Feel the heat: How weather and fuels affect temperature during fires

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Feel the heat: How weather and fuels affect temperature during fires

Hur väder och bränslen påverkar temperaturen vid bränder

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Abstract

Fire plays a critical role in shaping forest ecosystems, influencing biodiversity, nutrient cycling and vegetation structure. Understanding the factors that control fire temperature is essential, as fire strongly affects ecological outcomes such as regeneration and habitat composition. In particular, the interaction between fuel characteristics, weather conditions and fire temperature remain insufficiently understood, especially in the oak-dominated forest of Scandinavia.

This study aims to investigate how variations in weather and fuels influence temperature variability during fires through: (1) calibrating the range of temperatures and respective residence times observed during experimental fires in oak-dominated forests, (2) evaluating the relative importance of weather conditions and fuels upon temperature during fires, and (3) ranking different fuel types in respect to their impact in fire temperatures.

Using a field-based experimental approach, and controlled burns at six locations in southern Sweden we collected data on fuel composition, fire temperature and concurrent weather variables. Analysis was made using Principal Component Analysis and Random Forest regression models.

The results show that fuel characteristics, especially the presence and biomass of Calluna (*Calluna vulgaris* L.), are the strongest predictors of maximum and cumulative fire temperatures. From 100 g/m^2 of Calluna the fire temperatures increased rapidly and plateaued after. The more biomass of Calluna the higher the fire temperatures were, mainly in the range of 700ºC. Weather variables, such as relative humidity, mean temperature and wind speed, also influenced temperature but to a lesser extent. Notably, mid-range humidity levels (55%) were associated with prolonged heat durations, likely due to increased smoldering.

Results of this study support the development of more flexible and ecologically informed prescribed burning strategies in Swedish forests through bringing new insights into the complex dynamics between fuel types, weather and fire temperature.

Keywords: Ecological impacts, forest fuels, oak forests, prescribed burning, forest fire, ignition experiments, temperature variability.

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Abbreviations

Abbreviation	Description
CanFIRE	Canadian Fire Effects Model
FOFEM	First Order Fire Effects Model
LANDIS-II	Landscape Change Model
PCA	Principle Components Analysis
PDP	Partial Dependence Plot
RFM	Random Forest Model
RH	Relative humidity

1. Introduction

Fire is a chemical reaction known as combustion, which occurs when fuel, oxygen and heat combine to produce flames and energy. This process plays a critical part in shaping ecosystems, influencing biodiversity, nutrient cycling and habitat structure (Verma & Jayakumar 2012; Keane 2014; Pausas & Keeley 2023). Fire is a natural disturbance in many forested ecosystems, that affects local, regional and global biochemical cycles, and shapes ecosystem dynamics (Pausas & Keeley 2023).

Fire behavior and its effects depend on fuels, weather conditions and topography(Keane 2014). These elements interact shaping fire spread, intensity and severity (Keeley 2009). Understanding how these factors influence fire is essential for developing effective fire management strategies and predicting wildfire behavior.

The fire temperature is a critical control of fires' ecological effects. Low-intensity fires may remove ground and understory vegetation, causing little mortality of canopy trees. In contrast, high-intensity fires can lead to canopy tree mortality, high levels of consumption of soil organics, ultimately leading to replacement of the existing canopy with a new cohort. Spatial and temporal patterns of temperature variability closely track the variability in fire behavior and its effects (Gedalof 2011). For example, soil heating alters microbial activity, leading to combustion of organic matter and influencing the amount of charcoal that, in turn, controls soil chemical composition such as abundance of phenols, which are shown to inhibit regeneration of trees in boreal forests (Verma & Jayakumar 2012; Pluchon *et al.* 2016). Regeneration of certain tree species relies on temperatures reaching a specific threshold to trigger seed germination (Neary *et al.* 2005) that further underscores the value of understanding temperature variability during fires.

Weather conditions, particularly wind speed, temperature, humidity and precipitation play a role in determining fire behavior. Wind can dramatically increase the rate of fire spread, while high humidity and rainfall both suppress ignition and combustion (Westerling *et al.* 2006). Weather conditions are a result of the regional climate. Changes in climate often entail changes in the frequency of extreme fire weather conditions (Yang *et al.* 2015).

Fuel properties, including type, quantity, distribution and moisture content, are critical factors influencing fire behavior. Fires tend to spread more easily and burn more intensely in environments where fuels are dry, continuous and abundant (Agee & Skinner 2005). Broadleaf and coniferous fuels have different "burn behaviors". Broadleaf fuels generally retain more moisture and consequently fires in deciduous forests tend to be of low intensity (Bobek *et al.* 2019). Coniferous fuels on the other hand, have high resin and oil content with lower water content (Kush *et al.* 2019). These features make them highly combustible and increase fire spread rate (Schimmel & Granström 1997; Kush *et al.* 2019). Thinning, logging and fire suppression can significantly alter fuel dynamics. Retaining the understory vegetation or post-harvest debris can increase the continuity of flammable material across the landscape. Understanding how fuels affect fire spread and severity is key to implementing proactive fire management strategies (Agee & Skinner 2005; Keane 2014).

In Sweden, fire historically played a crucial role in maintaining diverse forest ecosystems. Frequent fire of varying severity maintained landscapes dominated by a mosaic of cohorts, with portions of landscapes exhibiting fire return intervals of 30 to 50 years, while others featuring century-long intervals (Niklasson & Granström 2000). However, since the 1800s fire suppression and land use changes have led to the strong decrease of fire as a disturbance factor in Swedish forests (Granström & Niklasson 2008). Decline in fire activity and introduction of Norway spruce (*Picea abies*) in production forests led to changes in regional vegetation, particularly in southern Sweden (Lindbladh *et al.* 2014).

Since the early 2000s, prescribed burning has gained attention in Sweden as a part of conservation-oriented forest management (Cogos *et al.* 2020). Controlled burns can reduce fuel loads, promote biodiversity and support the regeneration of light demanding species like Scots pine (*Pinus sylvestris*) and pedunculate Oak (*Quercus robur* L.) (Nilsson *et al.* 2005; Drobyshev *et al.* 2021). While prescribed burnings have proven benefits, like creating habitat and reducing fuel load, it also involves a risk of uncontrolled fire spread (Roces-Díaz *et al.* 2022; Collins *et al.* 2023). The Swedish Environmental Protection Agency has published a report where they provide guidance for fire and burning in protected forests (Nilsson 2005). In the reports attachments they mention natural values that can benefit from prescribed burns, oak-dominated forests are not being discussed directly, but deciduous fires in general. In particular, deciduous forest that have emerged after fire disturbance with its associated fauna and flora (Nilsson 2005). They advise to burn forests with shallow ground water, which are nearby fragments of older deciduous forests, preferably with known occurrences of endangered fire-associated species. The timing they suggest is late summer and the burned areas should be fenced afterwards to prevent wildlife grazing (Nilsson 2005). No pre-fire measures are mentioned, and no specific fire temperature related aspects are part of the report.

In the oak-dominated forests of southern Sweden, fire has historically played a significant ecological role. Studies suggest that low-severity surface fires were common in the landscapes and contributed to maintaining open forest structures favorable to oak regeneration (Drobyshev *et al.* 2021). These fires reduced competition from shade-tolerant species, increased light availability and created soil conditions that promoted oak seedlings establishment and growth.

This thesis aims to analyze how weather and fuels influence temperature during fires. By identifying the main controls of temperature variability during fires, the study provides insight into relationships between fires and vegetation in oak forests in Scandinavia and informs decisions in managed forests, such as the removal of a specific fuel type to reduce fire temperature and its residence time (time in seconds where fire was at a specific temperature). Data collected in this study will be instrumental in parameterization of models, like LANDIS-II (Scheller *et al.* 2007), FOFEM (Lutes 2017) and CanFIRE (de Groot 2012), linking fire behavior to ecological effects of fires.

My overreaching question is how do fuels and weather conditions influence fire temperature regimes? I was particularly interested in (1) calibrating the range of temperatures and respective residence times observed during experimental fires in oak-dominated forests, (2) evaluating the relative importance of weather conditions and fuels upon temperature during fires, and (3) ranking different fuel types in respect to their impact on fire temperatures.

2. Materials and Methods

2.1 Study sites

The data was collected in six locations in southern Sweden (Figure 1). The vegetation zones ranged from nemoral to boreo-nemoral (Sjörs 1999). The dominant tree species were pedunculate oak (*Quercus robur* L.), silver birch (*Betula pendula* Roth), European beech (*Fagus sylvatica* L.) and the forest floor was dominated by different species, for example Calluna (*Calluna vulgaris* L.), bilberries (*Vaccinium myrtillus* L.), redberry (*Vaccinium vitis-vidaea* L.), grasses, ferns and mosses.

The four sites (Ekenäs, Sandvik, Åby säteri, Skarhult), which are part of Olga Wepryk's Master Thesis (Wepryk 2023), were burned during spring 2022 and 2023. The fifth and sixth site (Hagestad and Högahyltan) were burned during spring 2024. The sites were chosen to represent variability in the composition of forest fuels in oak-dominated forests.

