Effects of fuel and weather conditions on forest fire behaviour in Southern Sweden in oak dominated forests

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Effects of fuel and weather conditions on forest fire behaviour in Southern Sweden in oak dominated forests

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Keywords: Forest fire, forest fuel, fire weather, ignition experiments, prescribed burning

Swedish University of Agricultural Sciences
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Abstract

Fire activity is influenced by weather and climate, fuels, ignition agents, and human activities. Fire suppression policy in Sweden resulted in a gradual decrease in the annually burnt areas, changes in fuel loads and a decline in species diversity. Prescribed burning is recommended as a management tool for fire-prone ecosystems to support conservation policies and, eventually, mitigate large high-intensity wildfires.

This study analysed fire behaviour as a function of fuel characteristics and weather conditions in oak dominated forests in Southern Sweden. I was specifically interested in thresholds indicative of accelerated fire spread and conditions leading to increased consumption of ground fuels. I also studied whether regional weather indices provide predictive power with respect to local fire behaviour. Data from 105 ignition experiments at seven study sites laid the ground for the database used in analyses. Data collection involved the collection of meteorological on-site data, pre- and post-fire fuel inventories, and measurements of fire behaviour.

The minimum wind above 2.5 m/s and the temperature above 15°C positively affected fire spread. High relative humidity and the low amount of dry fuel had a negative effect on fire spread. The fire spread slowed down when the value of relative humidity exceeded 35 % and the fuel amount dropped below 1000 g/m^2. Fire spread slowed down when the relative humidity exceeded 40 %, and litter depth fell below 0.05 m. Total fuel consumption grew when the fuel amount exceeded 3000 g/m^2 and the fire spread rate fell below 0.05 m/s. Fuel amount and relative humidity affected total consumption. Total consumption grew when the fuel amount exceeded 1800 g/m^2, while the relative humidity fell below 30 %. Regional weather indices were poor predictors of fire behaviour.

The study identifies thresholds of fire behaviour in oak dominated forests that can be used by forest managers to plan prescribed burnings. The study highlights the need for further research covering a wider gradient of weather conditions.

Keywords: forest fire, forest fuel, fire weather, ignition experiments, prescribed burning

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Abbreviations

BEHAVE	Fire Behaviour Prediction and Fuel Modelling System
DC	Drought Code
CFFDRS	Canadian Forest Fire Danger Rating System
FFMC	Fine Fuel Moisture Content
FWI	Fire Weather Index
GAM	Generalized Additive Model
PC	Principal Component
PCA	Principal Components Analysis

1. Introduction

Fire activity is influenced by weather and climate, fuels, ignition agents, and human activities (Johnson, 1992; Swetnam, 1993). In natural forests, fire activity is predominantly influenced by climatic conditions (Stocks & Lynham, 1996; Flannigan & Wotton, 2001). The climate defines periods of fire-prone weather (Stocks & Lynham, 1996; Flannigan & Wotton, 2001). Drier conditions and extended fire seasons contribute to the increase in both frequency and severity of forest fires (Pausas & Keeley, 2021).

Forest fires have been common in Swedish forests prior to the middle of the 19th century when climate variability and human activities promoted their occurrence (Niklasson & Granström, 2000; Drobyshev et al., 2012; Cogos et al., 2020). Increase in the value of timber and a more efficient agriculture led to abandonment of fire as a forestry tool (Niklasson & Granström, 2000; Cogos et al., 2020). Together with less fire prone climate in post Little Ice Age period, these developments resulted in decline in fire activity. In Sweden, forest fire activity has decreased over the course of the 18th and 20th century (Drobyshev et al., 2012). The main reason for that has been suggested to be use of the fire as an agricultural tool as well as beginning of the fire suppression policy (Granström & Niklasson, 2008).

There is an ongoing debate on whether this decline has led to changes in species composition and associated changes in fuel loads of Swedish forests. The lack of fire and intensive forest management was likely responsible for an increase in the amount of fire-sensitive spruce and decline in fire adapted pine and, in southern Sweden, oak. The changes in vegetation cover influenced the type and abundance of forest fuels. In a majority of situations, the fuel loads in the Swedish forests have increased and became dominated by coniferous fuels. With presence of effective ignition and fire-prone weather, such fuels would favour stand replacing fires, particularly under the conditions of extreme drought. Although the modern fire activity in Scandinavia is significantly lower than that reconstructed over the 15 – 18th centuries (Niklasson & Granström, 2000), climate change may lead to increased fire activity (Flannigan et al., 2009).

Forests fire is a crucial element of the natural disturbance regime, promoting oak regeneration and biodiversity of oak dominated ecosystems (Petersson et al., 2020; Drobyshev et al., 2021; Stambaugh et al., 2022). Thick bark and resprouting abilities of oak species (Larsen & Johnson 1998) made them well adapted to low severity fires (Stambaugh et al., 2022). Oak can sprout from the roots even though the shoot is top killed by fire (Abrams, 1992; Stambaugh et al., 2022) and successfully regenerate on burned sites facing moderate and low browsing pressure (Petersson et al. 2020). Fires also create forests that provide enough sunlight for oak germination and growth (Abrams, 1992; Stambaugh et al., 2022). In southern Scandinavia, forest fires have been an important disturbance agent promoting oak regeneration (Niklasson et al., 2002, Drobyshev et al., 2021).

During recent decades, forest managers tried to bring fire back to the forest by using prescribed burnings (Faulkner et al., 1989; Brown et al., 1991; Eriksson et al., 2013; Fernandes et al., 2013; Orsolya et al., 2014). Forest management with usage of prescribed burnings addresses the need to mitigate increase in the frequency of severe wildfires (Donovan & Brown, 2007; Pausas et al., 2008). Hence, prescribed burnings may help reduce the risk of large and high-severity wildfires (Boer et al., 2009).

1.1 Forest fuels and fire behaviour

1.1.1 Forest fuels

Forest fuels control ease of ignition, fire size, and fire intensity. Fine fuels (litter, twigs, herbs, shrubs) demonstrate relative ease of ignition and combustion, thus they are the primary source of energy driving the behaviour of the flame front in a forest fire (Rothermel, 1972). Accumulation and continuity of fuels in a landscape result in high severity, large fires (Ryan et al., 2013). Type of fuel defines fire intensity. Fine fuels promote rapid fire spread, while logs, fuels creating deep duff or canopy foliage create hot, intense fires (Keane, 2014).

Quantity and composition of fuel are the only factors of fire risks that could be modified as a part of forest management. Fuel management is a critical component of long-term fire management strategies aimed at reducing the risks and severity of wildfires (Pyne et al., 1996). Fuel management often involves reducing of fuel loads, changing their composition by increasing a fraction of less burnable fuels, and rearranging fuel loads in space to reduce their spatial continuity (Grote, 2009; Keane, 2014). The amount of available fuel, weather conditions and landform greatly affect energy release from fire and, ultimately, the possibility to suppress it (Pyne et al., 1996).

The fraction of the total fuel that is available for the fire is defined by weather, especially by relative humidity, wind, and drought (Ryan, 2002). Water content of fine fuel fractions is particularly important in controlling effectiveness of ignitions and fire spread. In the boreal and hemi-boreal forests, such fractions are composed of mosses, lichens, loose litter, foliage, and fine twigs. Short-term weather (hours to days) defines dynamics of water content in these fuels (Albini, 1976; Stocks et al., 1989). In turn, weather variability at the scale of weeks and months control moisture content and the possibility of combustion in the organic layers and surface logs (Stocks et al. 1989).

There is a knowledge gap in fuel management in Europe. Properties of coniferous fuels in boreal forests were researched (Ryan, 2002). However, the properties of deciduous fuels and interactions among them in Swedish forests are not well known.

1.1.2 Fire behaviour

Fire behaviour can be defined as the manner in how fuel ignites, flames are developed and fire spreads (Countryman, 1971). Rate of spread, flame geometry, and fireline intensity are usually used to describe fire behaviour (Tanskaknen et al., 2007). The goal of predicting fire behaviour is to assess what a fire will do (Pyne et al., 1996). Predicting fire behaviour can be done by using weather and fuel type-based indices such as the Canadian Forest Fire Danger Rating System (CFFDRS) (Van Wagner, 1987; Stocks et al., 1989) or the Fire Behaviour Prediction and Fuel Modelling System (BEHAVE) (Andrews, 1986). For example, the Canadian Fire Weather Index (FWI) has become a standard index to estimate fire danger conditions correlated to the weather in Europe (Fujioka, 2008). Hence, understanding if these indices predict fire behaviour on a local scale is important for fire management.

The rate of fire spread varies due to changing conditions, so the given number means an average value over a period of time (Pyne et al., 1996). The type, structure, and moisture content of fuels (Fosberg et al., 1970), as well as topography and wind (Rothermel, 1972), determine fire spread rate and flame characteristics. Fine dead fuel has the strongest effect on the spread rate of a surface fire (Pyne et al., 1996). Broadleaved stands produce slower fires than coniferous stands (Heisig, 2022).

1.2 Objectives of the thesis

The thesis analyses fire behaviour as a function of fuel properties and weather conditions to discover thresholds which make fire severe as well as to support the use of prescribed fires for forest management and biodiversity conservation. Fire temperature was analysed to find out which temperatures, and for how long appear during low-intensity fires. Observing what is the most common temperature and duration defines an impact of the temperature on the spot in microscale.

The specific objectives were:

1. To create a model that will show the effect of fuel and weather conditions on fire characteristics. Building such a model will help finding thresholds for safe yet efficient controlled burns.
2. To find out if there is a correlation between regional weather indices and fire behaviour on a local scale.

I tested the following hypotheses:

1. Litter depth in oak dominated forests should be negatively correlated with fire spread. The duff layer can act as an effective barrier for the heat transfer to the mineral soil at the time of surface fire (Pyne et al., 1996). Deciduous litter has high moisture content and is less prone to fire than coniferous litter (Wotton et al., 2007) which should result in slower fire spread rate.
2. The total fuel consumption negatively correlates with fire spread rate. Fire needs to be present longer in one spot to preheat fuels, hence larger amount of fuels should slow the fire spread rate.
3. Regional fire weather indices do not predict fire behaviour on a local scale. These indices provide a broad overview of fire-prone conditions in a larger area. However, fire behaviour is influenced by various local factors such as fuel particle properties and microclimate, which are not included in the calculations of indices (Rothermel, 1972).

