden – History, Research, Prescribed Burning and Forest Certification. International Forest Fire News, [online] Available at: <http://www.fire.uni-freiburg.de/iffn/iffn_30/17-IFFN-30-Sweden.pdf> [Accessed 15 April 2016].

Nilsson, B., Tyboni, M., Pettersson, A., Granström, A., Olsson, H. 2014. Punktgittertolkning av brandområdet i Västmanland. Redovisning av uppdrag från Skogsstyrelsen. Arbetsrapport 433. SLU, Institutionen för skoglig resurshushållning [online] Available at: <https://www.skogsstyrelsen.se/globalassets/mediaflowpro/bilder-mer-om-skog/bilder-skogsbranden-i-vastmanland/punktgittertolkning-av-brandomradet-i-vastmanland.pdf> [Accessed 07 May 2020].

Osborne Z. Todd, Kobziar N. Leda and Inglett W. Patrick, 2013. Fire and Water: New perspectives on fire’s role in shaping wetland ecosystems. Fire Ecology. 9(1), pp. 1-5. (doi: 10.4996/fireecology.0901001).

Ottmar D. Roger, Sandberg V. David, Prichard J. Susan and Riccardi L. Cynthia., n.d. Fuel characteristic classification system. [omline] Available at: < https://ams.confex.com/ams/pdfpapers/67236.pdf > [Accessed 15 March 2017]

Pausas Juli and Keeley Jon, 2009. A Burning Story: The Role of Fire in the History of Life. BioScience. 59(7), pp. 593-601.

Rolstad Jorund, Blanck Ylva-Li and Storaunet Olaf Ken, 2017. Fire history in a western Fennoscandian boreal forest as influenced by human land use and climate. Ecological Monographs. 0(0), pp. 1–27.

Ronkainen Tiina, Väliranta Minna and Tuittila Eeva-Stiina, 2013. Fire pattern in a drainage-affected boreal bog. Boreal Environment Research. 18, pp. 309-316.

Rydin Hakan, Sjors Hugo and Lofroth Michael., 1999. Mires. In: Rydin Hakan, Snoeijs Pauli and Diekmann Martin, ed. 1999. Swedish plant geography. Svenska Växtgeografiska Sällskapet, Uppsala. pp. 91-112.

Saito K. 2001. Flames. In: Johnson Edward and Miyanishi Kiyoko ed. Forest fires – Behavior and ecological effects. USA: Academic Press, pp. 11-54.

Sannikov S.N. and Goldammer J.G., 1996. Fire Ecology of Pine Forests of Northern Eurasia. In: Goldammer G. Johann and Furyaev V. Valentin, ed. 1996. *Fire in Ecosystems of Boreal Eurasia*. Springer-Science & Business Media, B.Y. pp.1-20

Schimmel Johnny and Granström Anders, 1997. Fuel succession and fire behavior in the Swedish boreal forest. Canadian Journal of Forest Research 27(8), pp. 1207-1216

Segerström Ulf and Emanuelsson Marie, 2002. Extensive forest grazing and hay-making on mires – vegetation changes in south-central Sweden due to land use since Medieval times. Vegetation History and Archaeobotany. 11, pp. 181-190.

Sillasoo Ulle, Väliranta Minna and Stiina Eeva, 2011. Fire history and vegetation recovery in two raised bogs at the Baltic Sea. Journal of Vegetation Science. 22 (2011), pp. 1084-1093.

Sweden's meteorological and hydrological institute (SMHI), 2016. Meteorological data for Sala meteorological station (1995 – 2016). [online] Available through: <www.smhi.se> [Accessed 01 Oktober 2019]

Swedish Forest Agency (SFA), 2014, Skoglig statistik för branden i Västmanland [pdf] Available at: http://www.skogsstyrelsen.se/Global/aga-och-bruka/Skogsbruk /Skador%20p%C3%A5%20skog /Brandskador/Skoglig_statistik_branden_V%C3%A4stmanland_version_1.0_2014-12-12.pdf [Accessed 30 March 2016]

Tack Ayco, 2015. Generalized linear models, Advanced Biostatistical Methods. Stockholm University, unpublished.

Tishkov A. Arkady, 2010. *Natural Disasters – Volume II*. [pdf] Encyclopedia of life support systems (EOLSS) – UNESCO. Available at: <http://www.eolss.net/sample-chapters/c01/E4-06-02-10.pdf> [Accessed 18 April 2016].

Volokitina A. V., 1996. Forest fuel maps. In: Goldammer G. Johann and Furyaev V. Valentin, ed. 1996. *Fire in Ecosystems of Boreal Eurasia*. Springer-Science & Business Media, B.Y. pp.239-252

Ward Darold 2001. Combustion Chemistry and Smoke. In: Johnson Edward and Miyanishi Kiyoko ed. Forest fires – Behavior and ecological effects. USA: Academic Press, pp. 56-77.