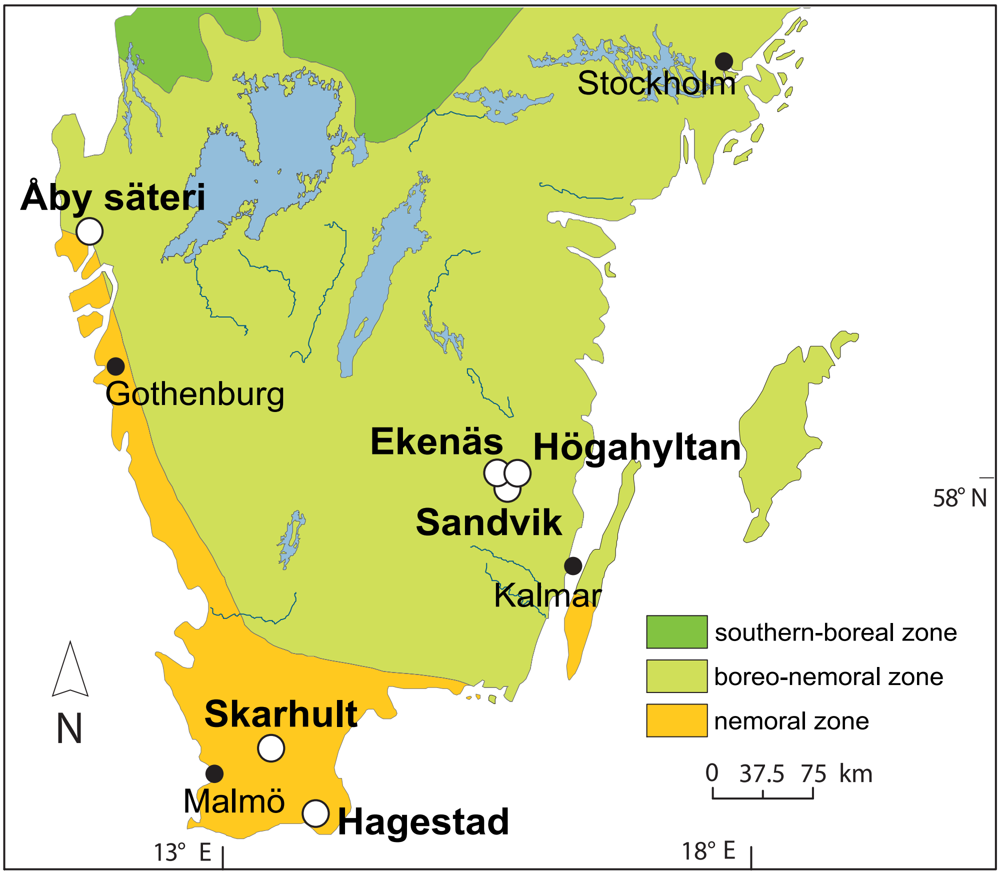

Figure 1 Location of the study sites and southern Sweden's vegetation zones (recreated with permission of Olga Wepryk).

Table 1 The mean annual temperature (ºC) and annual precipitation (mm) from the study sites from January 2022 until January 2025(Sveriges meteorologiska och hydrologiska institut 2025).

Site	Municipality	Mean annual temperature (ºC)	Annual precipitation (mm)	Vegetation zone
Ekenäs	Nybro	8.51	486	boreo-nemoral
Hagestad	Ystad	8.93	749	nemoral
Högahyltan	Nybro	8.51	486	boreo-nemoral
Sandvik	Nybro	8.51	486	boreo-nemoral
Skarhult	Eslöv	8.93	749	nemoral
Åby säteri	Sotenäs	7.21	1168	boreo-nemoral

2.2 Plot design and pre-ignition measurements

Figure 2 Burns in Hagestad, A and B show the metal rods in the middle of the plots and markings along the edge. C shows a sample square of fine fuels before collection, while D shows the same samples square after the physical removal of fine fuels before burn.

The establishment of the plots started with finding sites with continuous fuels, like oak leaves or heather, and setting the GPS location. The plot size was 2 m x 5 m, except for Hagestad where some plots had continuous fuel conditions for more than just 5 m, the plot size was 2 m x 10 m to get more data points. Every plot had a 1 m safety belt, where vegetation was removed to the mineral soil and the soil was watered. In the center line of the plots, metal rods were placed at a distance of 1 m starting at the shorter edge (Figure 2 A, B). This was used for measuring fire spread. The metal rods were marked every 20 cm of their height to be able to estimate flame height during the fire.

Before igniting the plots with a propane torch, the organic layer thickness was measured in three random spots within the plot. One fuel sample prior (Figure 2 C, D) and one sample after the burn were taken from 0.5 m x 0.5 m squares and put into separate plastic bags with labels. The first sample was taken from the safety belt. The fuel samples included all the material reaching from organic layer to the bare mineral soil. A fine fuel sample was taken from the close proximity of the plot to assess fuel moisture, containing the top, driest layer of the litter in quantity from 30 g to 150 g.

The plots were ignited in wind direction and at the shorter edge of the plot. A line of 2 m was ignited as the start of the fire line.

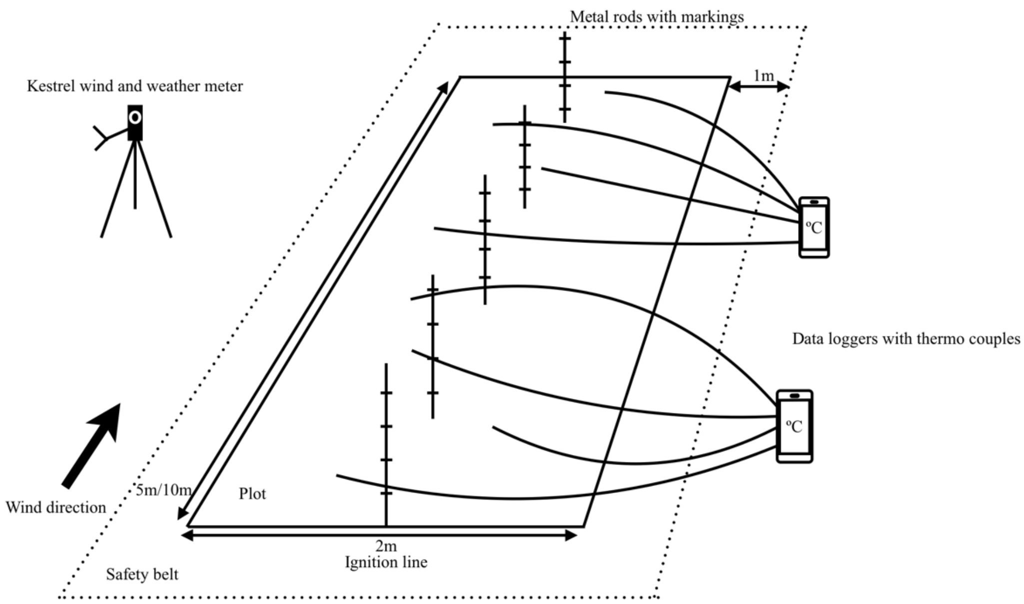

Figure 3 Visualization of the plot design with Kestrel wind and weather meter and Data loggers with thermocouples (made by author).

The structure was taken from Olga Wepryk's Master Thesis (Wepryk 2023) and inspired by field studies from Sweden (Schimmel & Granström 1997), Finland (Tanskanen et al. 2007) and Canada (Alexander & Quintilio 1990) (Figure 3). 105 of the data points are taken from Olga Wepryk's Master Thesis (Wepryk 2023), except the data from the Hagestad and Högahyltan site which were collected in 2024.

2.3 Data collection during fires

During the fires we measured wind speed (m/s), humidity (%) and current temperature (ºC) with a Kestrel wind and weather meter (FIRE-2721771, 5500FWL), which was placed on a tripod a few meters away from the plots. The fires temperature was measured in four or in eight (Hagestad) points throughout the plot by thermocouples, placed on the top of the litter layer, among the fine fuels, which were connected to data loggers (Sefram 9814). The usage of thermocouples and data loggers was inspired by Frida Plathner (Aamodt *et al.* 2024). Each fire was recorded with a phone camera from ignition until the plot was ending or the fire died. When fire and combustion were over, the remaining fuel sample was taken inside the plot.

2.4 Laboratory work

Fuel samples collected in the field were sorted into the different fractions, for example oak leaves, Calluna and grasses. Any fuels that could not be clearly identified were grouped into a category called "other". Fine fuels and the compact layer of the organic soil horizon were handled separately. All of the fractions were then dried at 105ºC for 12 hours. The samples were weighed before each drying cycle. This drying step was repeated every 12 hours until the weight of the samples stopped changing. For the fuel samples collected after the fire, we used the same drying protocol but without separation of the fuels into fractions.

2.5 Data analysis

Data analysis was made using R (version 4.1.1) (R Core Team 2024) and RStudio (Posit team 2025). The data set was prepared with all the variables related to weather, fuel characteristics and fire activity. Predictors, like Calluna, Humidity and Principal components, and their associated fuels, were defined in a dedicated vector, while response variables were selected from a predefined list using an index. I chose for temperature a threshold above 60ºC, because this is the temperature where proteins coagulate, and the plant tissue is getting damaged (Precht *et al.* 2012). Another important threshold, specifically one for oak, is the temperature of 200ºC. Boerner and Brinkman (2003) mention that mean fire temperatures that exceeded 200ºC, led to the volatilization of nitrogen, which in return can help create better conditions for oak establishment.

2.5.1 Principal components analysis (PCA)

PCA is a method to reduce dimensions of the variables' space (Karamizadeh *et al.* 2013). I used the principal components analysis, operated on the pre-fire dry weight of specific fractions to reduce dimensions in the fuel data. Prior to analysis, I normalized the data to account for the differences in absolute values. I used the package factoextra (Kassambara & Mundt 2020) to conduct the Principal Components Analysis (PCA). Furthermore, the package vegan (Oksanen et al. 2025) was also used for the PCA on the fuel data, as well as to get site loadings for the regression analysis.

2.5.2 Impact of fuels upon temperature variability

To address the first research question, which was about finding out the range of temperatures and respective residence times observed during experimental fires in oak-dominated forests, I created temperature profiles in the form of bubble plots. The plots were combining fuel characteristics with fire temperature and duration data. To understand the impact of particular fuel type to the fire temperatures, I calculated the proportion of selected fuel types in each combination of minimum temperatures and minimum residence times. In a similar way, I also used PC2 to map its contribution to temperature variability. I binned minimum temperatures into eight classes and residence times (duration above temperature thresholds) into eleven classes. Each bubble in the plot represents the frequency of a specific temperature-duration combination, with bubble size indicating the amount of fuel present (g/m^2). This visualization allowed me to assess how different fuels contribute to the distribution and intensity of fire temperature regimes. I selected fuel types that were the most abundant in the data and those with contrasting effects of temperatures.

2.5.3 Random Forest Model (RFM)

To model the relationship between the predictors and the response variable, I used the Random Forest regression model (Breiman 2001). The model was configured with 500 trees, and the number of variables randomly sampled at each split was set to the square root of the total number of predictors, which is $\sqrt{27} \approx 5.2$. For research question 3, I used the package caret (Kuhn 2008) to train the data in the Random Forest Model (RFM) and its temperature analysis. The package randomForest (Liaw & Wiener 2002) was used for training, testing and bootstrapping the data. Predictor importance was assessed using the standard permutation method, which measures the increase in prediction error when each variable is randomly shuffled – indicating how crucial each variable is for accurate predictions. To evaluate the stability and variability of importance rankings, I applied a bootstrapping approach.