2. Study area

I conducted the study in four locations in southern Sweden. Study areas were chosen based on covering the difference in fuel composition and fuel amount. The locations were in the nemoral and boreo-nemoral vegetation zones (Sjörs, 1963). The locations were Skarhult (Eslöv Municipality, nemoral), Ekenäs (Nybro Municipality), Sandvik (Nybro Municipality), and Åby säteri (Sotenäs Municipality, all boreo-nemoral).

In Eslöv municipality, the mean annual temperature is 8.5°C and annual precipitation is 669 mm. In Nybro municipality, the mean annual temperature is 7.7°C and annual precipitation is 488 mm. In Sotenäs municipality, the mean annual temperature is 7.1°C and annual precipitation is 686 mm (Figure 1) (Climate Change Knowledge Portal, 2021).

The experiments included seven different forest stands (Table 1). Species composition in the forest tree layer was dominated by pedunculate oak (*Quercus robur* L.) in oak dominated stands, silver birch (*Betula pendula* Roth) in the birch dominated stand, and European beech (*Fagus sylvatica* L.) in the beech dominated stand.

Table 1. Stand description.

Stand Name	Stand Type	Standing Volume (m^3/ha)	Stand Age (years)	Soil Type
Ekenäs (1)	oak dominated mixed	333	Uneven	sandy moraine
Sandvik (2)	oak dominated stand	198	Uneven	primeval rock
Åby säteri (3)	birch dominated stand	95	23	clay loam
Åby säteri (4)	oak dominated stand	187	50	moraine
Skarhult (5)	beech dominated stand	269	74	sandy loam
Skarhult (6)	oak dominated mixed	290	49	clay loam
Skarhult (7)	oak dominated	149	60	sandy loam

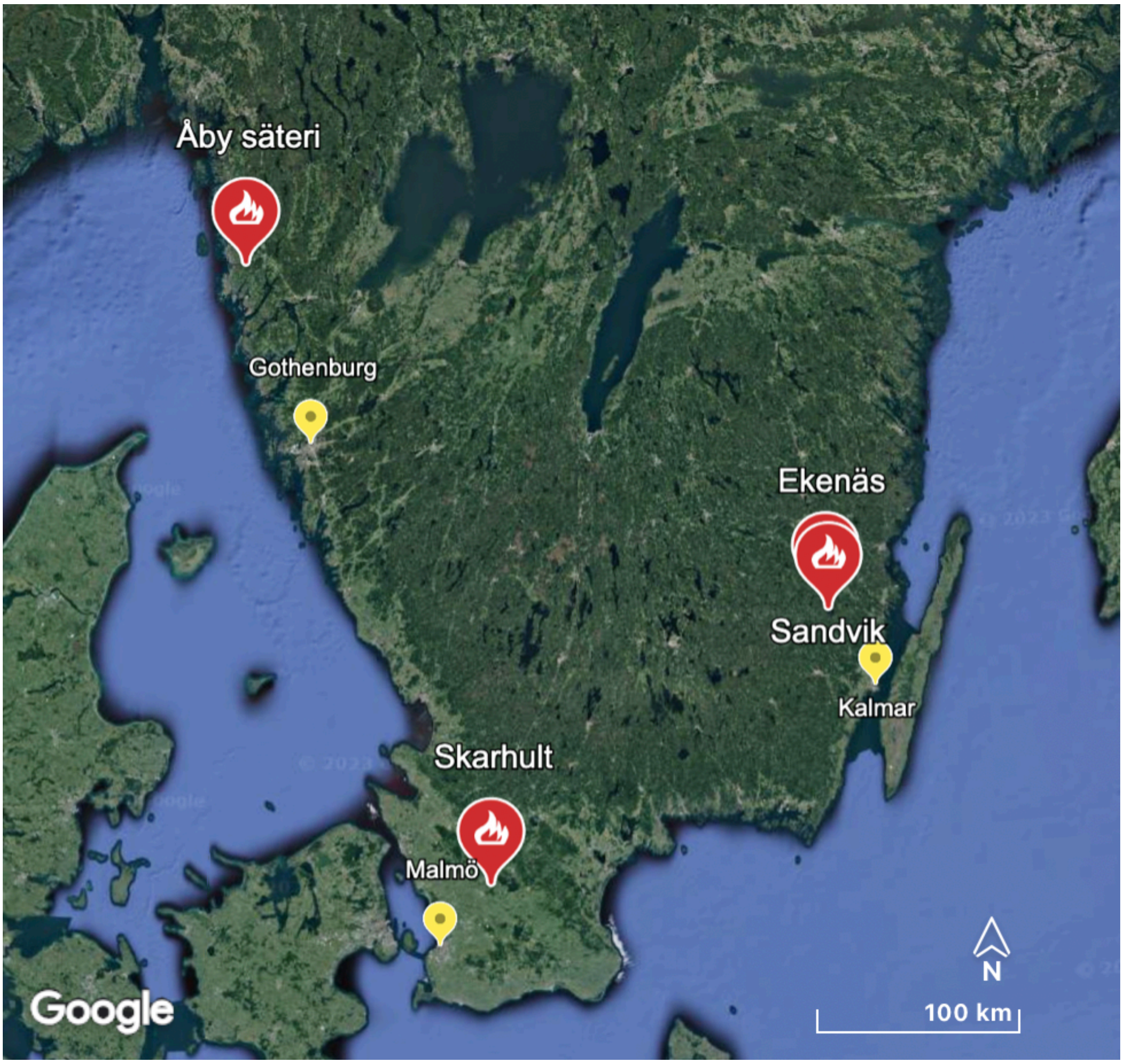

Figure 1. Location of the study areas in southern Sweden.

2.1 Experimental plot design and pre-ignition measurements

The overall layout of experimental plots was inspired by field studies made in Sweden (Schimmel & Granström, 1997), Finland (Tanskanen et al., 2007), and Canada (Alexander & Quintilio, 1990), and adjusted for the scale and research questions of this project (Figure 2). The plots were chosen with the most homogenous fuel possible. The size of the plot was 2 m wide and 5 m long with an additional 1 m wide safety belt with removed vegetation to the bare mineral soil. The safety belt was watered to ensure the safety of the experiment. Six - 1m tall metal rods were placed on the centre line of each burning plot to enable within-plot observations of the fire spread and flame heights. The metal rods had height markings every 20 cm and were put in a straight line with 1 m spacing. The first metal rod on the plot marked the ignition line and the beginning of the plot. The plot position was recorded with GPS coordinates and a compass.

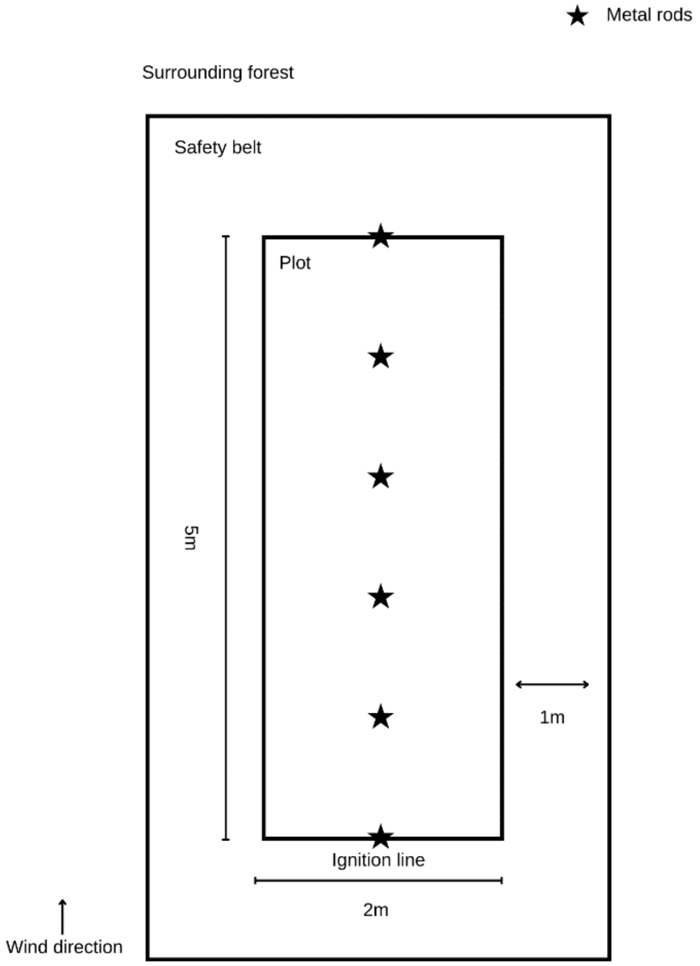

Figure 2. The design of an experimental plot.

Prior to the ignition, the thickness of the organic litter was measured in 3 random places within the plot. A sample of the amount of fuel was taken from the safety belt. The amount of fuel sample consisted of all the fuel fitting into a square size of 0.5 m x 0.5 m. It was all the organic layer that was in the square, all the way down to the mineral soil. While fuel was collected all the green vegetation, deadwood and remaining fuels were separated. The fuel type on each site was assessed visually in a percentage. A sample of fuel to assess moisture content was taken in the closest surroundings of the plot and consisted of the top duff layer of the litter containing mainly leaves. The amount of that material varied from over 30g to 150g. All the collected samples were sealed in plastic bags and weighed on the same day.

2.2 Ignition experiments and data collection

Ignition experiments were conducted in the spring of 2022 and spring of 2023. The first burning occasion took place in Åby säteri and the last in Ekenäs. There were altogether 105 sample plots made under 13 days. Each plot was ignited with the direction of the wind. Ignition was made at the edge of the plot and a line of 2 m was ignited each time as a start of the fireline. During the fire, the wind speed, humidity, and current temperature were recorded by a Kestrel wind and weather meter placed on a tripod. The temperature of the fire was recorded by a data logger at four random points within the plot (Figure 3). The fire was recorded by a phone camera from the ignition moment until the fire stopped itself or because of the plot's border. After the fire ended and there was no glowing combustion, a sample of remaining fuel was taken. The sample consisted of all the left fuel collected from a square size 0.5 m x 0.5 m, all the way down to the mineral soil.