Winder Monika, 2015. Correlation and regression, BL8002 Biological Statistics and Experimental Design. Stockholm University, unpublished.

Dataset

Swedish department of Land survey (Lantmateriet) (2015). Property Map (Fastighetskarta)

Swedish department of Land survey (Lantmateriet) (2015). Vegetation Map (GSD-Vegetationsdata)

Swedish department of Land survey (Lantmateriet) (2016), Aerial Photos: “Pan sharpened" IRF images produced by Lantmäteriets regular supply of quality used (8 bit radiometric resolution). All images are photographed by the National Land Survey with a digital camera (Vexcel UltraCam Eagle) from about 3700 m (above ground), which gives an approximate ground resolution of 25 cm (image scale about 1:35 500). The pre-fire aerial photos are photographed at various times in spring / early summer 2014. The post-fire aerial photos are photographed August 16.

Swedish department of Land survey (Lantmateriet) (2016). Terrain Map (Terrängkartan)
Swedish Environmental Protection Agency (Naturvårdsverket) (2009). Land Cover Map (Naturtypkartering – KNAS6)

Computer software

ArcGIS 10.3.1 for desktop (2015). USA: Environmental Systems Research Institute, Inc. (ESRI).
ENVI 5.0 (2015). USA: Harris Corporation
Microsoft Office (2016). USA: Microsoft
Microsoft Excel (2016). USA: Microsoft
R Development Core Team (2008). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria
Summit Evolution (2012). USA:DAT/EM Systems International.

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Last but not the least; I would like to thank my wife Maria for her care and understanding.

Appendix 1

Field survey protocol form

Sampling point:		Type:	Hummock		Open water		Pine bog		Lågstarr		Wet lawn		Black surface		
Coordinates:			Other:												
Data-time:		Total Cover	Moss		Vascular		Shrubs		Trees		Water				
Photos Number:			Other												

V. Hight ______ Fuel ______

Burnt (%) ______ Severity ______

General Description:

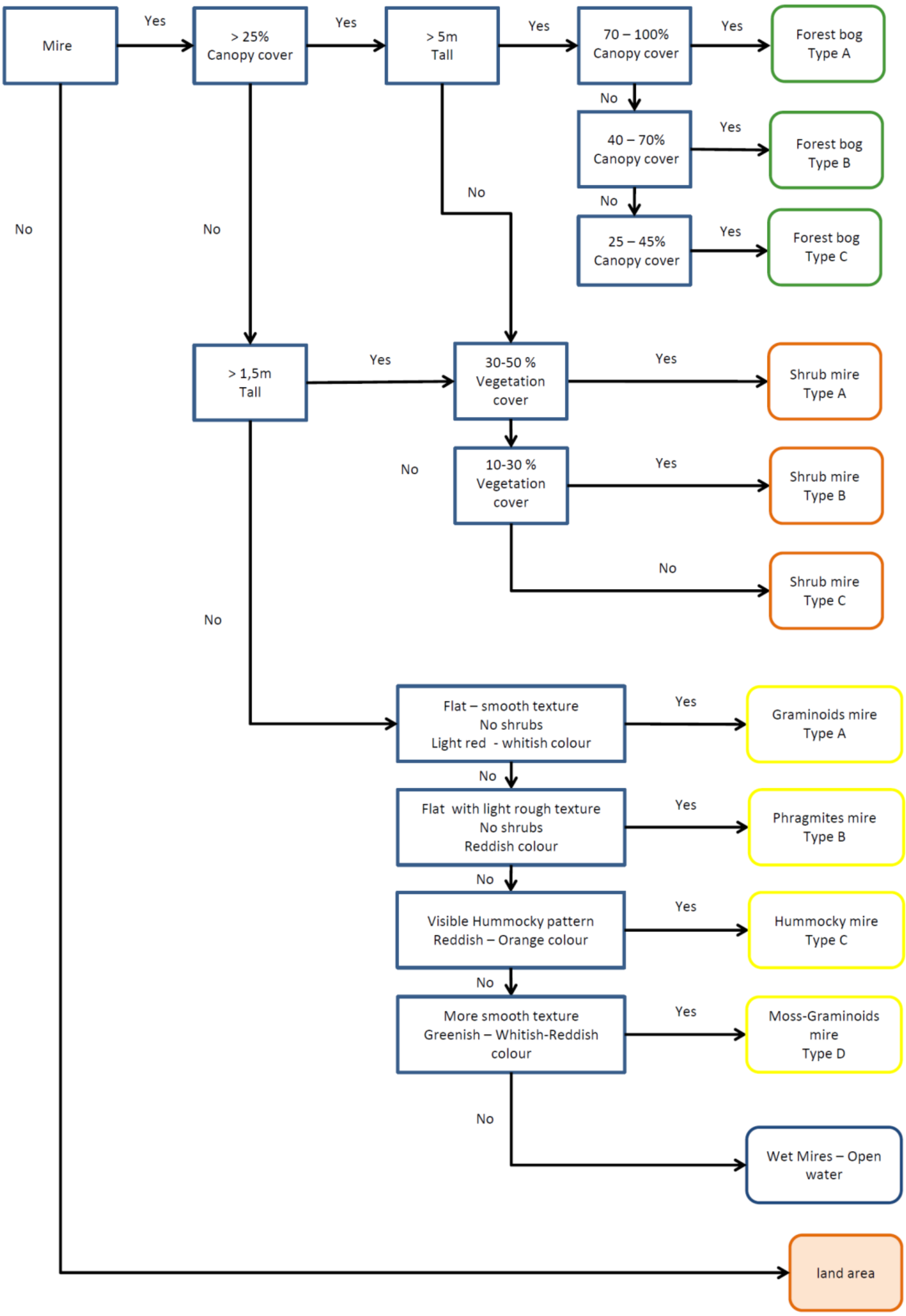
Species	Plot		Quadrat 1		Quadrat 2		Quadrat 3	
	exist	%	exist	%	exist	%	exist	%
1.								
2.								
3.								
4.								
5.								
6.								
7.								
8.								
9.								
10.								
11.								
12.								
13.								
14.								
15.								