The model was repeatedly trained on random subsets comprising 70% of the original dataset. This process produced a distribution of each predictor's importance scores.

I created Partial Dependence Plots (PDP) with confidence intervals to answer the second research question. I computed the mean and standard deviation of the PDPs from the bootstrap samples and chose four predictors (maximum temperature, cumulative temperature, duration above threshold and Calluna) to create the graphs.

3. Results

3.1 Fuels

3.1.1 Fuels variability – PCA

OakBranch, Birch, Pine, Oak, Aspen, Moss, and Redberry were the most influential fuels in my dataset explaining 45.5% of the total variance (Figure 4).

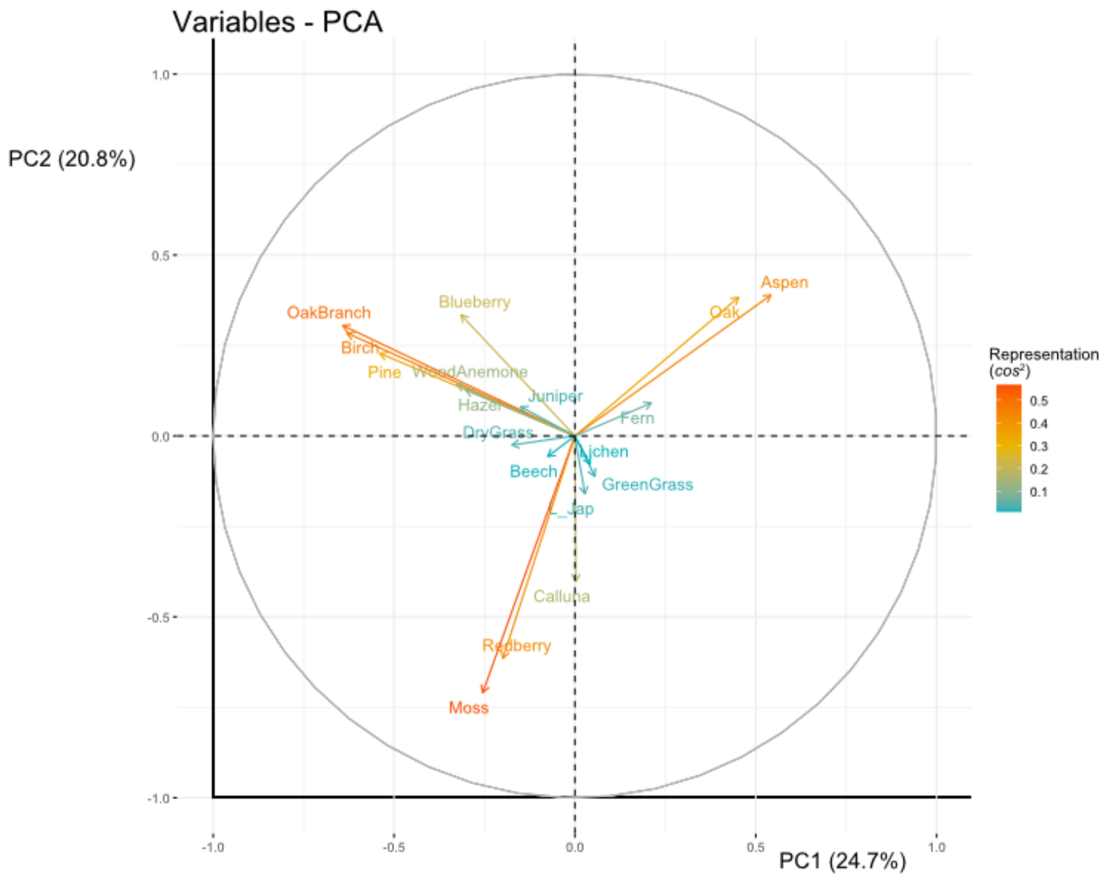

Figure 4 Distribution of specific fuel components along the first two principal components (PC1 and PC2). PC1 explains 24.7% and PC2 explains 20.8% of the total variance. The cos^2 values indicate how well each component is represented on this plot: values close to 1 mean good representation, while values close to 0 mean poor representation.

3.1.2 Impact of fuels upon temperature variability

Temperatures of the fire recorded on the forest floor varied from 17ºC to 963ºC, mainly staying below 400ºC, with the most frequent (from 20 to 60 seconds) being 300ºC and below. Temperatures in excess of 700ºC were observed on few occasions and they lasted less than 30 seconds.

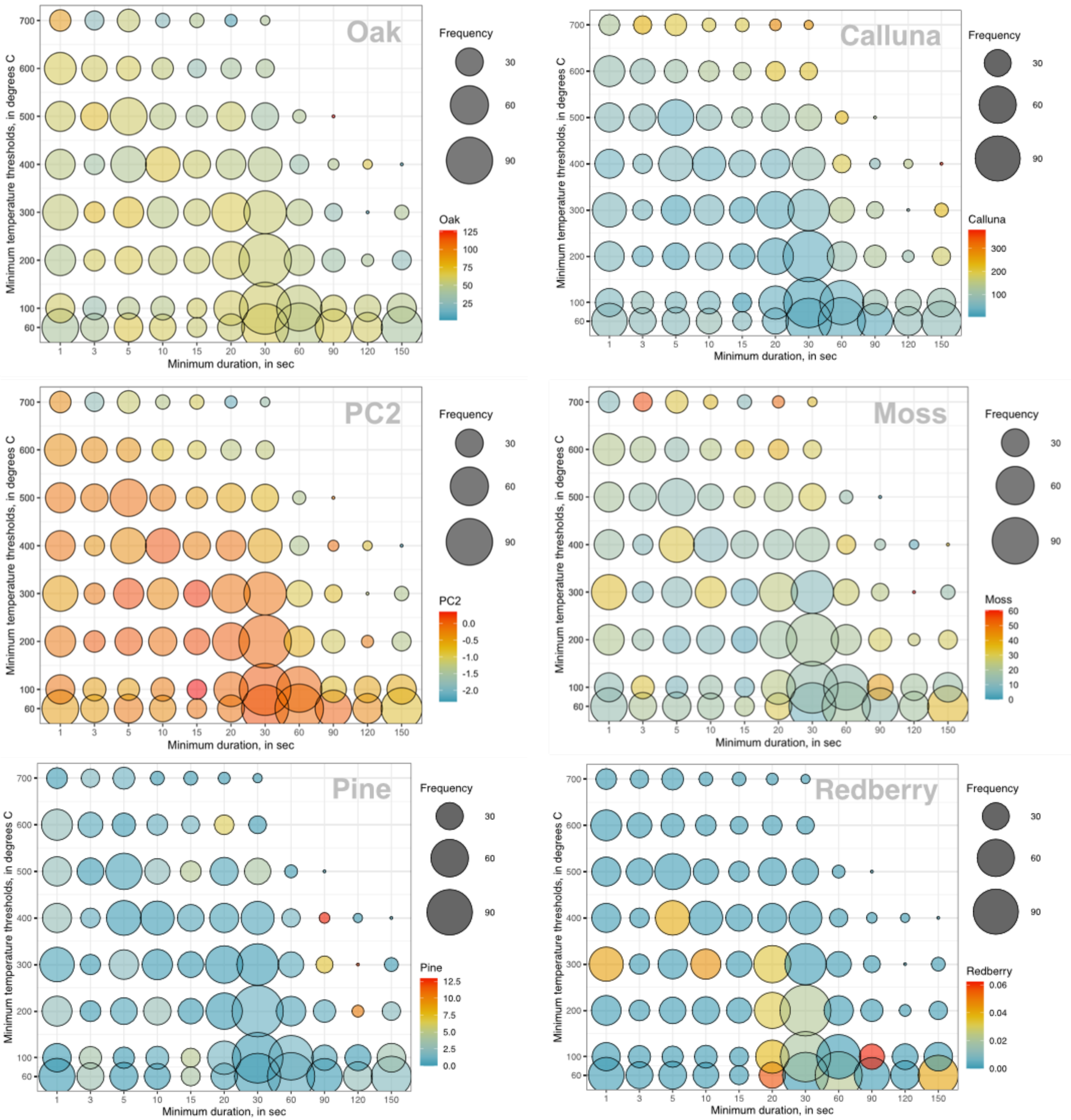

Figure 5 Pattern of temperature variability during fires as a function of dry mass of specific fuels. Size of the bubbles represents the number of instances when fire temperature stayed a specific time (OX axis) over a specific temperature threshold (OY axis). Color represents the mean dry mass g/m^2 of a fuel type for each combination of duration and minimum temperature. In case of the PC2 plot the color presents the mean contribution of that principal component for a particular bubble.

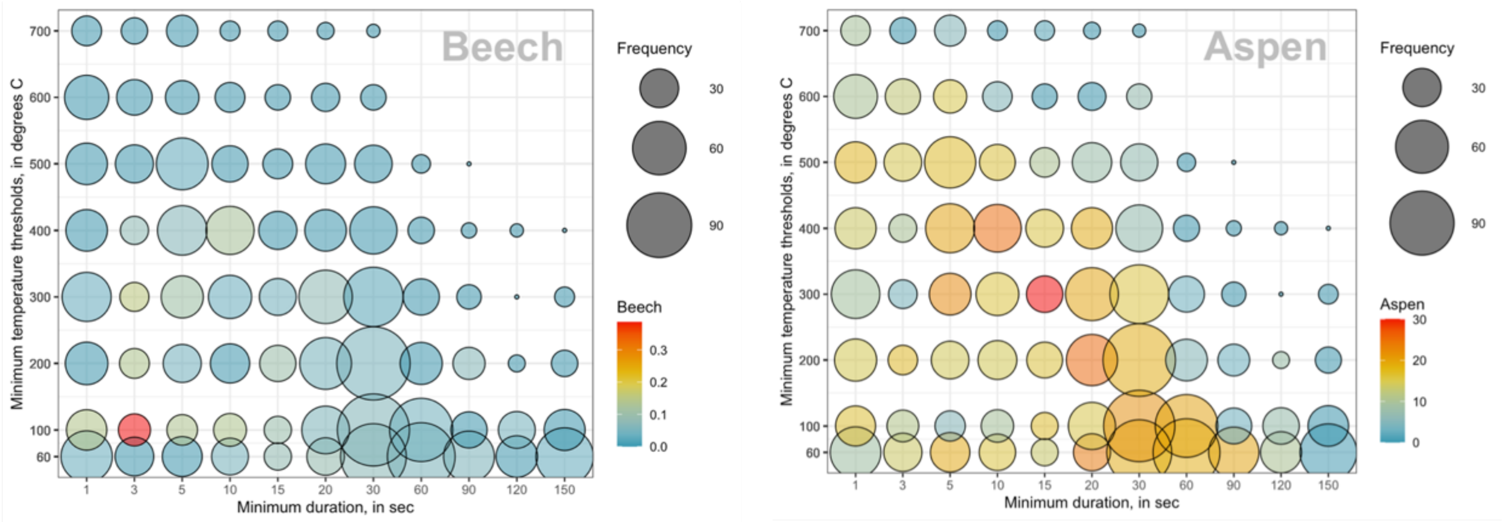

Figure 5 continued.