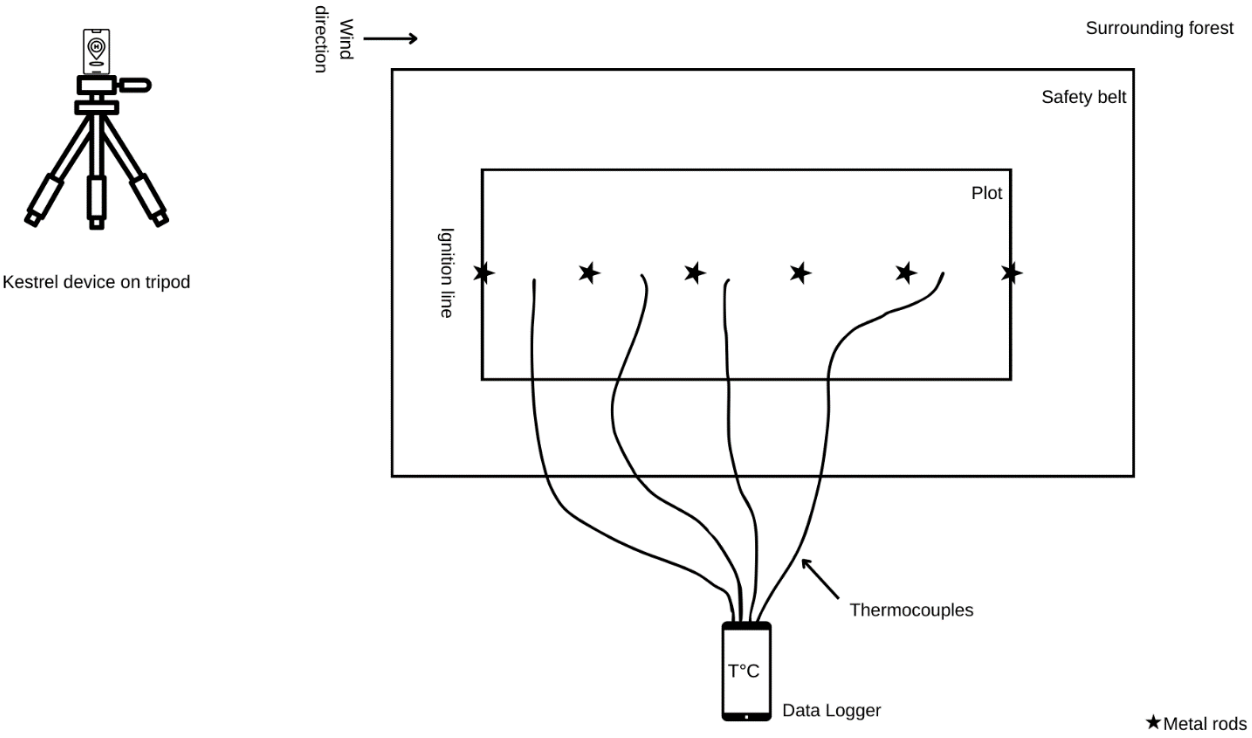

Figure 3. Placement of Kestrel and Data Logger on experimental plot.

3. Methods

3.1 Laboratory work

I separated different fuel fractions in samples collected prior to the ignition experiments. Unrecognisable parts from the fuel were put into a fraction named “other”. Duff and more compact layers of organic soil horizon were treated separately. These were dried at 105°C over the course of 12 hours. I checked changes in the samples’ weight every 12 hours until no change was observed. Samples were measured prior to and following drying. For the samples collected after the ignition experiments, no fuel fractions were separated.

3.2 Analytical approach

Data analysis was conducted using R (version 4.1.1) (R Core Team, 2021), RStudio (Posit Team, 2023), and the following packages: (1) caret (Kuhn, 2008); (2) corrplot (Wei & Simko, 2021); (3) dplyr (Wickham et al., 2023); (4) ggcorrplot (Kassambara, 2023); (5) gratia (Simpson, 2023); (6) mgcv (Wood, 2011); (7) vegan (Oksanen et al., 2022). Mean values of the amount of species were calculated considering the number of plots these species were recorded on. I wanted the mean values to accurately represent the recorded data, hence only the sites where given species were recoded. Including sites where I didn't record certain species would introduce bias and put noise to the results.

3.2.1 Principal Components Analysis (PCA)

The Principal Components Analysis (PCA) is a technique of multivariate statistics. It is used to reduce the dimensionality of data while keeping, as much as possible, variability in the covariates. PCA often reveals relationships that were not previously suspected, hence it allows interpretations that would not come up in the ordinary way (Johnson & Wichern, 2007). As a classical statistical technique, this analysis is widely used in various research fields, fire modelling included (Jiménez-Ruano et al., 2017). I used PCA to understand relationships between fuels and construct a reduced set of fuel variables. The Broken-Stick Model allowed me to determine the number of principal components that should remain in the analyses (van Buuren, 2023). I used ggcorrplot package (Kassambara, 2023) for PCA, and vegan package (Oksanen et al., 2022) for the Broken-Stick Model.

3.2.2 Generalized Additive Model (GAM)

The Generalized Additive Model (GAM) helps to describe non-linear relationships among variables. GAM offers a flexible method for identifying these variables' effects in exponential family models and other likelihood-based regression models (Hastie & Tibshirani, 1986). In my analysis, I used GAM to reach insights into the possible relationships among variables, as well as find out their significance. I did not record variations in topography across my study areas, considering them as a random factor in the analyses. With the purpose of finding out the effects of weather conditions and forest fuels on fire behaviour in oak dominated forests, I calibrated several GAM regressions for each of the tested hypotheses. The output of the model was verified with the use of a cross-validation technique. Cross-validation is a model evaluation technique that assesses how well a statistical model generalizes to an independent dataset (Berrar, 2017). I used mgcv package (Wood, 2011) for getting the GAM and caret package (Kuhn, 2008) for getting the cross-validation of GAM models.

3.2.3 Temperature data

Analyses of temperature regime was challenging because of two different scales that variables were recorded at. Temperature was recorded at the interval scale while duration – ratio scale. I put the data into subjectively designed categorical scales that allowed me to understand temperature variations in range of observed durations. I binned observed temperatures into seven temperature classes constrained by the following minimum temperatures: 60°C; 100°C; 200; 300°C; 400°C; 500°C; and 600°C. I binned the duration of temperature above a particular threshold into ten residency time classes: 1s (the initial data resolution), 3 sec, 5 sec, 10 sec, 15 sec, 20 sec, 30 sec, 60 sec, 120 sec, 160 sec. To avoid doubling the data temperatures that reached minimum temperature of certain category were assigned only to that one category. For example, temperature 150°C was assigned only to the category “minimum 100°C” to not be taken into account two times.

4. Results

4.1 Forest fuels

On average oak fuels accounted for 328g/m^2 of the total fuel amount on the sites where oak was present (Figure 4). The proportion of the fuel components varied across sampled areas (Figure 5). The average total mass of fuel prior to the fire was 1344 g/m^2. Duff was on average 75.7 g (Figure 6). Following the fires, the average mass of fuel was reduced to 652 g/m^2. Litter depth before the ignition varied from ca 2 to ca 10 cm with an average of 4.5 cm (Figure 7).

To get to know the relationships between different fuels I ran a correlation matrix (Figure 8). The correlation matrix suggests the strongest correlation between oak fuels, aspen and blueberry what describes the property of my dataset.

Following the Broken-Stick Model, I retained the first five principal components of the PCA. Oak, birch, and aspen had the highest contributions to the first principal component, and lingonberry with moss to the second principal component (Figure 9). These values are also well-represented by the PC, the cos^2 close to 1 suggested a strong association between the variable and the PC.

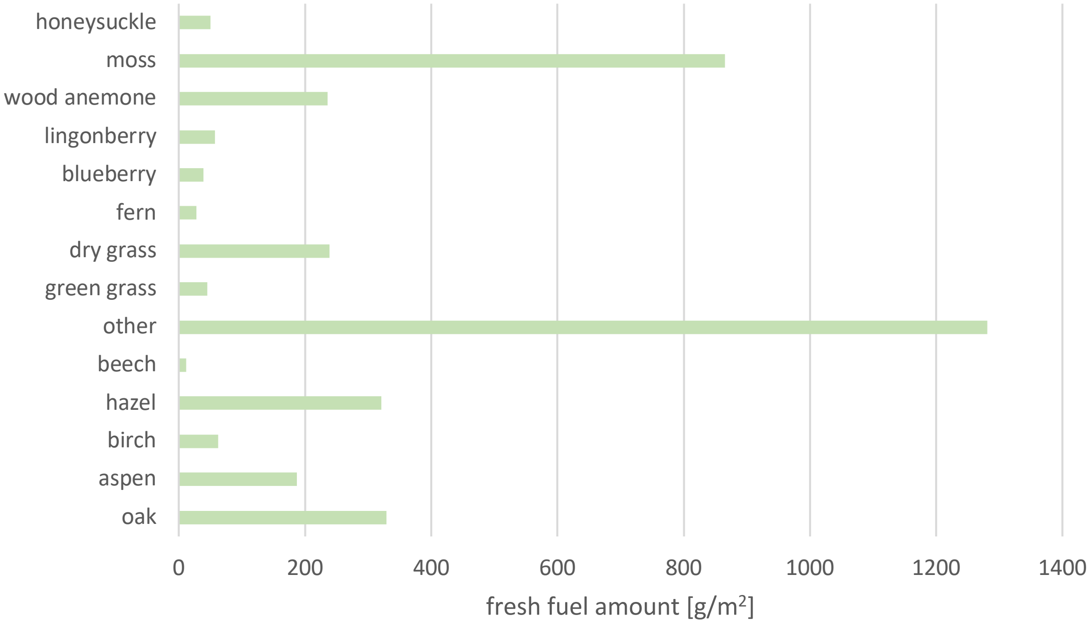

Figure 4. Mean values of fresh fuel distribution [g/m^2] on the studied sites.