Notes:

Appendix 2

Aerial photos vegetation-interpretation key

Aerial Photo Stereo Interpretation Vegetation Key

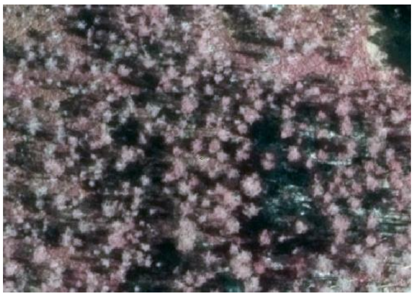


Appendix 3

Aerial photo interpretation calibration key

Vegetation types Classification

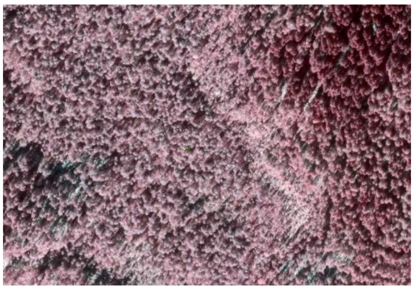
Pine bog types




Trees Cover: 60-80%

Tree Height: 5-7m

Shrub Cover: 60-70%




Trees Cover: 45-55%

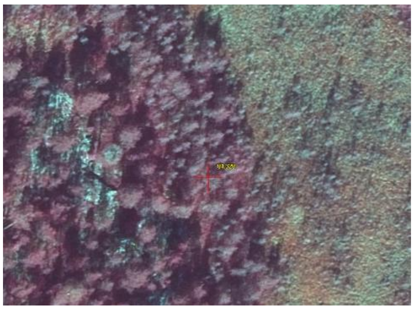
Tree Height: 9-12m

Shrub Cover: 60-70%


Trees Cover: 30-40%

Tree Height: 4-6m

Shrub Cover: 45-55%




Trees Cover: 30-40%

Tree Height: 10m

Shrub Cover: 50-60%


Trees Cover: 25-35%

Tree Height: 6-8m

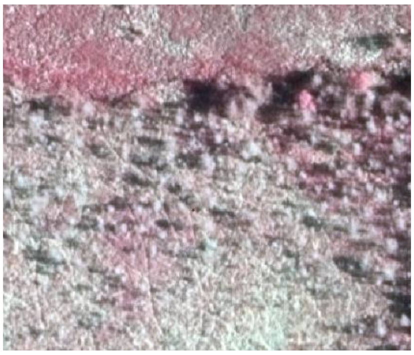
Shrub Cover: 50-60%

Shrub mire types

Trees Cover:
40-60%

Tree Height:
0,5-3m

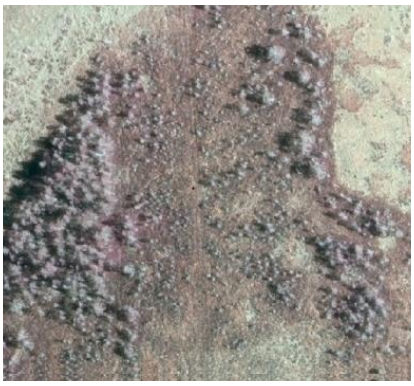
Shrub Cover:
50-70%



Trees Cover:
10-30%

Tree Height:
2-3m

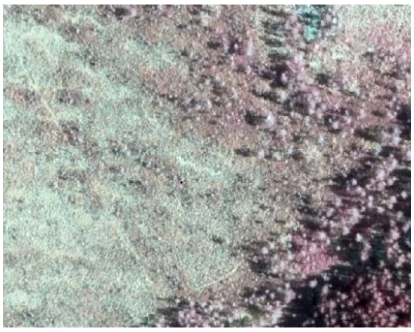
Shrub Cover:
50-70%



Trees Cover:
10-20%

Tree Height:
0,5-3m

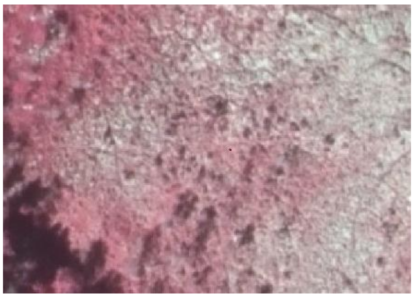
Shrub Cover:
70-80%



Trees Cover:
5-10%

Tree Height:
0,5-1,5m

Shrub Cover:
50-60%

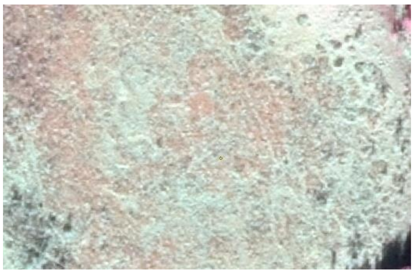


Trees Cover:
2-6%

Tree Height:
0,5-1,5m

Shrub Cover:
50-60%

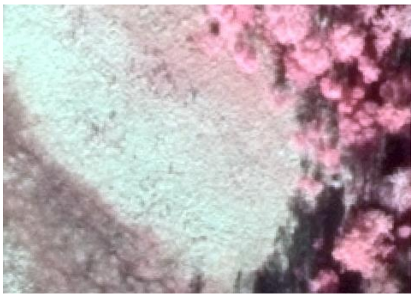
Open mire types



Moss Cover:
90-100%

Sedge:
20%

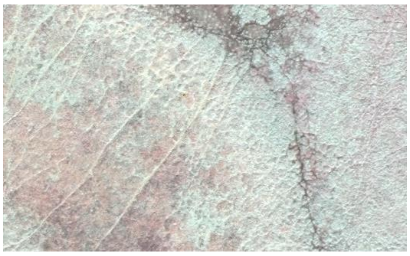
Small Shrubs:
25%



Moss Cover:
90-100%

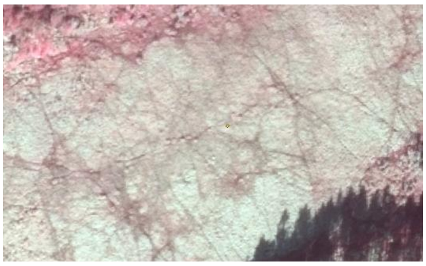
Sedge:
%

Small Shrubs:
25 - 30%