Higher values of oak mean dry mass are concentrated at low temperatures and short durations (e.g., 200-300ºC, ≤ 20 seconds), indicating that oak fuels are associated with lower temperature regimes (Figure 5). Contribution to higher temperature regimes is limited, but the highest concentration of mean dry mass is found at 700ºC and at 1 second.

Heather (*Calluna vulgaris* L.) has a similar range of responses across all temperatures and duration combinations (Figure 5). Temperatures of 600ºC and above along with durations ranging from 3 to 30 seconds are associated with high mean dry mass of Calluna. The most common frequencies (30-60 seconds) and low to moderate temperatures (100ºC-400ºC), are associated with the lowest mean dry mass of Calluna.

PC2 representing oak branches, moss, redberry and birch has strongest contributions (red/orange bubbles) to intermediate temperatures and duration classes (e.g., 200-400ºC, 5-30 seconds) (Figure 5). The highest mean dry mass of PC2 is found at 15 seconds and 100ºC.

Higher abundance of mosses was associated with temperatures reaching 700ºC for at least 3 seconds (Figure 5).

Pine abundance is concentrated at low to moderate temperatures (60ºC-300ºC) and longer durations (30-150 seconds). The mean dry mass remains rather low with just small outliers at 90 seconds and 400ºC and 120 seconds and 200ºC (Figure 5).

Redberry shows a lower amount of mean dry mass compared to the other fuels. The strongest contributions are at 20-30 seconds and temperatures of 300ºC and below. Redberry has overall redder spots at longer durations (<20 seconds) and mid-temperatures (>300ºC), staying under the 500ºC line (Figure 5).

Beech displays that concentration of dry mass is in the low temperatures (100-300ºC) and short to moderate durations (1-60 seconds) (Figure 5). Higher beech values were concentrated at low temperature thresholds (100ºC) and short durations (3 seconds). There is almost no presence of beech fuels at higher minimum temperatures (>400ºC).

Aspen has higher mean dry mass values observed at a wider range of temperatures (60ºC – 500ºC) with a broad duration time and reaching from 1 second to 90 seconds (Figure 5). The highest frequencies occurred in the mid-duration (30 seconds) and low to moderate temperature range (60ºC to 200ºC). The highest mean dry mass of aspen was recorded at 15 seconds and 300ºC.

3.2 Evaluation of the relative importance of weather conditions and fuels upon fire temperatures

3.2.1 Predictor importance

Using RFM I divided predictors into 3 groups: fire, fuel and weather variables, and identified main predictors and their ranking of importance (Figure 6, Figure 7, Figure 8). Calluna was the most important predictor of maximum temperature, cumulative temperature and duration of threshold (60ºC), followed by the PC2 and relative humidity mean. PC2 and relative humidity alternated in second and third places, whereas oak always ranked in fourth place. The predictors show a clear hierarchy with the top 4 being consistent. The fuels were spread out over the whole ranking, whereas the three weather predictors were always in the top 12. Fire spread rate was always in the middle field of rankings in this study.

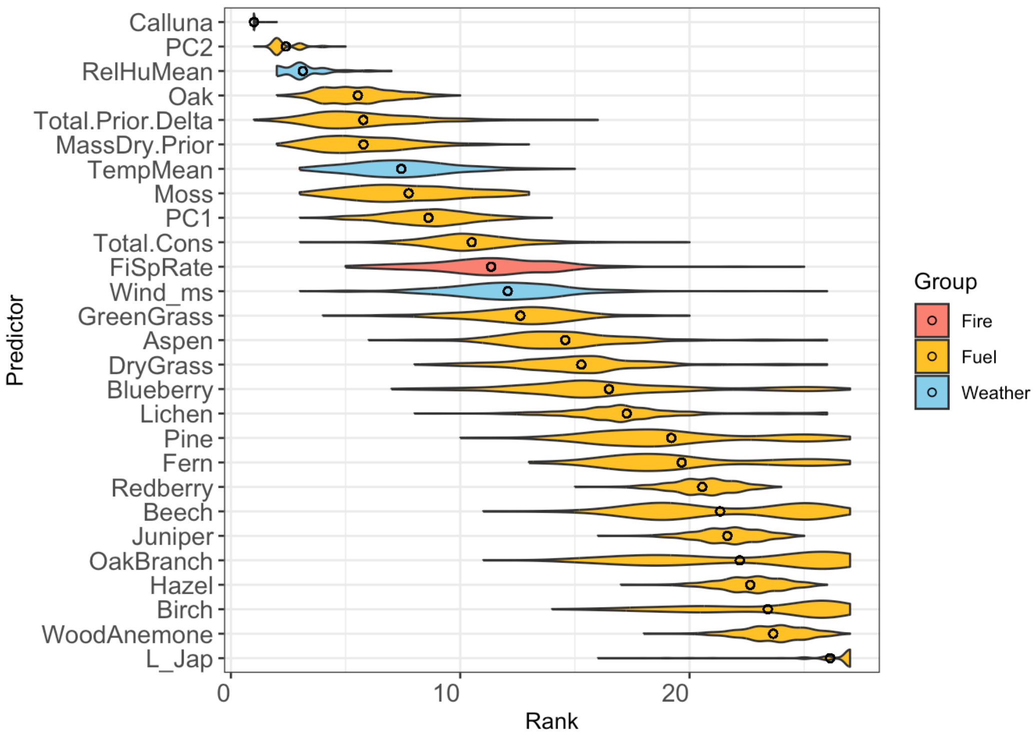

Figure 6 Ranking the predictors according to their importance in the Random Forest Model with maximum temperature as the response variable.

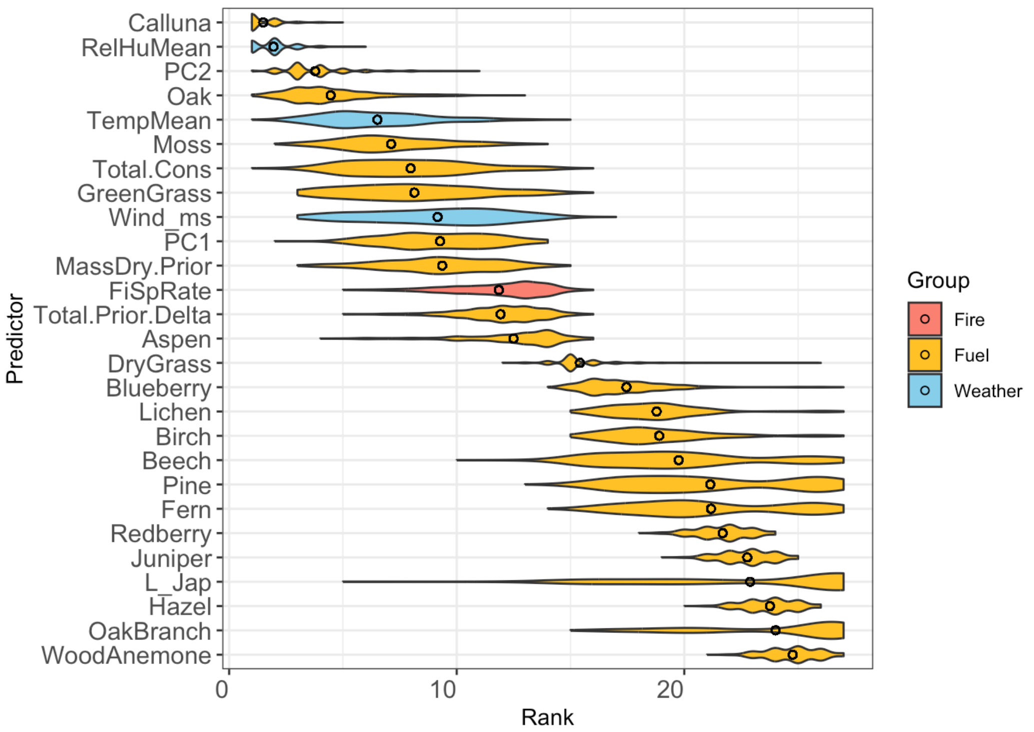

Figure 7 Ranking the predictors according to their importance in the Random Forest Model with cumulative temperature ºC as the response variable.