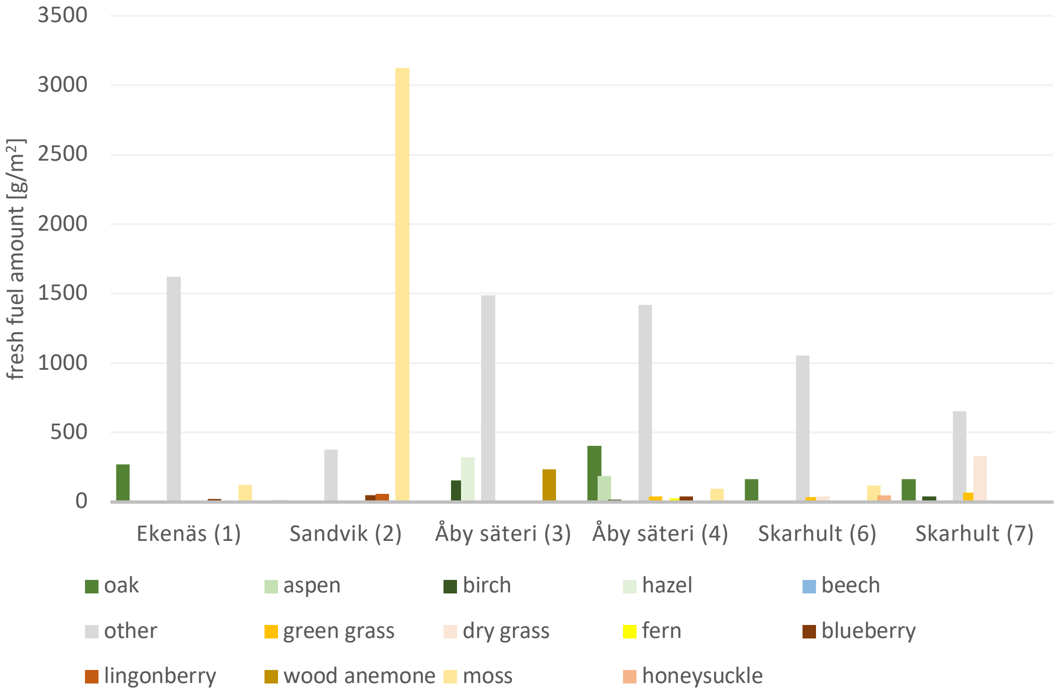

Figure 5. Fresh fuel distribution [g/m^2] across stands.

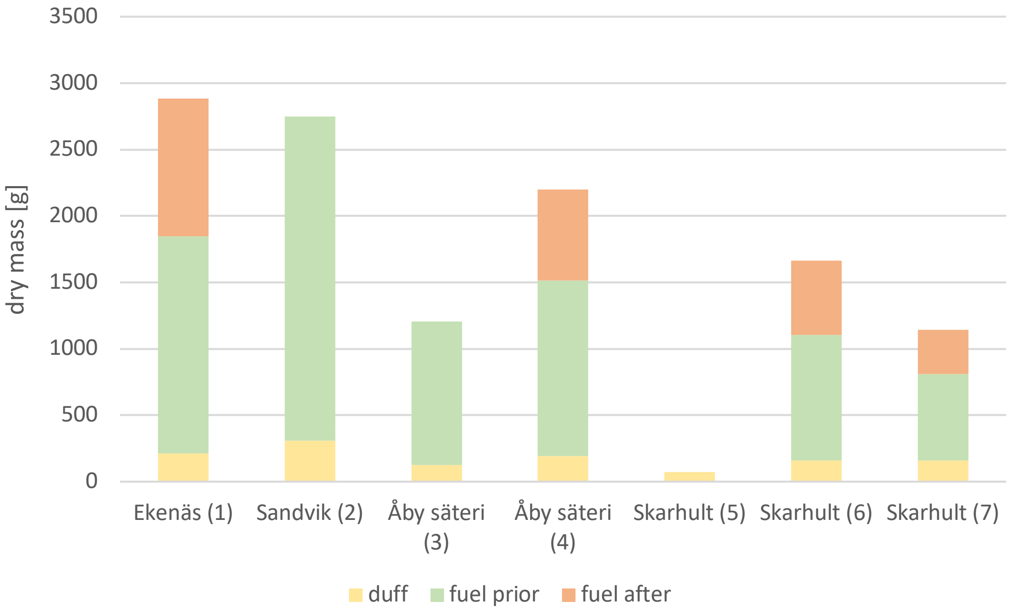

Figure 6. Sample's dry mass [g] distribution across stands. There was no fuel consumption recorded on sites (2), (3) and (5).

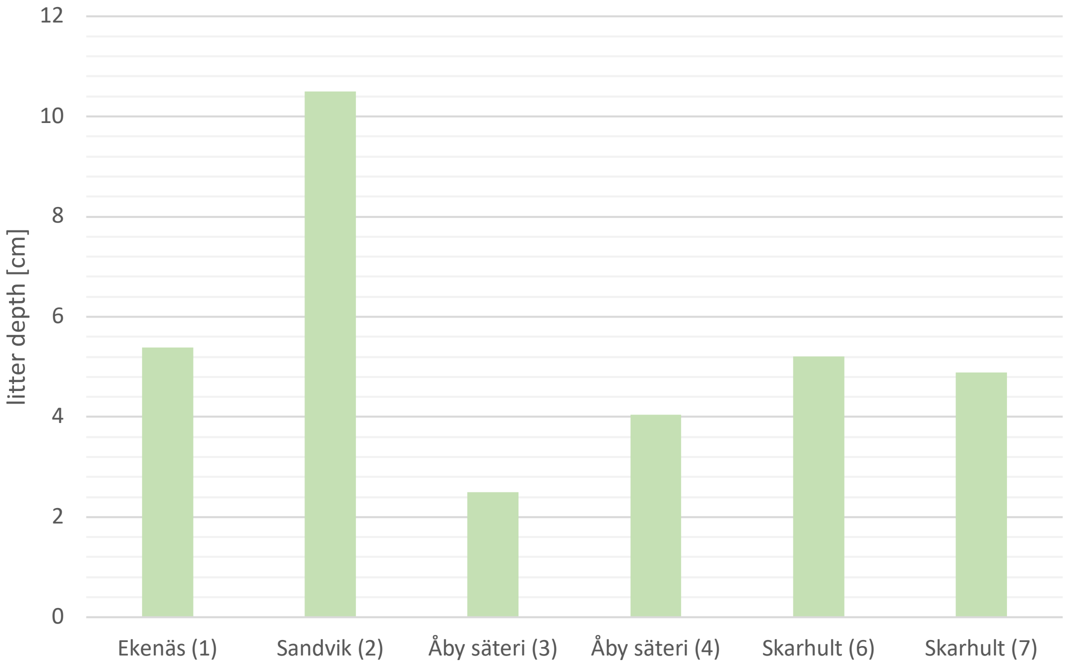

Figure 7. Average litter depth [cm] among studied locations.

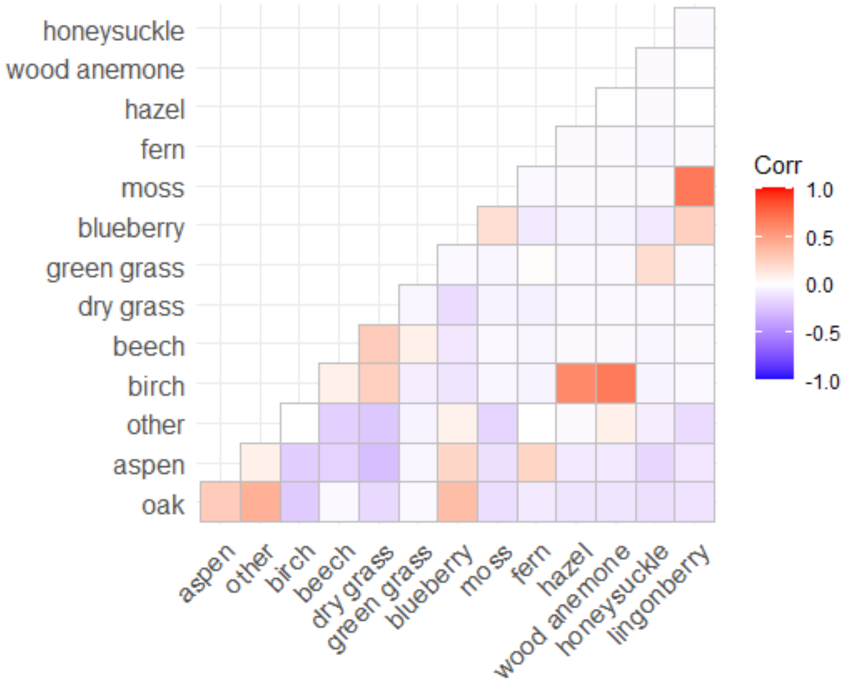

Figure 8. Correlation matrix among the amount [g] of different fuels on the ground floor of the studied stands.

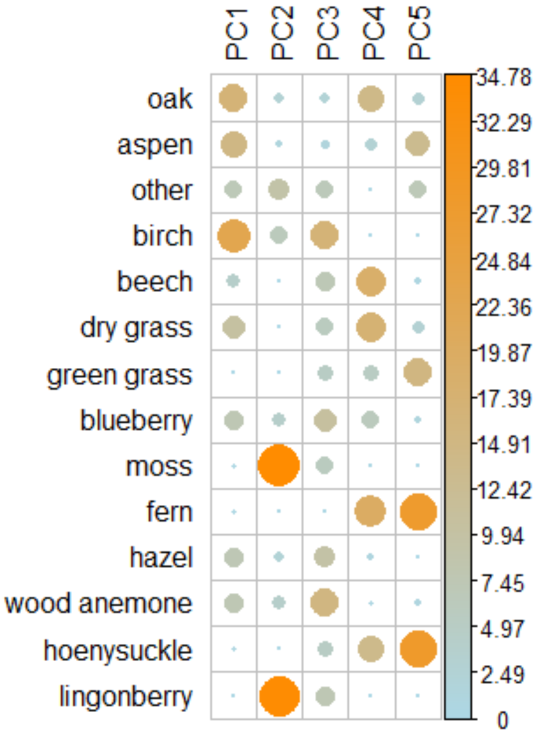

Figure 9. Contribution of each variable (fuel type) to the variance explained by each principal component.

During the ignition experiments, short-term weather was recorded (Table 2). Recorded values fit in the average spring weather conditions in southern Sweden (Yang et al., 2015).

Table 2. Short-term weather variables on the studied sites.