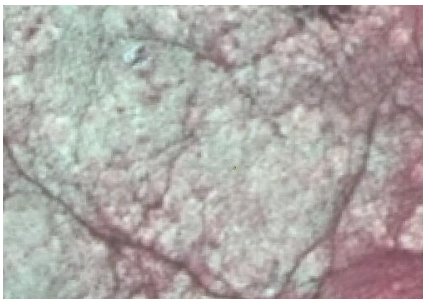
Moss Cover:
90-100%
Hummock
Sedge:
10%

Small Shrubs:
15 %



Moss Cover:
100%
Flat with
Carex
Sedge:
10%

Small Shrubs:
5 %



Moss Cover:
85%
Flat reed
Phragmites
3D texture
Sedge:
8-10%

Small Shrubs:
40 %

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2021:14	Författare: Maria Grånemo "I stand here. I will not move" – Women in forestry in northern Sweden during the 20th century
2021:15	Författare: Tim Schacherl Evaluating Drought Impacts on Ecosystem Water Use Efficiency of Three Different Boreal Forest Sites
2022:01	Författare: Alice Cosatti The end of the timber frontier in northern Sweden – Early logging, natural forests and the frontier concept
2022:02	Författare: Pontus Nyqvist Utvärdering av metod för att morfologiskt särskilja björkarterna Betula pendula och Betula pubescens
2022:03	Författare: Julia Nygårdh Mosippans (Pulsatilla vernalis L.) reaktion på brandstörning – En populationsstudie på en av Sveriges rikaste mosippslokaler
2022:04	Författare: Oskar Karlsson Effects on natural seed regenerated Silver birch (Betula pendula Roth) and Downey birch (Betula pubescens Ehrh) by mechanical soil scarification and environmental factors
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2022:06	Författare: Louise Nordström Growth and development of Eucalyptus grandis seedlings in response to arginine phosphate application
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