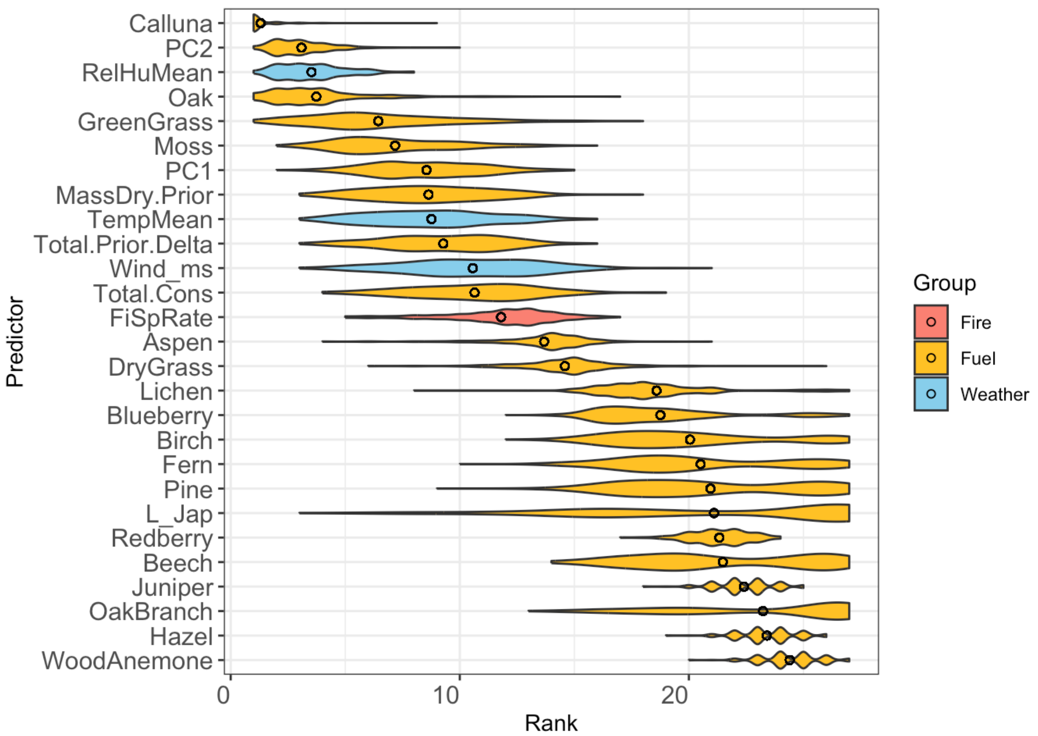

Figure 8 Ranking the predictors according to their importance in the Random Forest Model with temperature above the threshold, in seconds, of 60ºC as the response variable.

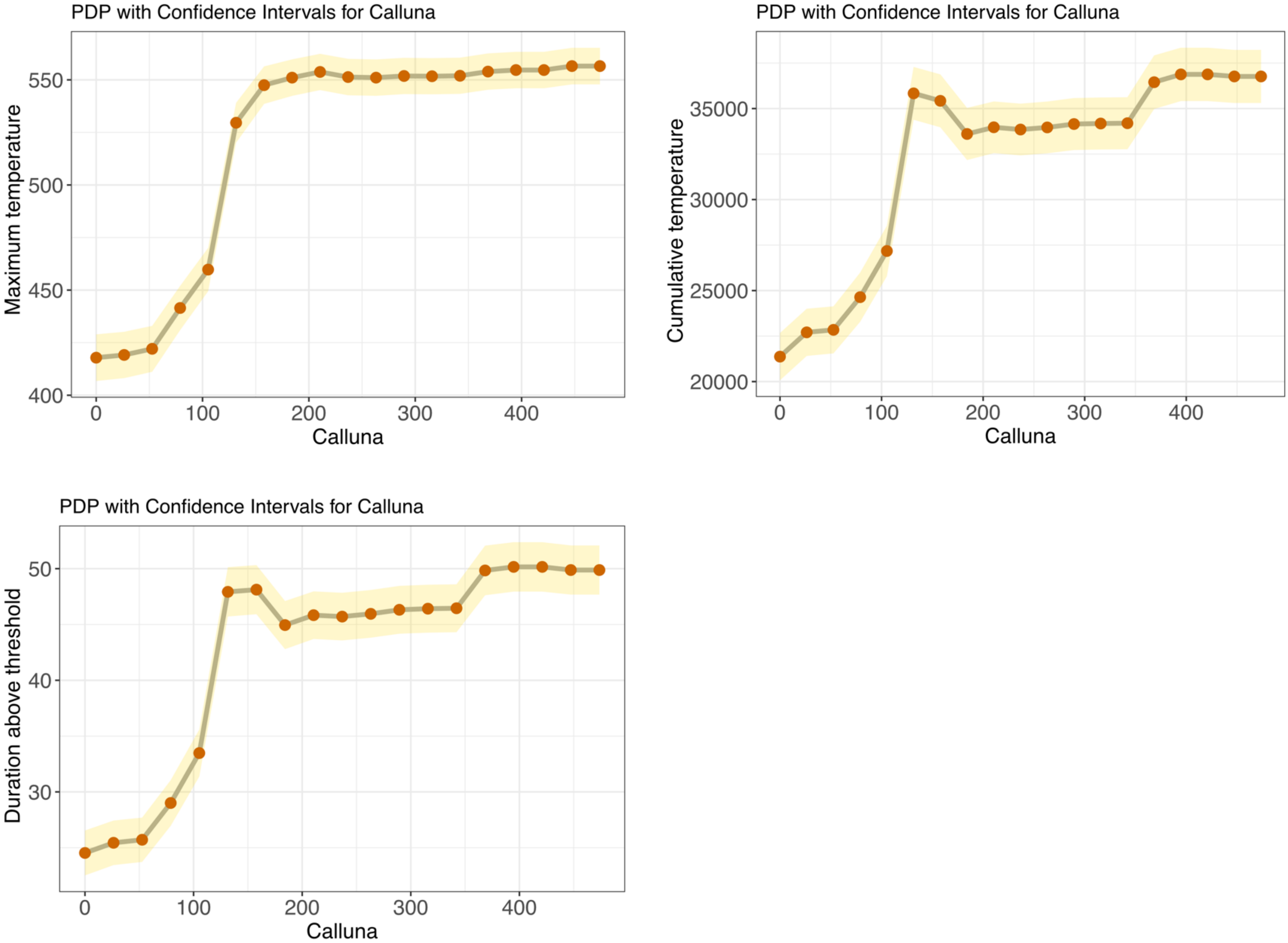

Figure 9 Response of maximum temperature, cumulative temperature and temperature duration above the threshold to Calluna (g/m^2) in random forest regression. Confidence intervals are shown by yellow shading. Y-axis is the average of the predictions made by all the individual trees in the forest. Cumulative temperature is the sum of the temperatures above 60ºC sampled with one second resolution.

Calluna always ranked first (Figure 6, Figure 7, Figure 8). The mass of heather of 100g/m^2 appeared as an important threshold in the temperature dynamics (Figure 9): sites with the mass of heather above this value showed increases in the response variables.

3.2.2 Weather conditions

Partial Dependence Plots (PDP) visualize the partial effect of each environmental variable on the modelled fire temperature metrics. For each of the predictors (relative humidity mean, wind speed and mean temperature) separate PDPs were created with three indices relative humidity mean, duration above 60ºC (threshold) and mean temperature.

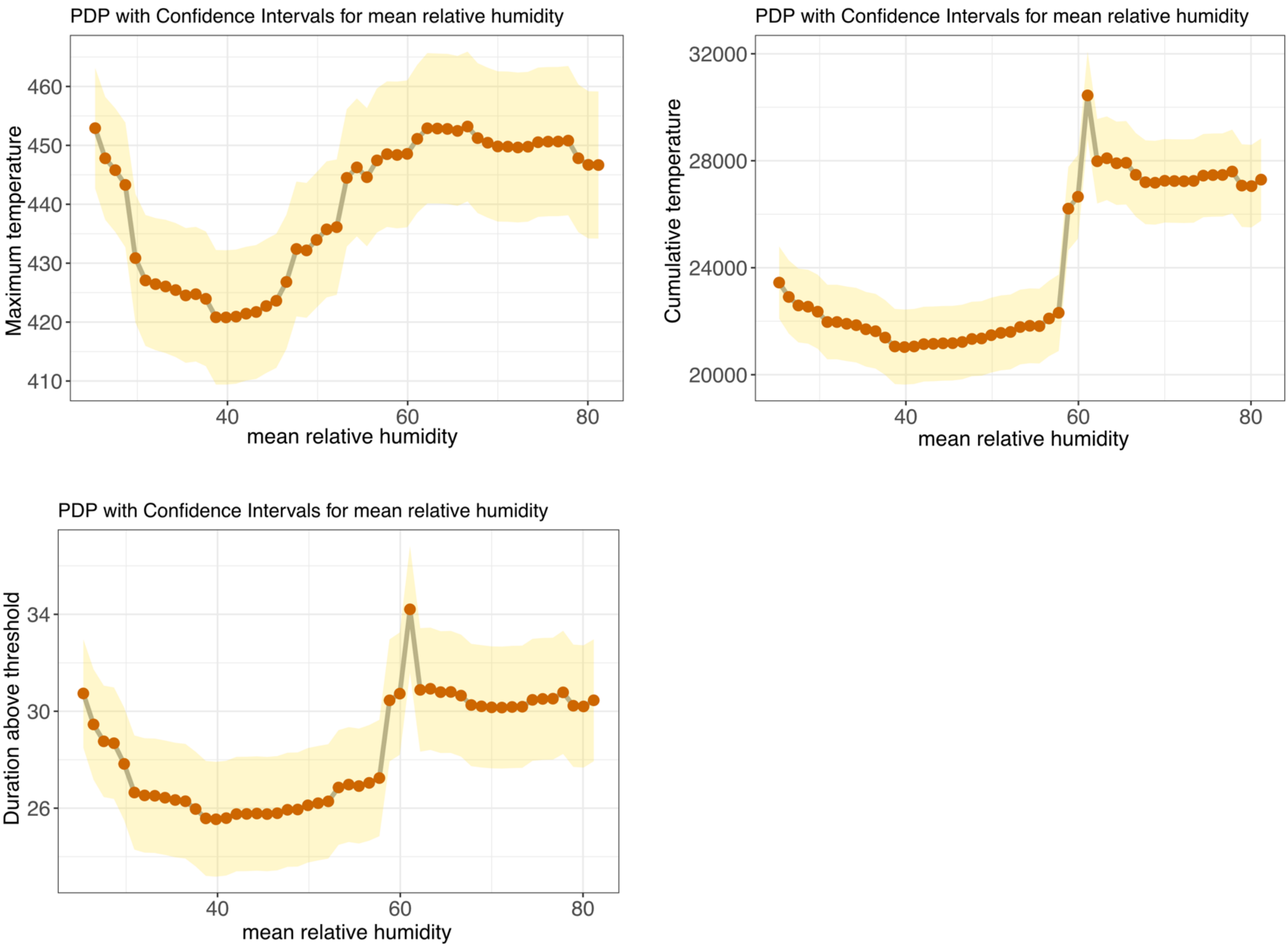

Figure 10 Response of maximum temperature, cumulative temperature and temperature duration above the threshold to relative humidity (%) in random forest regression. Confidence intervals are shown by yellow shading. Y-axis is showing the average of the predictions made by all the individual trees in the forest. Cumulative temperature is the sum of the temperatures above 60ºC sampled with one second resolution.