	Temperature [°C]	Relative Humidity [%]	Wind [m/s]
Average	15.0	35.9	1.5
Min	7.0	23.2	0
Max	27.6	81.9	36.0

4.2 Fire spread

The fire spread rates ranged from 0.0035 m/s to 0.0435 m/s. On average fire spread rate was 0.0126 m/s. According to our model, stronger wind and higher temperature have a highly significant positive impact on fire spread (Figure 10). Each point on the figure represents a data point collected on the site. Colours represent the impact of variables on fire spread the warmer the colours the stronger positive impact. According to the model 52.2% of the variance in the response variable is explained by the predictors.

This model accounted for 22.5% of the variation of fire spread in the validation exercise (Figure 11). Solid line represents the regression line showing relationship between observed and predicted values. Dashed line represents where observed values equal predicted. If the values are mainly below this line, they are considered as underestimated if opposite – overestimated. Based on cross-validation, our predicted values in fire spread model tend to be underestimated.

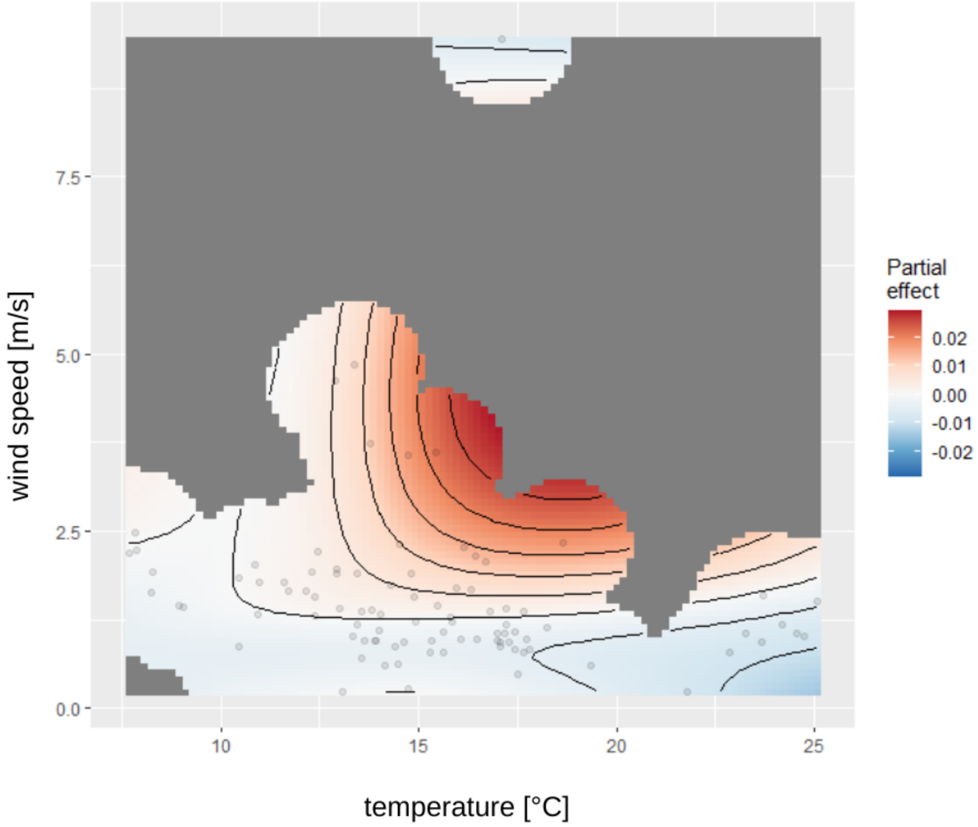

Figure 10. Impact of wind speed [m/s] and temperature [°C] on fire spread [m/s].

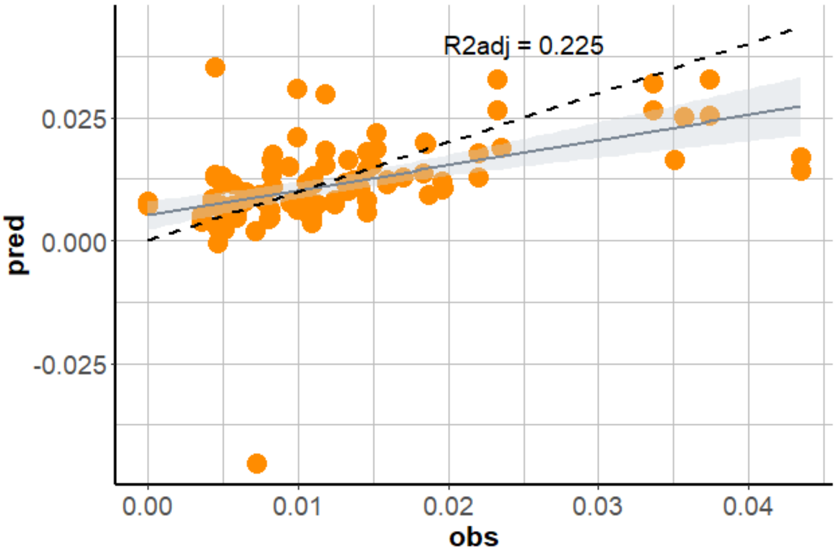

Figure 11. Cross-validation of the model showing the impact of wind speed [m/s] and temperature [°C] on fire spread [m/s].

Higher relative humidity and lower amount of fuel had a negative impact on fire spread (Figure 12). According to the model 51.6% of the variance in the response variable is explained by the predictors. This model accounted for 5.1% of the variation of fire spread in the validation exercise (Figure 13). Based on cross-validation, our predicted values in fire spread tend to be underestimated.

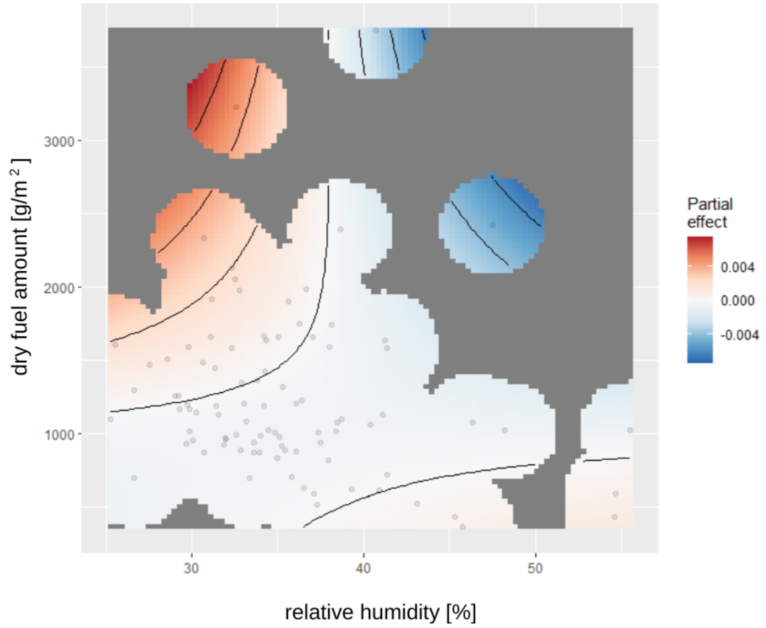

Figure 12. Impact of relative humidity [%] and dry fuel amount [g/m^2] on fire spread [m/s].

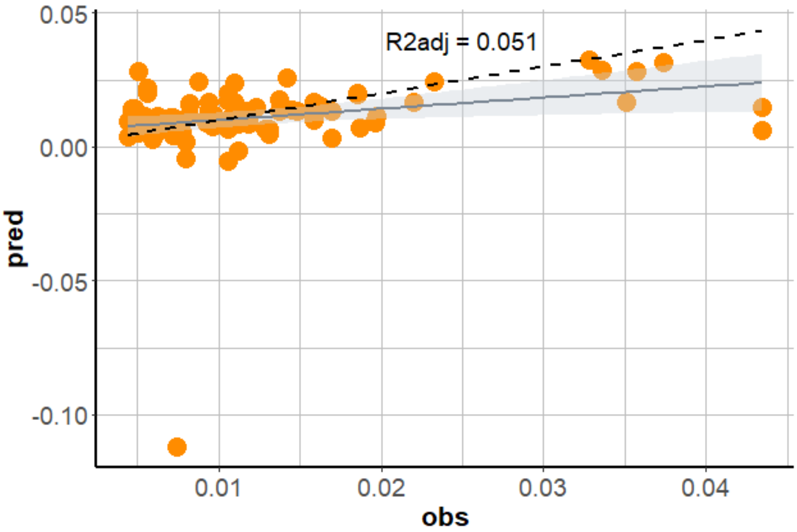

Figure 13. Cross-validation of the model showing the impact of relative humidity [%] and fuel amount [g/m^2] on fire spread [m/s].

Bigger litter depth and higher relative humidity had a negative impact on fire spread (Figure 14). According to the model 19.6% of the variance in the response variable is explained by the predictors. This model accounted for 1.7% in the variation of fire spread in the validation exercise (Figure 15). Based on cross-validation, our predicted values in fire spread model tend to be underestimated.

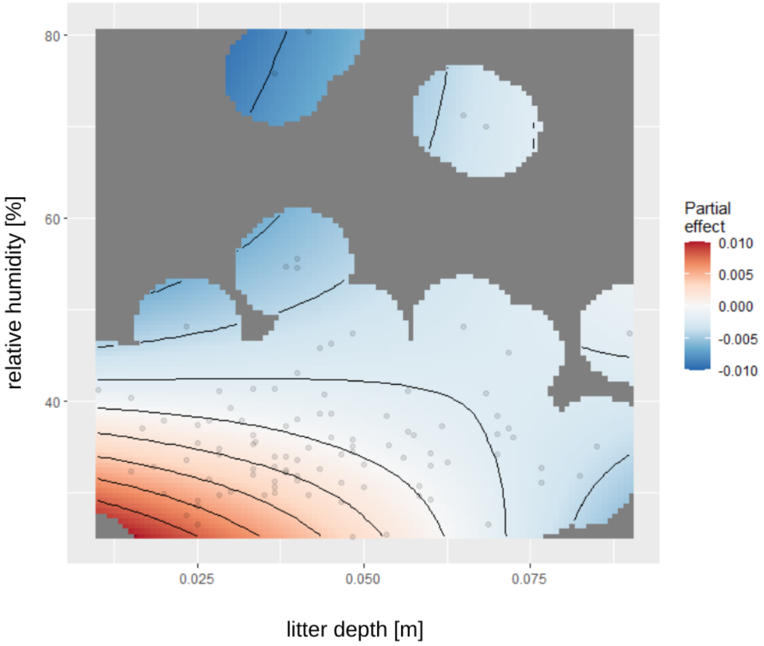

Figure 14. Impact of litter depth [m] and relative humidity [%] on fire spread [m/s].

