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Estimating Future Forest Fire Risk in Gävleborg County Sweden in 2041-2070 Following RCP 8.5

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Abstract

Forest fires can act as an ecosystem service by providing habitat renewal, controlling pests, and reducing the risk of extreme fires, but can at the same time disturb an ecosystem negatively. Furthermore, forest fires release carbon dioxide into the atmosphere, damage property, and lead to health issues. With climate change, forest fires are expected to increase in both frequency and intensity in many areas of the world. However, models predict different results for future forest fire occurrence. The recent increase of forest fires in Sweden calls for a greater understanding of the future change in forest fire risk. The aim of this thesis is to estimate the future forest fire risk score and fire occurrence in Gävleborg county in Sweden in 2041-2070. The future forest fire risk was adjusted to climate projections of RCP 8.5. The method included a development of a simple model using the most important forest fire risk parameters in Gävleborg county in present-day. The construction of the model was done by a literature study as well as fitting the models risk score areas to observed fire data. A present-day estimation of forest fire risk score in 2006-2010 was done based on the developed model. A validation of the model against past observations of actual fire occurrence was performed and lastly the future forest fire risk score was predicted. The validation of the model showed okay agreement. The results showed an increase of forest fire risk score in Gävleborg county in the future compared to the present-day. The factors deemed most important for forest fire occurrence were temperature, precipitation, aspect, forest type and distance to water course and water surfaces. In conclusion, the increase of areas with 'very high' risk score and 'high' risk score in the predicted future scenario could indicate an increase of the total annual number of fires in the summer season from 12 in the present-day to 16 in a future scenario in Gävleborg county.

Keywords: Future forest fire risk, RCP 8.5, Gävleborg county, Climate change, Forest fire

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> The wind is rising, we must try to live.
> - Paul Valéry

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1 Introduction

Forest fires globally lead to disruption of vegetation, high economic costs, health- and respiratory issues and increased carbon dioxide releases to the atmosphere (Bowman et al., 2009). Furthermore, an increase in forest fires can result in habitat loss and negatively affect biodiversity as seen in boreal forests (Palm et al., 2022). At the same time, forest fires contribute to habitat renewal and landscape heterogeneity, and act as an important ecosystem service by controlling pests and decreasing the risk for extreme fires (Flannigan et al., 2009; Pausas, 2019). It is likely that forest fires contribute to global warming (Flannigan et al., 2009), an effect which is expected to increase in the future, specifically in boreal regions (Oris et al., 2014).

The behavior of forest fires will probably change in a future climate (Doerr & Santín, 2016), as will the frequency of mega fires and other extreme fire events (Flannigan et al., 2009). Increased temperature will likely increase fire intensity (Doerr & Santín, 2016), prolong the fire season (Flannigan et al., 2009) and increase the severity of fires (Flannigan et al., 2013). However, global predictions of future fire risk have large regional variabilities (Krawchuk et al., 2009) especially in response to temperature increase (Flannigan et al., 1998). Forest fires in Sweden have been constant through the 20th century with an increasing trend in the latest years (Granström & Sjöström, 2020).

Forest fire risk depends on factors such as climate, human activities, and vegetation (Hantson et al., 2016). In Sweden, it has been shown that climatic variables have a strong correlation with forest fire activity (Drobyshev et al., 2012). Fuel moisture (i.e., the moisture of the leaves and bushes on the ground) and latitude were the most important factors controlling forest fire risk in Sweden according to Cimdins et al. (2022). Population density and road density were ranked as second most influential (Cimdins et al., 2022). Pinto et al. (2020) found the most important variable for occurrence of forest fires in Sweden to be human induced factors such as population density and road density, although climate variables were also deemed a main factor.