Confidence intervals for the relative humidity mean show different thresholds at which the indices maximum temperature, cumulative temperature and duration above threshold spike (Figure 10). For duration above threshold and cumulative temperature (the added durations of temperatures exceeding 60ºC) the threshold is at around 60% of relative humidity mean. They both showed a dip at 40% relative humidity and after the spike they level off. For the maximum temperature this threshold starts a bit earlier and less abrupt, at around 53% relative humidity mean. It starts with a decrease at the lover humidity levels and plateaus at the higher relative humidities.

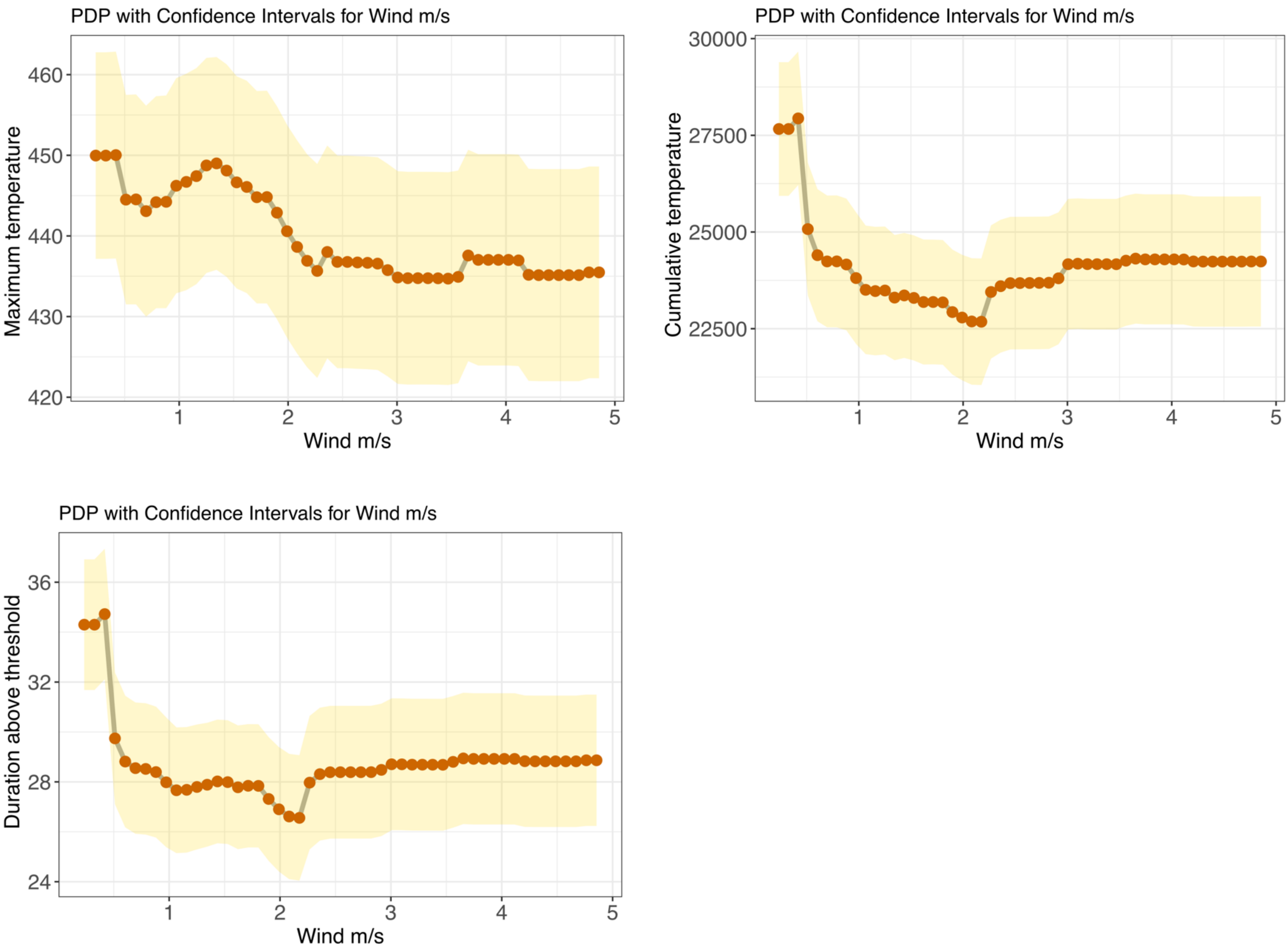

Figure 11 Response of maximum temperature, cumulative temperature and temperature duration above the threshold to wind speed m/s in random forest regression. Confidence intervals are shown by yellow shading. Y-axis is the average of the predictions made by all the individual trees in the forest. Cumulative temperature is the sum of the temperatures above 60ºC sampled with one second resolution.

Cumulative temperature and duration above threshold are similar (Figure 11), as seen in Figure 10, with a decrease in the start at around 0.5 m/s. After this decrease both, cumulative temperature and duration above threshold make a small increase again at 2.3 m/s. Maximum temperature on the other hand declined gradually with increasing wind speed and flattens towards the end.

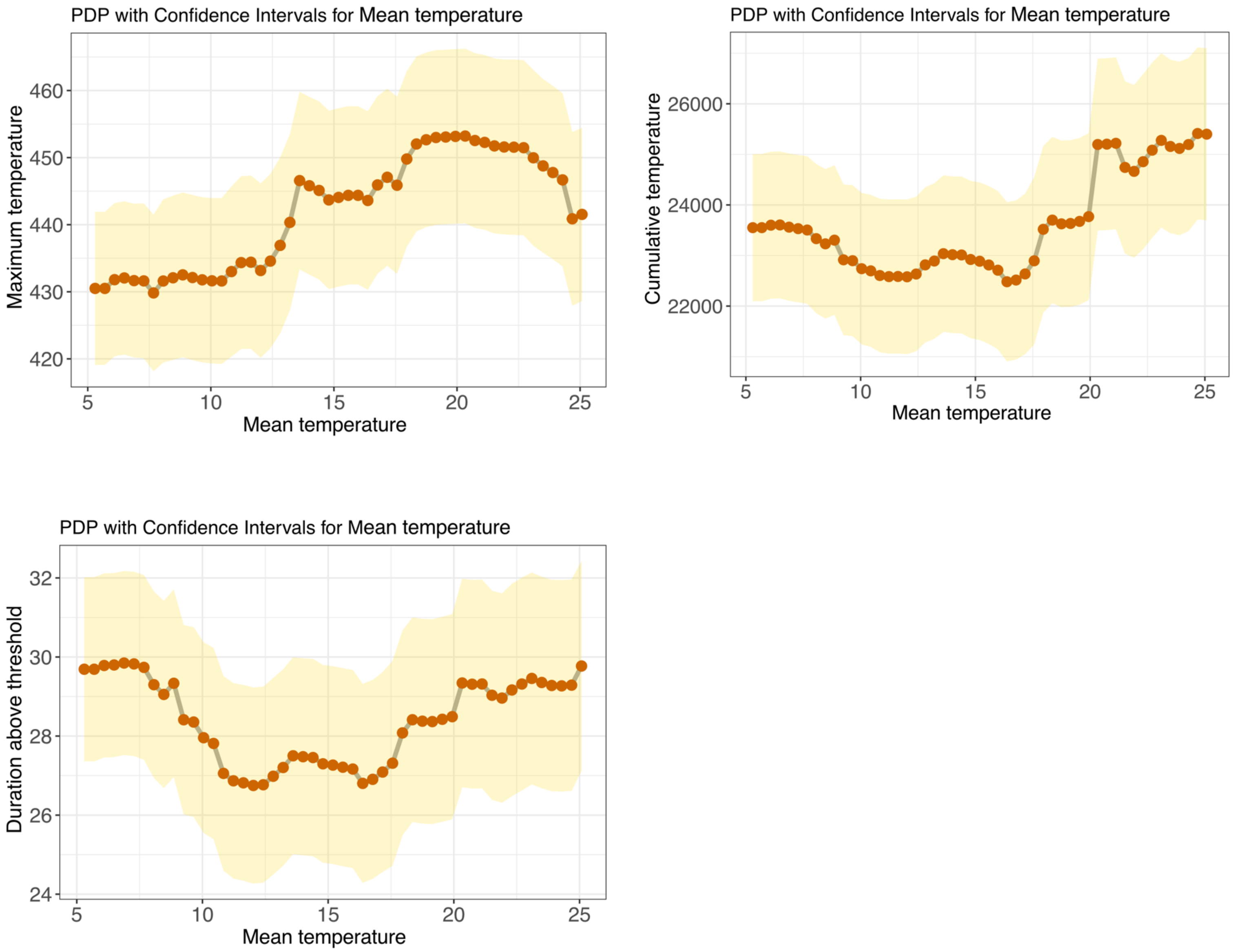

Figure 12 Response of maximum temperature, cumulative temperature and temperature duration above the threshold to mean temperature (ºC) in random forest regression. Confidence intervals are shown by yellow shading. Y-axis is the average of the predictions made by all the individual trees in the forest. Cumulative temperature is the sum of the temperatures above 60ºC sampled with one second resolution.

The confidence intervals for mean temperature are shown (Figure 12). Each weather index has its own distinct graph. Maximum temperature increases with higher mean temperature and cumulative temperature has a stronger increase at 20ºC mean temperature with a slight increase following. Duration above threshold shows a dip at 16ºC, after which an upward trend at higher temperatures follows.