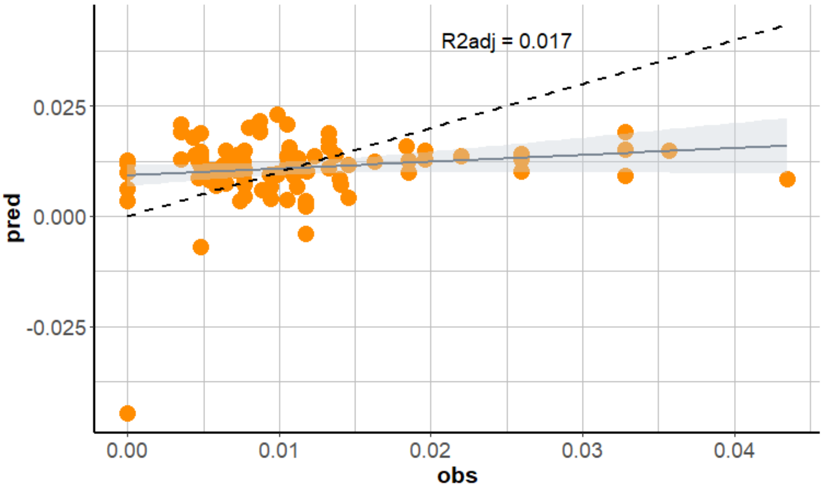

Figure 15. Cross-validation of the model showing impact of litter depth [m] and relative humidity [%] on fire spread [m/s].

4.3 Total consumption

The total consumption was positively affected by high amount of fresh fuel and low fire spread (Figure 16). According to the model 62.8% of the variance in the response variable is explained by the predictors. This model accounted for 0.1 % in the variation of fire spread in the validation exercise (Figure 17). Based on cross-validation, our predicted values tend to be overestimated.

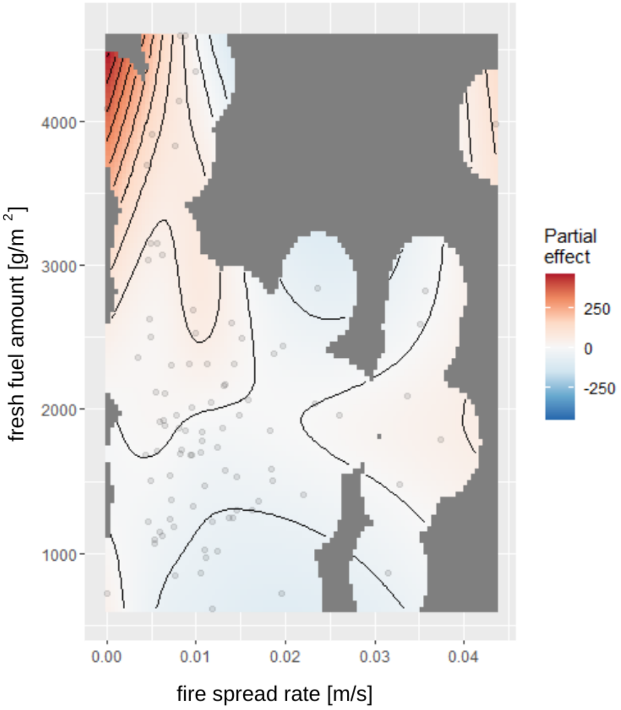

Figure 16. Impact of fire spread rate [m/s] and amount of fresh fuel [g/m^2] on total consumption of ground fuels[g].

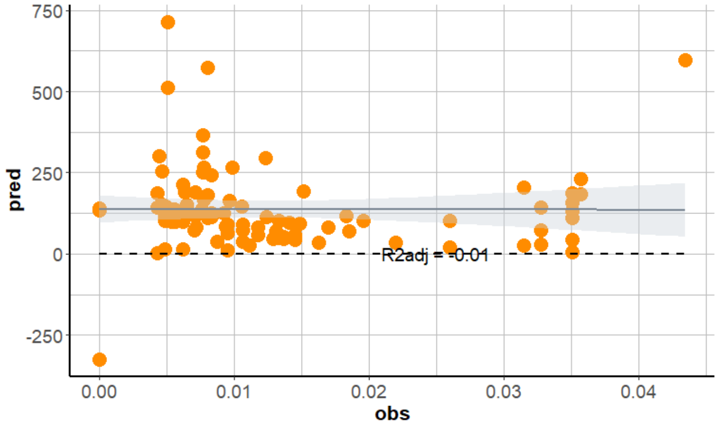

Figure 17. Cross-validation of the model showing impact of fire spread rate [m/s] and amount of fresh fuel [g/m^2] on total consumption of ground fuels[g].

The total consumption was positively affected by low relative humidity and high amount of fresh fuel (Figure 18). According to the model 41.9% of the variance in the response variable is explained by the predictors. This model accounted for 1.7% in the variation of fire spread in the validation exercise (Figure 19). Based on cross-validation, our predicted values in total consumption model tend to be overestimated.

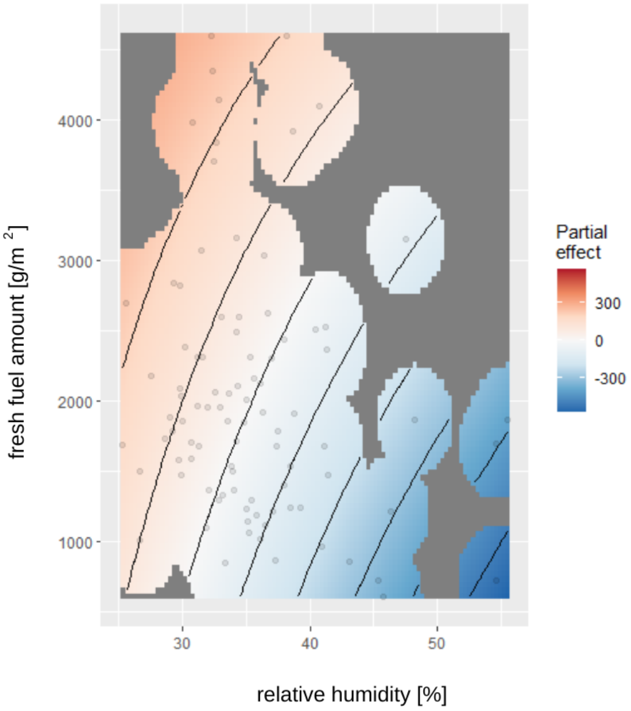

Figure 18. Impact of relative humidity [%] and amount of fuel [g/m^2] on total consumption of ground fuels[g/m^2].

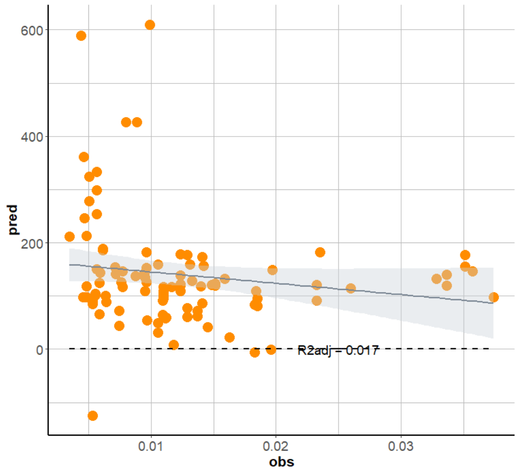

Figure 19. Cross-validation of the model showing impact of relative humidity [%] and amount of fuel [g/m^2] on the total consumption of ground fuels [g/m^2].

The total consumption was positively affected by high fuel amount but not litter depth (Figure 20). According to the model 84.6% of the variance in the response variable is explained by the predictors. This model accounted for 4.3% in the variation of fire spread in the validation exercise (Figure 21). Based on cross-validation, our predicted values tend to be overestimated.

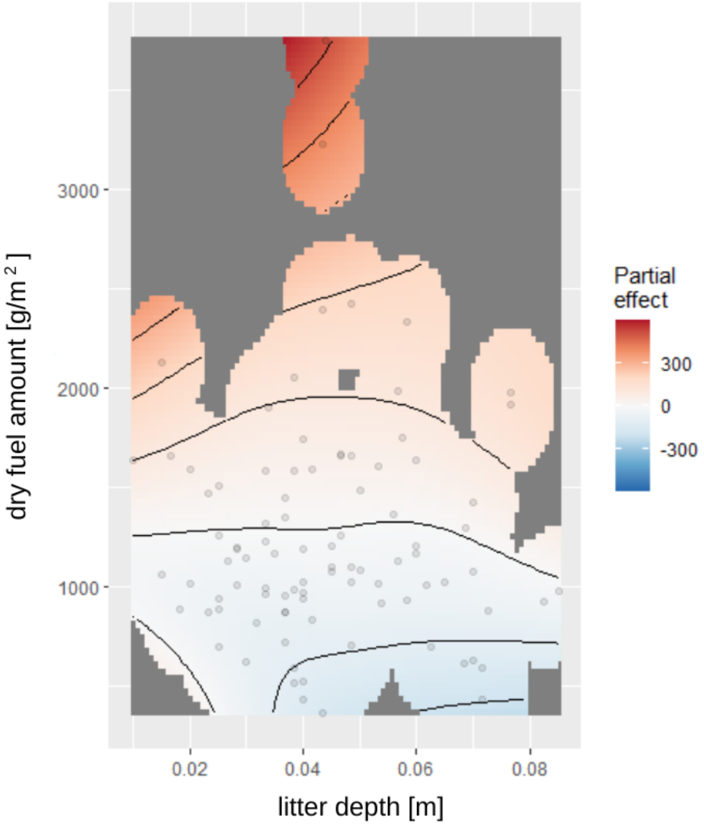

Figure 20. Impact of litter depth [m] and amount of fuel [g/m^2] on total consumption [g/m^2].