Estimations of forest fire risk depend on which future climate scenario and area is considered. Globally, hydrological responses to climate change will have regional variability making wet areas wetter and dry areas dryer (Held & Soden, 2006). This hydrological response is a result of the increase in lower tropospheric water vapor which will slow down the atmospheric circulation (Held & Soden, 2006). When focusing on Sweden, future climate projections show an annual increase in precipitation with a regional uncertainty for the summer period, where southern Sweden have a trend of decreasing precipitation (Hanssen-Bauer et al., 2005; Markku et al., 2004). The global mean surface temperature has increased by 1.09°C since 1850-1900 and is expected to increase further until at least 2040 (IPCC, 2023). The warming of Europe is faster than the global average and is expected to continue to develop in that direction (Bednar-Friedl, 2022). The climate scenario Representative Concentration Pathway of 8.5 (RCP 8.5) is the highest RCP scenario developed by the International Panel of Climate Change (IPCC) which predicts concentrations of greenhouse gases in the atmosphere and its consequences. It assumes a high population growth, high energy demands and limited technology development (Riahi et al., 2011).

Global models of future forest fire risk generally predict an increase over the entire globe in multiple scenarios, including the whole of Sweden (Flannigan et al., 2013). Global models generally have a lower level of detail in the data used for predictions which will generalize the results. Regional models predict different results in Sweden. Some show a higher risk in the whole of Sweden (Krikken et al., 2021), some show a higher risk in southern Sweden and a lower risk in northern Sweden (Yang et al., 2015), while others show no increase over Sweden (Migliavacca et al., 2013). This points to a knowledge gap in detailed future forest fire risk mapping in historic risk areas, such as Gävleborg county in Sweden, and there has been calls for more understanding on this subject (Granström, 2009).

1.1 Aim

The aim is to estimate the future forest fire risk score (FFRS) and fire occurrence in Gävleborg county in 2041-2070. The future FFRS is adjusted to a climate projection of RCP 8.5. Specific objectives are:

- To determine a simple model explaining the most important forest fire risk factors in Gävleborg county in present-day (2006-2010)
- To estimate the present-day forest fire risk score in 2006-2010
- To validate the method against past observations of actual forest fire occurrence
- To estimate the future forest fire risk score in 2041-2070

The research question is 'What is the forest fire risk score in Gävleborg county in 2041–2070, relative to the present-day forest fire risk score, in the context of global warming?'. The hypothesis is that the FFRS will increase in Gävleborg county in 2041-2070 due to the expected rise in temperature in a future climate.

1.2 Study area

Gävleborg county is located in the middle of Sweden (Figure 1). According to Statistics Sweden (Statistiska Centralbyrån) the approximate area of Gävleborg is 18,000 km^2 and 89% of the land is forested (2020a, 2020b). Gävleborg county has a yearly average temperature of 4°C and the area receives on a yearly average between 550-650 mm of precipitation (Harris et al., 2020; SMHI, 2023). The summers in Gävleborg have the peak temperature in July and peak precipitation in August (Harris et al., 2020). The future climate data for RCP 8.5 for Gävleborg in the years 2041–2070 points towards an increase in both average summer temperature and summer precipitation according to Swedish Meteorological and Hydrological Institute (2021a; 2021b).

Forest fires in Sweden have long been a natural part of the ecological disturbance, but in the latest years an increasing trend in fire occurrence and size has been observed (Granström & Sjöström, 2020). Gävleborg county was one of the five counties most affected by the extreme forest fires in 2018 which is why it is chosen for this analysis (Myndigheten för samhällskydd och beredskap, 2018b).