4. Discussion

4.1 The contribution of fuels to fire temperature

Calluna exhibited the strongest influence on variability in fire temperatures (Figure 5). Heather is a small shrub with a dense and fine-branched, twiggy structure. It contains volatile organic compounds, mainly terpenes, as well as oils and resin, which promote its flammability (Isidorov *et al.* 2022). Pine appeared to have a strong influence on higher fire temperature thresholds (400-600ºC) and intermediate durations (20-90 seconds) (Figure 5), aligning with its known flammability due to resin-rich needles (Kush *et al.* 2019). Pine's fuel properties facilitate high intensity burning, but in Figure 6 Pine ranks in the lower end as a predictor of fire temperature. Redberry indicated the ability of being able to carry moderate fire temperatures over a shorter duration, but lower temperature over longer durations, with its distinct combination where mean dry mass was highest (Figure 5). PC2, compared to Calluna, had a rather broad distribution in the moderate spectrum, represented in fires of short to moderate duration and low to moderate temperature, indicating its role in sustaining and carrying the fire. Hotter fires were associated with a lower percentage of mean dry mass of PC2, which includes fuels from oak-branch and birch. Moss showed varying contributions to fire temperature across most thresholds and durations, except for one at 700ºC, suggesting a negligible role in fires, likely due to its high-water retention capacity and low combustibility (Moore *et al.* 2017). The moss that burned at 700ºC could have been rather dry already, which is corresponds to the minimum duration of 3 seconds at which it occurred (Figure 5Figure 5). Aspen on the other hand displayed moderate contributions to variability in fire temperatures, less extensive than Calluna but more pronounced than beech or oak. Aspen seems to be burning very quickly, carrying the fire only for shorter durations and at lower intensities, following findings described by Nesbit *et al.* (2023). More broadleaf species are showing similar tendencies in studies from Plathner *et al.* (2022) and Oliveira *et al.* (2023). In contrast, oak and beech were associated with lower fire temperature thresholds and short fire residence times (Figure 5), suggesting a more passive role in fire propagation - likely due to higher moisture content and lower flammability (Bobek *et al.* 2019).

Calluna, aspen and pine are the most critical fuels influencing intense and sustained fire behavior, whereas oak, beech and redberry seem to rather inhibit higher temperatures and damp the fire, leading to lower intensities. This pattern is also being described by Plathner et al. (2022). There is a visible high variability of patterns in the different fuels, as well as heat variability (Figure 5) followed consequentially by variability in ecological effects. The highest fire temperatures were caused by Calluna, allover intermediate associated with moss, redberry and aspen, while lower with oak and beech.

4.2 Weather contribution to fire temperature

Relative humidity shows non-linear effects in contribution to fire's temperature (Figure 10). The decline in maximum and cumulative temperature at low humidity may reflect limited moisture buffering in fuels, leading to quicker ignition but lower total heat release. The mid-range spike (60%) in cumulative temperature and duration above threshold signal for optimal conditions for longer smoldering. This may be a threshold beyond which higher humidity dampens fire intensity. Low humidity values are known to be an important part of extreme fire weather, together with high temperatures (Pereira et al. 2020). Interestingly, RH of 55% and above was associated with a higher maximum temperature of the fire (Figure 10). This finding seems counterintuitive as normally, higher fire temperatures and extreme fire weather are associated with lower RH (Jain *et al.* 2022). However, it can be explained by shifting from flaming to smoldering combustion. The "spike" at mid-range RH might not reflect more intense flames, but longer-lasting, lower-intensity fires, which can produce higher cumulative heat. Smoldering is often enhanced under moderate RH, where fuels aren't too wet (Frandsen 1987). Another explanation could be fuel composition and its structure. A lower fuel packing ratio supports heat transfer and consequentially enhances rate of fire spread, while higher packing ratio reduces the fire spread through a slower heat transfer. There might have been a higher packing ratio of fuels in researched forests, slowing down the fire, holding it in place and thereby adding towards cumulative temperature (He *et al.* 2021). In this study the range of variability available in weather conditions can also be an influence on these outcomes.

Wind had suppressive effects on cumulative temperature and duration above threshold of 60ºC at lower wind speeds (Figure 11), starting at 0.5 m/s, which is surprising, because wind is often linked to increasing fire spread (Beer 1991). However, wind may have dispersed heat more quickly and inhibited heat accumulation. The flat trend in maximum temperature maybe suggests that peak temperatures are less sensitive to wind than cumulative temperatures. The decrease in oxygen levels during a fire, leads to a longer ignition time, consequently reducing flame temperatures (Yang *et al.* 2022). Fast heat dissipation may have led to not enough energy being supplied to the specific points. The burned plots in this study were rather short compared to natural fires, which may have led to wind not having a great chance on influencing the fire temperatures.

The maximum temperature increased with higher ambient temperature (Figure 12). The dips in cumulative temperature and duration above thresholds near 16ºC followed by increases are an artefact of the dataset in this study.
The violin graphs (Figure 6, Figure 7, Figure 8) give us a clear ranking of the predictors, putting even more emphasis on Calluna, RH, PC2 and oak. Fuels seem to dominate the weather predictors and are fundamental for temperature behavior in this study. Fuel types influence the fire spread, but in case of larger fires weather condition become the dominant factor (Podur & Martell 2009). Fires then tend to burn fuels depending on their availability, rather than burning the highly flammable fuels first.

4.3 Forest management implications

Oak regeneration in Southern Sweden has been shown to positively respond to historical fires (Drobyshev *et al.* 2021). Current efforts to maintain oak in forest canopies increasingly involve the use of prescribed low severity fires. Knowledge of temperature variability during such fires is critical for preserving a pool of oak meristems surviving fire above and below ground. My study provides baseline data on the variability of fire temperatures expected during such burns. The study findings suggest that reducing the amount of heather and pine fuels, the typical components of fuel loads in many oak-pine forests can be effective means in reducing maximum temperatures and fire residence time and, in this way, ensuring low severity of fire. Keeping a prescribed burn at a low-severity with a fire temperature of 200ºC, helps oak establishment and alters the soil conditions to its advantage (Boerner & Brinkman 2003).

The findings of this thesis support the improvement and development of flexible, fuel-specific guidelines that expand the range of conditions under which prescribed fires can be conducted safely. Understanding how different fuels influence fire temperature and duration is critical for managers wanting to specifically benefit oak establishment. Furthermore, using fire as a natural disturbance, knowing temperature variability can be a help to create more of a mosaic in the landscapes, thereby supporting and aiming for the ecosystem's ecological resilience (Felton *et al.* 2024).

5. Conclusion

1. Calluna is the strongest predictor for fire temperature, followed by relative humidity, PC2 and oak.
2. Fuels have a greater influence on fire temperature than weather.
3. There is a need to improve Sweden's guidelines specifically for prescribed burns in oak-dominated forests.
4. There is a need for further research including a wider range of weather conditions, as a limitation for this study was mild weather predictors, poorly reflecting those occurring during natural fires.
5. There is a need for experiments with greater size of the burn plots, as it is hard to monitor natural fire behavior without capturing full winds potential.

References

Aamodt, E., Jiang, L., Fjellgaard Mikalsen, R., Olav Snersrud, D., Vermina Plathner, F., Sjöström, J., Rosnes, M. & Synnøve Skilbred, E. (2024). Development of large lab-scale fire dynamics experiments relevant for Scandinavian wildfire behaviour. *Journal of Physics: Conference Series,* 2885(1), 012069. https://doi.org/10.1088/1742-6596/2885/1/012069

Agee, J.K. & Skinner, C.N. (2005). Basic principles of forest fuel reduction treatments. *Forest Ecology and Management,* 211(1), 83-96. https://doi.org/https://doi.org/10.1016/j.foreco.2005.01.034

Alexander, M.E. & Quintilio, D. (1990). Perspectives on experimental fires in Canadian forestry research. *Mathematical and Computer Modelling,* 13(12), 17-26. https://doi.org/https://doi.org/10.1016/0895-7177(90)90095-5

Beer, T. (1991). The interaction of wind and fire. *Boundary-Layer Meteorology,* 54(3), 287-308. https://doi.org/10.1007/BF00183958

Bobek, P., Svobodová-Svitavská, H., Pokorný, P., Šamonil, P., Kuneš, P., Kozáková, R., Abraham, V., Klinerová, T., Švarcová, M.G., Jamrichová, E., Krauseová, E. & Wild, J. (2019). Divergent fire history trajectories in Central European temperate forests revealed a pronounced influence of broadleaved trees on fire dynamics. *Quaternary Science Reviews,* 222, 105865. https://doi.org/https://doi.org/10.1016/j.quascirev.2019.105865

Boerner, R.E.J. & Brinkman, J.A. (2003). Fire frequency and soil enzyme activity in southern Ohio oak–hickory forests. *Applied Soil Ecology,* 23(2), 137-146. https://doi.org/https://doi.org/10.1016/S0929-1393(03)00022-2

Breiman, L. (2001). Random Forests. *Machine Learning,* 45(1), 5-32. https://doi.org/10.1023/A:1010933404324

Cogos, S., Roturier, S. & Ostlund, L. (2020). The origins of prescribed burning in Scandinavian forestry: the seminal role of Joel Wretlind in the management of fire-dependent forests. *European Journal of Forest Research,* 139(3), 393--406. https://doi.org/10.1007/s10342-019-01247-6

Collins, L., Trouvé, R., Baker, P.J., Cirulus, B., Nitschke, C.R., Nolan, R.H., Smith, L. & Penman, T.D. (2023). Fuel reduction burning reduces wildfire severity during extreme fire events in south-eastern Australia. *Journal of Environmental Management,* 343, 118171. https://doi.org/https://doi.org/10.1016/j.jenvman.2023.118171

de Groot, B. (2012). *CANFIRE model*. Frontline Express. https://ostr-backend-prod.azurewebsites.net/server/api/core/bitstreams/b99345d6-5157-4500-bcc6-fc333bc89d20/content

Drobyshev, I., Niklasson, M., Ryzhkova, N., Gotmark, F., Pinto, G. & Lindbladh, M. (2021). Did forest fires maintain mixed oak forests in southern Scandinavia? A dendrochronological speculation. *Forest Ecology and Management,* 482. https://doi.org/10.1016/j.foreco.2020.118853