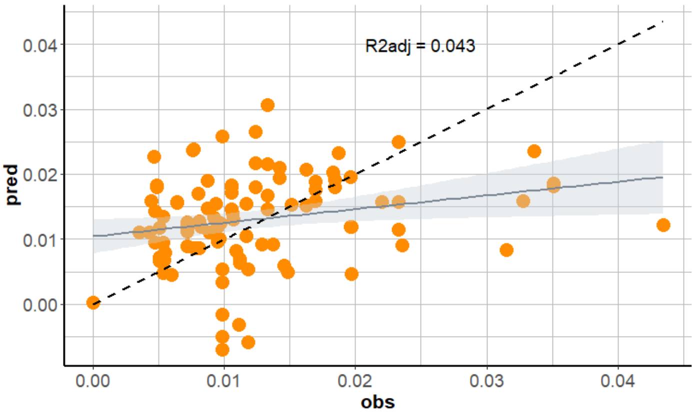

Figure 21. Cross-validation of the model impact of litter depth [m] and amount of fuel [g/m^2] on total consumption [g/m^2].

4.4 Fire weather indices

Fire weather index and fine fuel moisture content (FFMC) are used to assess fire hazard. FFMC quantifies the ease of ignition and the flammability of fine fuels (Stocks et al., 1989). According to our model fire weather indices did not have a significant impact on fire spread (Figure 22). According to the model 38.6% of the variance in the response variable is explained by the predictors. This model accounted for 13.3% in the variation of fire spread in the validation exercise (Figure 23).

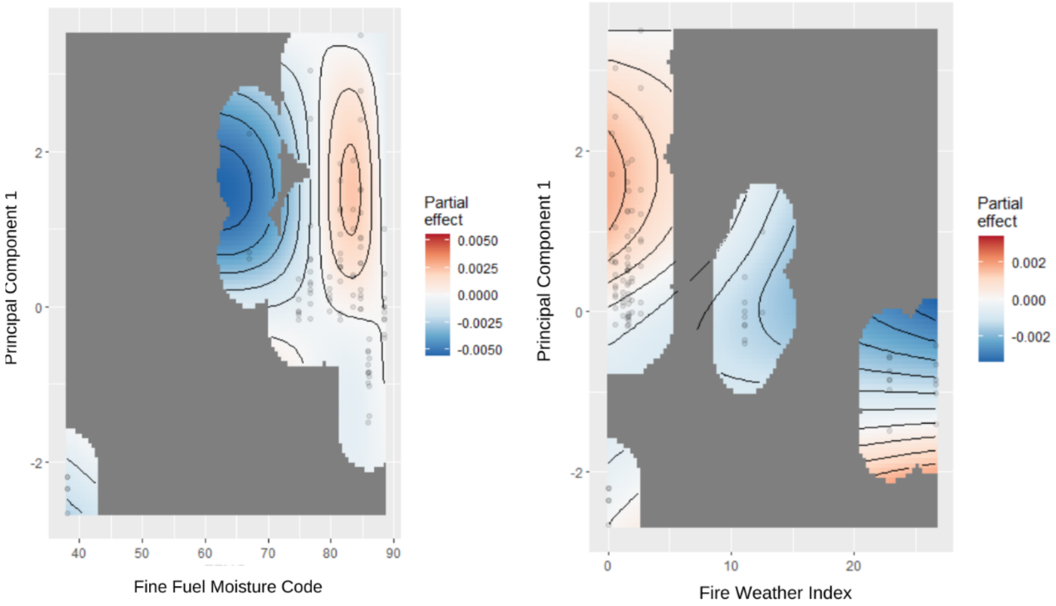

Figure 22. Impact of fire weather indices (FFMC, FWI) and the first principal component on fire spread [m/s].

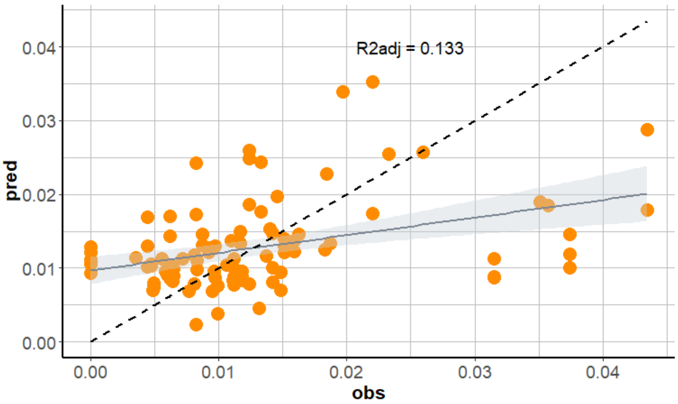

Figure 23. Cross-validation of the model showing impact of fire weather indices (FFMC, FWI) and the first principal component on fire spread [m/s].

Drought code (DC) represents the moisture content of organic layer (Stocks et al., 1989). Amount of available fresh fuel had positive impact on total consumption, while DC did not show correlation (Figure 24). According to the model 64.8% of the variance in the response variable is explained by the predictors. This model accounted for 0.12% in the variation of total consumption in the validation exercise (Figure 25) Based on cross-validation, our predicted values tend to be underestimated.

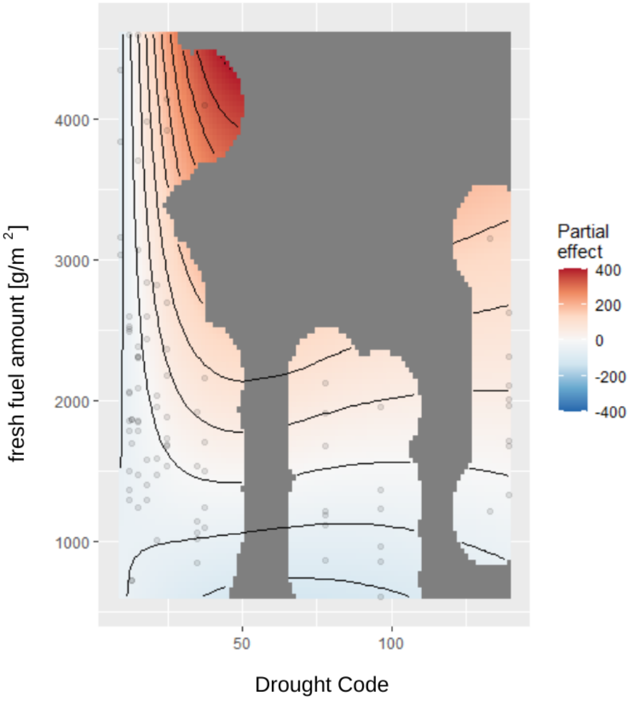

Figure 24. Impact of drought code and amount of fresh fuel [g/m^2] on total consumption [g/m^2].

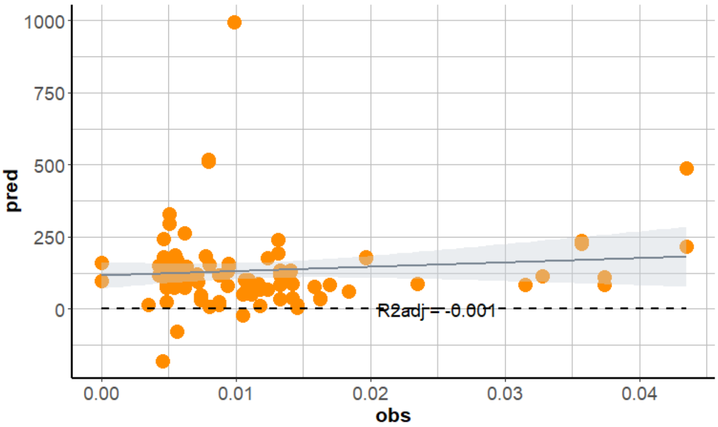

Figure 25. Cross-validation of the model showing impact of drought code and amount of fresh fuel [g/m^2] on the total consumption of ground fuels [g/m^2].

4.5 Fire temperature

Temperature during the fire varied from 17.9°C to 717.2°C. During the ignition experiments, the temperatures stayed largely below 300°C. Temperature exceeded 600°C just on few occasions and it did not last longer than 15 seconds (Figure 26).

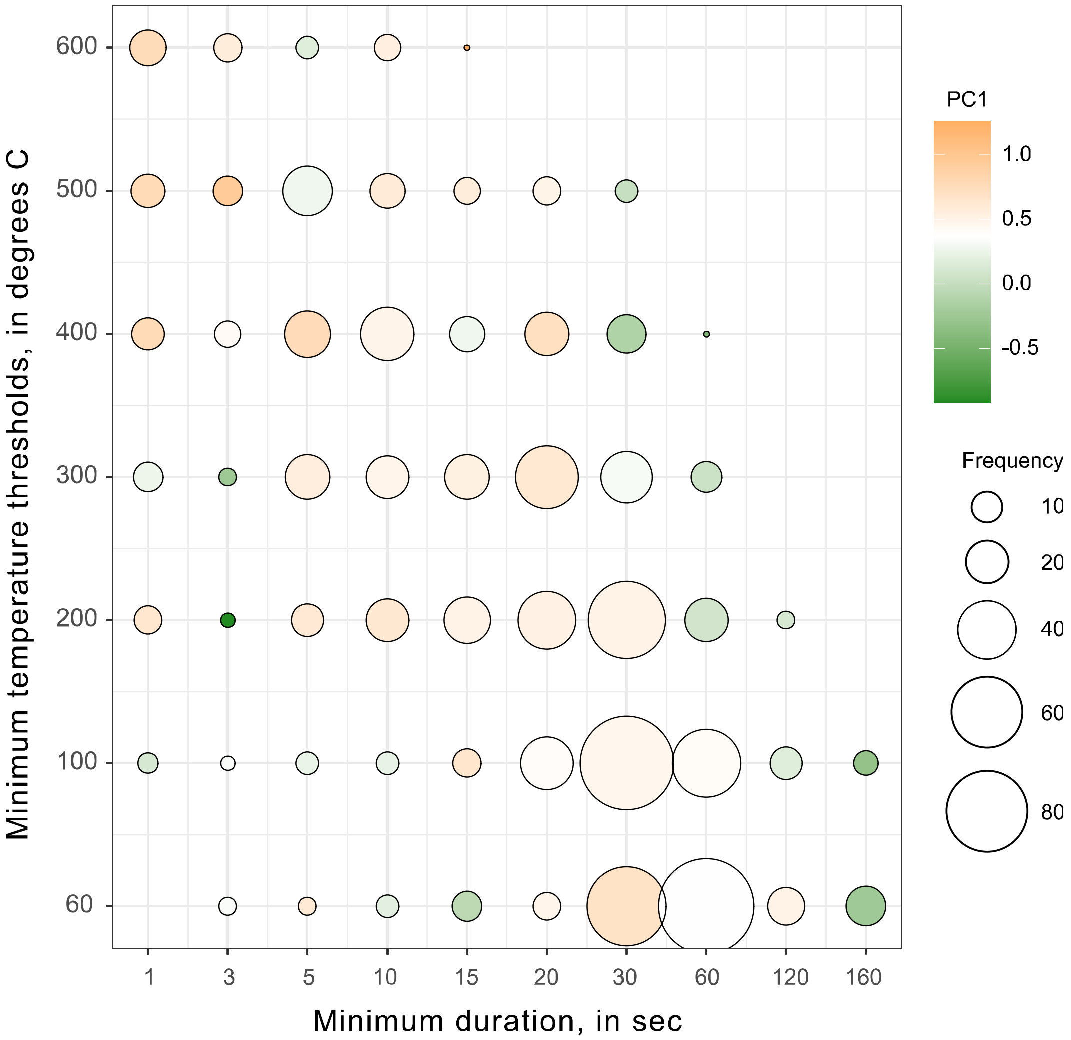

Figure 26. Duration [s] of given fire temperature [°C] thresholds and their correlation with the first principal component in the categorical scale.