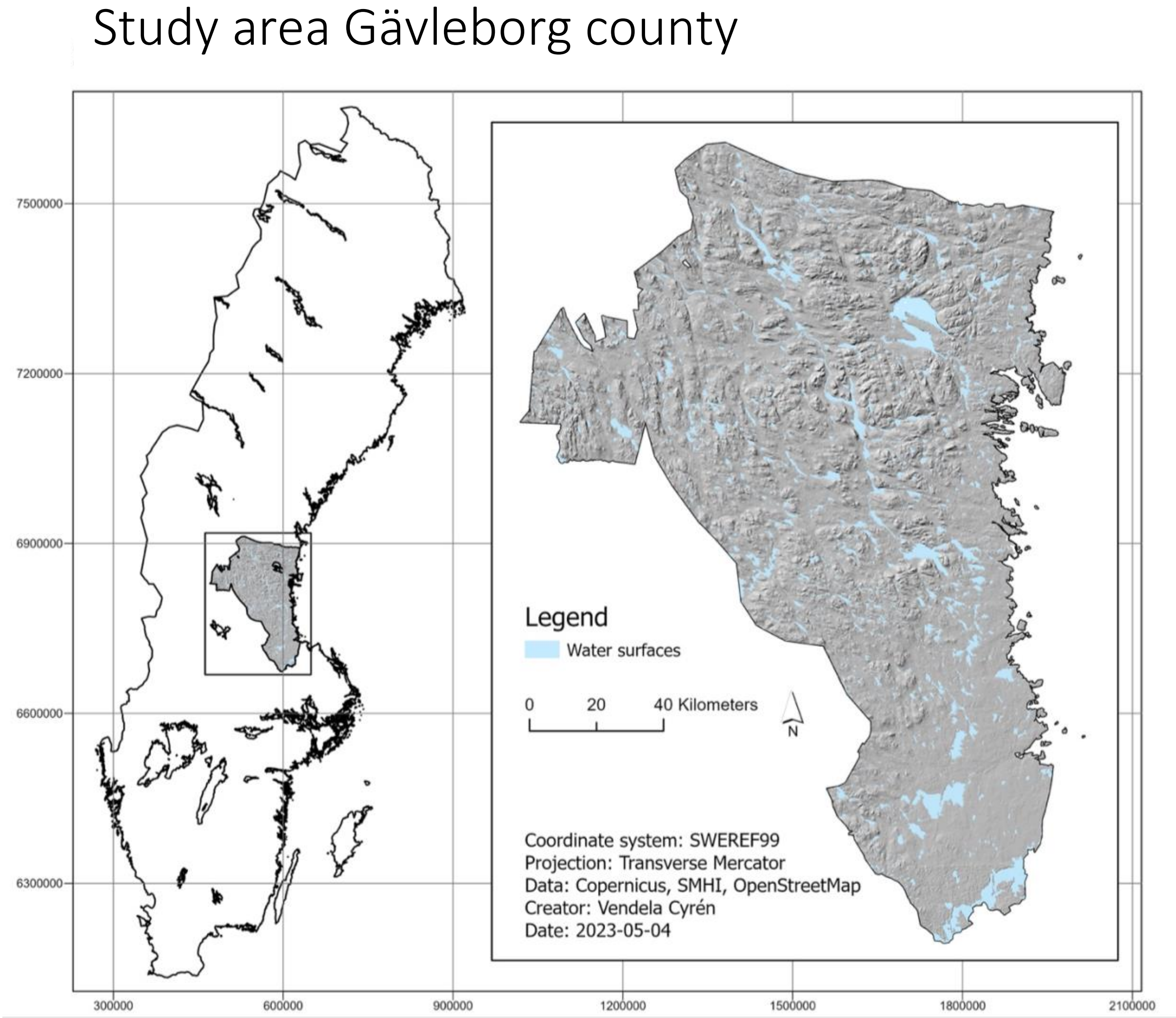


Figure 1. Location of study area Gävleborg county in Sweden. Blue color indicates water surfaces.

2 Methods

To predict the future forest fire risk in Gävleborg, a simple model for forest fire risk score (FFRS) was created. The model included ten parameters that affect flammability, ignition and spread, together accounting for forest fire risk (Table 2). Climatic variables of precipitation and temperature, morphological variables of slope and aspect, anthropogenic variables of distance to settlement, main roads and agricultural fields, and attenuation variables of forest type and distance to water courses and water surfaces were included in the forest fire risk score model. The specific data used can be found in Section 2.1.