Felton, A., Seidl, R., Lindenmayer, D., Messier, C., Löf, M., de Koning, J., Ranius, T., Hedwall, P.-O., Trinidad, M., Torres-Garcia, M. & Felton, A. (2024). The choice of path to resilience is crucial to the future of

production forests. *Nature Ecology & Evolution,* 8. https://doi.org/10.1038/s41559-024-02473-x
Frandsen, W.H. (1987). The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. *Canadian Journal of Forest Research,* 17(12), 1540-1544. https://doi.org/10.1139/x87-236
Gedalof, Z. (2011). Climate and Spatial Patterns of Wildfire in North America. In: McKenzie, D., Miller, C. & Falk, D.A. (eds) *The Landscape Ecology of Fire*. Springer Netherlands. 89-115. https://doi.org/10.1007/978-94-007-0301-8_4
Granström, A. & Niklasson, M. (2008). Potentials and limitations for human control over historic fire regimes in the boreal forest. *Philosophical Transactions of the Royal Society B-Biological Sciences,* 363(1501), 2353--2358.
He, Q., Liu, N., Xie, X., Zhang, L., Zhang, Y. & Yan, W. (2021). Experimental study on fire spread over discrete fuel bed-Part I: Effects of packing ratio. *Fire Safety Journal,* 126, 103470. https://doi.org/https://doi.org/10.1016/j.firesaf.2021.103470
Isidorov, V.A., Pirożnikow, E., Spirina, V.L., Vasyanin, A.N., Kulakova, S.A., Abdulmanova, I.F. & Zaitsev, A.A. (2022). Emission of volatile organic compounds by plants on the floor of boreal and mid-latitude forests. *Journal of Atmospheric Chemistry,* 79(3), 153-166. https://doi.org/10.1007/s10874-022-09434-3
Jain, P., Castellanos-Acuna, D., Coogan, S.C.P., Abatzoglou, J.T. & Flannigan, M.D. (2022). Observed increases in extreme fire weather driven by atmospheric humidity and temperature. *Nature Climate Change,* 12(1), 63-70. https://doi.org/10.1038/s41558-021-01224-1
Karamizadeh, S., Abdullah, S.M., Manaf, A.A., Zamani, M. & Hooman, A. (2013). An Overview of Principal Component Analysis. *Journal of Signal and Information Processing,* 4(3B), 173-175. https://doi.org/10.4236/jsip.2013.43B031.
Kassambara, A. & Mundt, F. (2020). factoextra: Extract and Visualize the Results of Multivariate Data Analyses. https://CRAN.R-project.org/package=factoextra
Keane, R.E. (2014). *Wildland Fuel Fundamentals and Applications*. 1 edition, Springer Cham. https://doi.org/https://doi.org/10.1007/978-3-319-09015-3
Keeley, J.E. (2009). Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire,* 18, 116-126. https://doi.org/10.1071/WF07049
Kuhn, M. (2008). Building Predictive Models in R Using the caret Package. *Journal of Statistical Software,* 28(5), 1 - 26. https://doi.org/10.18637/jss.v028.i05
Kush, J., Maggard, A., Barlow, B. & Armstrong, J. (2019). *Prescribed Fire: The Fuels Component*. https://www.aces.edu/blog/topics/fire/prescribed-fire-the-fuels-component/ [25.04.2025]
Liaw, A. & Wiener, M. (2002). Classification and Regression by randomForest. *RNews,* 2(3), 18-22. https://CRAN.R-project.org/doc/Rnews/
Lindbladh, M., Axelsson, A.L., Hultberg, T., Brunet, J. & Felton, A. (2014). From broadleaves to spruce - the borealization of southern Sweden. *Scandinavian Journal of Forest Research,* 29(7), 686--696.

Lutes, D.C. (2017). *FOFEM 6.4: First Order Fire Effects Model user guide*.
Moore, P.A., Lukenbach, M.C., Kettridge, N., Petrone, R.M., Devito, K.J. & Waddington, J.M. (2017). Peatland water repellency: Importance of soil water content, moss species, and burn severity. *Journal of Hydrology,* 554, 656-665. https://doi.org/https://doi.org/10.1016/j.jhydrol.2017.09.036
Neary, D.G., Ryan, K.C. & DeBano, L.F. (2005). *Wildland fire in ecosystems: effects of fire on soils and water*. https://doi.org/10.2737/rmrs-gtr-42-v4
Nesbit, K.A., Yocom, L.L., Trudgeon, A.M., DeRose, R.J. & Rogers, P.C. (2023). Tamm review: Quaking aspen's influence on fire occurrence, behavior, and severity. *Forest Ecology and Management,* 531, 120752. https://doi.org/https://doi.org/10.1016/j.foreco.2022.120752
Niklasson, M. & Granström, A. (2000). Numbers and sizes of fires: Long-term spatially explicit fire histrory in a Swedish boreal landscape. *Ecology,* 81(6), 1484-1499. https://doi.org/https://doi.org/10.1890/0012-9658(2000)081[1484:NASOFL]2.0.CO;2
Nilsson, M. (2005). *Naturvårdsbränning*
Vägledning för brand och bränning i skyddad skog.
Nilsson, S., Niklasson, M., Hedin, J., Eliasson, P. & Ljungberg, H. (2005). Biodiversity and sustainable forestry in changing landscapes - principles and Southern Sweden as an example. *Journal of Sustainable Forestry,* 21(2/3), 11--43.
Oksanen, J., Blanchet, F.G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., Minchin, P.R., O'Hara, R.B., Simpson, G.L., Solymos, P., Stevens, M.H.H., Szoecs, E. & Wagner, H. (2025). *vegan: Community Ecology Package*. https://CRAN.R-project.org/package=vegan]
Oliveira, A.S., Silva, J.S., Guiomar, N., Fernandes, P., Nereu, M., Gaspar, J., Lopes, R.F.R. & Rodrigues, J.P.C. (2023). The effect of broadleaf forests in wildfire mitigation in the WUI – A simulation study. *International Journal of Disaster Risk Reduction,* 93, 103788. https://doi.org/https://doi.org/10.1016/j.ijdrr.2023.103788
Pausas, J.G. & Keeley, J.E. (2023). Evolutionary fire ecology: An historical account and future directions. *BioScience,* 73(8), 602-608. https://doi.org/10.1093/biosci/biad059
Pereira, M.G., Parente, J., Amraoui, M., Oliveira, A. & Fernandes, P.M. (2020). The role of weather and climate conditions on extreme wildfires. In: Tedim, F., Leone, V. & McGee, T.K. (eds) *Extreme Wildfire Events and Disasters: Root Causes and New Management Strategies*. 55--72. https://doi.org/10.1016/B978-0-12-815721-3.00003-5
Plathner, F.V., Sjostrom, J. & Granström, A. (2022). Influence of tree species on surface fuel structure in Swedish forests. In. 1157-1166. https://doi.org/10.14195/978-989-26-2298-9_176
Pluchon, N., Vincent, A., Gundale, M., Nilsson, M.C., Kardol, P. & Wardle, D.A. (2016). The impact of charcoal and soil mixtures on decomposition and soil microbial communities in boreal forest. *Applied Soil Ecology,* 99, 40-50. https://doi.org/10.1016/j.apsoil.2015.11.020
Podur, J.J. & Martell, D.L. (2009). The influence of weather and fuel type on the fuel composition of the area burned by forest fires in Ontario, 1996–2006.

Ecological Applications, 19(5), 1246-1252. https://doi.org/https://doi.org/10.1890/08-0790.1
Posit team (2025). *RStudio: Integrated Development Environment for R*. http://www.posit.co/]
Precht, H., Christophersen, J., Hensel, H. & Larcher, W. (2012). *Temperatur und Leben*. 1 edition, Springer Berlin, Heidelberg. https://doi.org/https://doi.org/10.1007/978-3-642-65708-5
R Core Team (2024). *R: A Language and Environment for Statistical Computing*. https://www.R-project.org/]
Roces-Díaz, J.V., Santín, C., Martínez-Vilalta, J. & Doerr, S.H. (2022). A global synthesis of fire effects on ecosystem services of forests and woodlands. *Frontiers in Ecology and the Environment,* 20(3), 170-178. https://doi.org/https://doi.org/10.1002/fee.2349
Scheller, R.M., Domingo, J.B., Sturtevant, B.R., Williams, J.S., Rudy, A., Gustafson, E.J. & Mladenoff, D.J. (2007). Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution. *Ecological Modelling,* 201(3-4), 409-419. https://doi.org/10.1016/j.ecolmodel.2006.10.009
Schimmel, J. & Granström, A. (1997). Fuel succession and fire behavior in the Swedish boreal forest. *Canadian Journal of Forest Research,* 27(8), 1207-1216. https://doi.org/10.1139/x97-072
Sjörs, H. (1999). The background: geology, climate and zonation. *Acta Phytogeographica Suecica,* 84, 5-14.
Sveriges meteorologiska och hydrologiska institut (2025). *Ladda ner väderobservationer*. https://www.smhi.se/data/hitta-data-for-en-plats/ladda-ner-vaderobservationer/precipitationMonthlySum/66430 [02.06.2025]
Tanskanen, H., Granström, A., Larjavaara, M. & Puttonen, P. (2007). Experimental fire behaviour in managed Pinus sylvestris and Picea abies stands of Finland. *International Journal of Wildland Fire,* 16(4), 414-425. https://doi.org/https://doi.org/10.1071/WF05087
Verma, S. & Jayakumar, S. (2012). Impact of forest fire on physical, chemical and biological properties of soil: A review. In.
Wepryk, O.T. (2023). *Effects of fuel and weather conditions on forest fire behaviour in Southern Sweden in oak dominated forests.* Sveriges lantbruksuniversitet.
Westerling, A.L., Hidalgo, H.G., Cayan, D.R. & Swetnam, T.W. (2006). Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science,* 313(5789), 940-943. https://doi.org/doi:10.1126/science.1128834
Yang, W., Gardelin, M., Olsson, J. & Bosshard, T. (2015). Multi-variable bias correction: application of forest fire risk in present and future climate in Sweden. *Nat. Hazards Earth Syst. Sci.,* 15(9), 2037-2057. https://doi.org/10.5194/nhess-15-2037-2015
Yang, Y., Fu, T., Song, F., Song, X., Wang, X.-L. & Wang, Y.-Z. (2022). Wood-burning processes in variable oxygen atmospheres: Thermolysis, fire, and smoke release behavior. *Polymer Degradation and Stability,* 205, 110158. https://doi.org/https://doi.org/10.1016/j.polymdegradstab.2022.110158

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The AI website elicit.com has partially been used to find research articles.

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