5. Discussion

Forest fuels and fire spread

Even though litter depth contributes to the overall fuel amount as a major component of the fuel load (Gormley et al., 2020), there was no correlation between fuel amount prior to the fire and litter depth in this study. This can be explained by the fuel compactness. Fuel compactness refers to the arrangement and density of combustible materials, while litter depth specifically relates to the layer of dead plant material on the forest floor. Fuel compactness is a function of the depth, amount, and size of fuel particles (Pyne et al., 1996). I did not measure the size of fuel particles, so I can not assess if the litter depth and fuel amount were correlated.

Analyses of local weather conditions and forest fuels showed that fire spread rate was lower with lower amount of fuel and a growing relative humidity (Figure 12). This suggests that removing fuel loads from the forest may slow down fire spread. However, the explained variation in the validation exercise is low which indicates that this relationship must be researched more.

Fire spread was negatively affected by high litter depth and high relative humidity (Figure 14), which supported my first hypothesis. The thicker the litter and the higher the relative humidity was, fire spread was lower. This may seem to stand in contrast with the effect of fuel amount and relative humidity on fire spread, but I assume fuel compactness may be an important component here. Fire behaviour is directly related to fuel load and fuel depth as they affect packing ratio which determines fuel compactness (Norton-Jensen, 2005). Compactness has an influence on oxygen supply and radiant energy transfer between particles through relation to the spacing of fuel particles (Pyne er al., 1996). Slower fire spread rates occur when the fuels are compacted (ibid).

Wind speed and temperature were the most important factors affecting fire spread. Fire spread was faster with stronger wind and higher temperatures (Figure 10). This factor was explained by 22.5% of the variation in the validation exercise. This outcome was expected as was shown in many studies (Pyne et al., 1996; Weise & Biging, 1996; Alexander, 2000; Karafyllidis & Thanailakis, 1997; Xuehua et al., 2016). However, I found out that the minimum wind speed and temperature for fire spread to be affected positively was 2.5 m/s and 15°C. These values open the threshold for fire spread, after which the fire spread accelerates.

The underestimation of all these predicted values was probably affected by a lot of observations within similar weather conditions. The fire spread model has explanatory power but is not explained well in the validation exercise. Hence, this model can be used for finding significant relationships but not for predictions. This points to a need for further research with a wider gradient of conditions.

Total consumption

Understanding the impact of fuel amount and relative humidity on total consumption has practical implications for fire management. The amount of fuel and relative humidity have a significant impact on total consumption (Figure 18). The higher fuel amount and lower relative humidity the total consumption was higher.

Analyses of fuel amount and litter depth suggest that fuel amount has a positive effect on total consumption, while litter depth does not seem to have an effect (Figure 20). These findings can contribute to the development of strategies to mitigate fire risk. For instance, in periods of low humidity, fuel management works focused on fuel removal can be planned.

The total consumption was affected positively by the amount of fresh fuel and fire spread (Figure 16), which does not support my third hypothesis. However, based on cross-validation this relationship explained only 0.1 % of the variation in the validation exercise (Figure 17). This suggests that my data was not differential enough.

Fuel composition defined by my principal components did not show significant impact on total consumption. It suggests that during low intensity fires under mild weather conditions type of fuel does not play a role in total fuel consumption.

Smouldering is a flameless form of combustion that occurs when oxygen reacts with the surface of solid fuels (Ohlemiller, 1995). Surface fires often ignite smouldering ground fires, and it generally occurs in tighter packed fuels (Pyne et al., 1996). However, no smouldering was recorded during my ignition experiments. Smouldering to occur needs harsher conditions, with a background of severe drought (Rein & Huang, 2021), that I did not cover in my study.

Predicted values in all three models for total consumption were overestimated, which implies that the value of an outcome should be lower. This overestimation probably was affected by a lot of observations within similar weather conditions. Even though, the total consumption model has strong explanatory power the validation in this part of analyses was very low. This means that model needs some refining to perform better at validation state when it comes to analyses of total consumption. These points to a need for further research with a wider gradient of conditions as well as need for model adjustment.

Regional weather indices

In this study, I did not find any significant correlation between regional weather indices and local fire behaviour (Figure 22; Figure 24), which supports my third hypothesis. Regional weather indices were built to predict fire behaviour based on the wide gradient of weather conditions and various fuels (Wotton, 2009). The answer to why the correlation between regional weather indices and the data I collected did not appear is complex. The regional fire weather model was built under consideration of different fuel types and various conditions. It provides generalized view of weather conditions over a larger area in larger timescales. The data I collected focus on oak dominated fuels and records of short-time weather conditions that are influenced by microclimate at the local scale. The regional fire weather model might not adequately capture the dynamics of fuel moisture content at a local level which influence fire behaviour at the local scale. Hence, one of the reasons for the lack of correlation can be lack of adaptation of regional fire weather model to Swedish conditions or it can be the scale of the experiment I conducted. The gradient I have covered may be too small to be compared with much wider gradient represented by regional fire weather model.

Fire temperature

Recorded fire temperatures show how long does given temperature stays in one spot during the fire. Correlating these temperature and duration categories with environmental factors can help understand how the fire affected the surroundings. For instance, the highest temperatures might correspond to areas with the most significant ecological impact.

Study limitations and further research

The fact that in the study I did not capture a wider gradient of weather conditions and fire hazards made it easy to work in the field but difficult to properly quantify responses of fire behaviour under more fire prone settings. Ignition experiments in this study were conducted under evidently mild conditions and my analysis is focused on moderate and relatively low values of fire hazard, which results in a moderate predictive skill of the developed statistical model. Further research to extended gradients of studied climatological indices is warranted.

6. Conclusions

- Fire spread was positively affected by wind speed and temperature. Fire spread accelerated when wind speed exceeded 2.5 m/s and temperature 15°C.
- Fire spread was negatively affected by high relative humidity and low fuel amount. Fire spread slowed down when the value of relative humidity exceeded 35 %, and fuel amount went below 1000 g/m^2.
- Fire spread was affected by litter depth and relative humidity. Fire spread slowed down when value of relative humidity exceeded 40 %, and litter depth dropped below 0.05 m.
- Total consumption was affected by fire spread rate and amount of fresh fuel. Total consumption grew when fuel amount exceeded 3000 g/m^2 and fire spread rate dropped below 0.05 m/s.
- Total consumption was positively affected by high fuel amount and low humidity. Total consumption grew when fuel amount exceeded 1800 g/m^2 and relative humidity dropped below 30 %.
- Regional fire weather indices did not predict fire behaviour on a local scale.
- There is a need for further research about fire spread as a function of weather conditions and forest fuels in oak dominated forests that would cover a wider gradient of conditions including extreme conditions.

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Popular science summary

When does the fire become a threat?

Olga Wepryk

Fire is an important part of ecosystems. It defines what species are present in the forest and in which amount. In Sweden forest fires were common until the middle of the 19th century. Since people started suppressing fires, the amount of burnable material (fuel) started accumulating in the forest. Moreover, the species that were growing in the forest have changed. Share of species, such as oak, that need fire for regeneration declined. It is debated if that change is a result of a lack of fire in the forests, or other factors such as intensive forest management. Due to climate change, we observe increased fire activity, which in combination with increased fuel amount creates a serious threat of wildfires.

Prescribed burning is a recommended tool in forest management to reduce accumulated fuel and as a result, help to protect forests from wildfires. Low intensity fires provide sunlight that is needed for oak germination and growth. However, there is a need to find out which conditions are good for doing low-intensity fires such as prescribed burnings and which conditions do constitute already a threat.

Hence, finding out the effects that fuel and weather conditions have on fire behaviour was one of the main targets of that study. Relationship between local fire behaviour and regional fire indices was also checked. Regional fire indices are tools used to assess and predict the risk of wildfires at a larger geographic scale, so how they contribute to local fire behaviour was analysed.

Within this research, 105 ignition experiments were conducted and during each of them local weather conditions, proceeding fire, and fire temperature were recorded. Ignition experiments where the forest floor was burned in oak-dominated forests gave us some understanding of what affects the fire spread and total consumption. Fire spread is the distance that fire moves per unit of time. Total consumption is the amount of fuel that the fire “ate” while spreading. To study these dependencies, on each research plot samples of fuel amount prior to the ignition, and after the ignition was taken.

Analyses of all collected data gave following results: (1) fire spread accelerates with higher temperature and stronger wind; (2) it slows down when the relative humidity is high and there is high amount of fuel available, (3) fire spread also slows down when relative humidity is high but litter depth is thin; (4) total consumption is higher when fuel amount grows and fire spread slows down; (5) total consumption also grows when there is high amount of fuel available and low humidity; (3) regional fire weather indices do not predict fire behaviour on a local scale.

These findings may help forest managers to make decisions about fire management in their forests, which is needed for preventing wildfires as well as promoting species that need fire for successful regeneration.

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