The development of the FFRS model (Section 2.4) originated in a literature study on studies calculating future and current forest fire risk. Each risk parameter was assumed to affect the forest fire risk with a specific weight which was preliminary estimated by literature study. The weighting coefficients of the risk parameters in the model were then adapted (i.e., fitted to the study area) by comparing the predicted risk for different parameters to observed fire data from 2001 to 2005 (Section 2.2). The data sets that varied through the different FFRS estimations were temperature and precipitation data. The other parameters were assumed to be the same or very similar. The classes of risk per parameter were decided based on previous research (Section 2.3, Table 2). After the model was adjusted to the study area based on data from 2001-2005, one present-day FFRS for 2006–2010 and a future FFRS for 2041–2070 were predicted. The present-day FFRS was used for validation of the model by comparing the predicted risk with observed actual fire occurrence (Section 2.5).

This type of method, of assigning risk to different ranges of the parameter and weighting them after importance, has been done previously in other areas of the world with good validation results (Busico et al., 2019; Gheshlaghi, 2019; Nikhil et al., 2021; Nuthammachot & Stratoulias, 2021; Parajuli et al., 2023; Sivrikaya & Küçük, 2022).

2.1 Data

The resolution of the data varied with the highest of 10x10 meters and the lowest of 4x4 km (Table 1). The data were collected in both vector and raster format and then harmonized into the coordinate system for Sweden (SWEREF99) and projection Transverse Mercator.

Table 1. List of the data used in the study with its corresponding parameter, source, year, and resolution.

Data	Parameter	Source	Year	Resolution
Digital elevation model	Slope	Copernicus	2011	25m
	Aspect			
Historical climate data	Temperature 2001–2010 June–Aug	Swedish Meteorological and Hydrological Institute (SMHI)	2001–2010	25m
	Precipitation 2001–2010 June–Aug			
Future climate data	Temperature 2041–2070 June–Aug	SMHI – CORDEX downscaled	2021	4000m
	Precipitation 2041–2070 June–Aug			
Settlements	Distance to settlements	Copernicus	2015	10m
Agriculture areas	Distance to agriculture	Jordbruksverket	2021	10m

Forest type	Forest type	Copernicus	2018	10m
Roads	Distance to main roads (over 70 km/h)	OpenStreetMap	2023	Vector
Water courses	Distance to water courses	OpenStreetMap	2023	Vector
Water surfaces	Distance to water surfaces	SMHI	2016	Vector
Observed forest fires	Point of fire 2001-2010 June–Aug	MODIS, NASA	2001-2010	Vector

2.2 Development of the forest fire risk score model

In this model of forest fire risk score, it was assumed that the parameters affect the forest fire risk with different weights, i.e., coefficients. A preliminary weighting coefficient was assigned to each parameter based on a literature review (Section 2.2.1). The model was further adjusted by comparing the predicted risk score of each parameter in 2001-2005 (temperature, precipitation, aspect, slope, distance to roads, distance to settlements, distance to agriculture, distance to water courses, distance to water surfaces and forest type) with observed fires in the same years in Gävleborg county. The parameters weighting coefficients were adjusted manually depending on the placement of the observed fires and the predicted risk zones until the fit between observed fires and predicted risk was good (Section 2.2.2). The variables final weighting coefficients can be seen in Table 3.

2.2.1 Literature review for preliminary model

The literature review was the first step in understanding the different parameters connection to forest fire risk. Factors that affect forest fires in Sweden most were fuel moisture and latitude, followed by population and road density when comparing multiple factors (Cimdins et al., 2022). Pinto et al. (2020) found that low population density and high road density increased fire risk together with fuel characteristics in Sweden. In other parts of Europe, other factors seemed to be important. A study in Italy found that climatic variables (precipitation and temperature) were most important followed by slope and forest type in second place, and urban areas and agricultural land in third place (Busico et al., 2019). Novo et al. (2020) found that vegetation and climatic parameters of wind, relative humidity, precipitation, and temperature had the highest importance in Spain. Sivrikaya and Küçük (2022) found that distance to roads, settlement, agriculture, and rivers were most important in Turkey.

2.2.2 Finalizing the FFRS model by assigning coefficients

Equation 1 shows our developed FFRS model. Each parameter describing forest fire risk (temperature, precipitation, aspect, slope, distance to roads, distance to settlements, distance to agriculture, distance to water courses, distance to water surfaces and forest type) has a risk score parameter (TEMP, PRE, ASP, SLO, ROA, SET, AGR, WCO, WSU and FOR) (Table 2).

Firstly, each predicted risk score parameter in 2001-2005 was compared individually with the location of observed fires in 2001-2005 by comparing the location of observed fires with the predicted areas of high or very high risk score. The weighting coefficient ($c_{TEMP} \ldots$) for each risk score parameter was raised if more than 50% of the fires were in a 'high' or 'very high' risk score and lowered if more than 50% of the fires were located in 'medium', 'low', or 'very low' risk score. From this, the preliminary weighting coefficiens were obtained.

Secondly, the final values of weighting coefficients (c_{TEMP} …) were obtained by predicting a total forest fire risk score for the years 2001-2005 based on the preliminary weights in step 1. The total predicted FFRS was compared to the occurrence of forest fires observed in the years of 2001-2005. By manually varying the values of the coefficients, the agreement between locations of observed fires in 2001-2005 and predicted total FFRS in the same period was optimized. The weighting coefficients were ranging from 0-1 and added up to 1. Results for the fitting are shown in Section 3.1.

The total forest fire risk score (FFRS in Equation 1) was rounded to the nearest integer and ranged from 1-5. The individual risk parameters (temperature, precipitation, aspect, slope, distance to roads, distance to settlements, distance to agriculture, distance to water courses, distance to water surfaces and forest type) were classified into risk score parameters according to literature (Section 2.3, Table 2). The risk score parameters (TEMP, PRE, ASP, SLO, ROA, SET, AGR, WCO, WSU and FOR) in Equation 1 ranged from 1 to 5. In other words, the FFRS model uses the value of the risk score of the parameter (1-5), not the value of the parameter. Each risk score parameter was multiplied with its coefficient and rounded to the nearest integer ranging from 1-5. 1 represented 'very low' risk and 5 'very high' risk depending on the values in Table 2 (Section 2.3). The FFRS was calculated in ArcGIS Pro version 2.4.0.

$$FFRS = (TEMP \times c_{TEMP}) + (WCO \times c_{WCO}) + (WSU \times c_{WSU}) + (PRE \times c_{PRE}) + (ASP \times c_{ASP}) + (FOR \times c_{FOR}) + (SLO \times c_{SLO}) + (AGR \times c_{AGR}) + (ROA \times c_{ROA}) + (SET \times c_{SET}) \tag{1}$$

Equation 1 shows our 'FFRS model' for forest fire risk score (FFRS) of a given location, for the average risk over an entire summer of a given period of years. The risk score parameters are as follows. *TEMP* for temperature risk score, *WCO* for distance to water course risk score, *WSU* for water surface risk score, *PRE* for precipitation risk score, *ASP* for aspect risk score, *FOR* for forest type risk score, *SLO* for slope risk score, *AGR* for distance to agriculture risk score, *ROA* for distance to road risk score and *SET* for distance to settlement risk score. All risk score parameters are a function of the local conditions of forest fire risk at any given location and summer season, as described in Table 2. c stands for the weighting coefficient for each parameter.

2.3 Assigning the risk classes to the parameters

Each risk score parameter was divided into five scores of forest fire risk of 'Very high risk' (value 5), 'High risk' (4), 'Medium risk' (3), 'Low risk' (2) and 'Very low risk' (1). The ranges of the values in each risk score were decided based on a literature review and adapted to the study area which can be seen below. The ranges and scores can be seen in Table 2.

2.3.1 Slope and aspect

Slope and aspect were derived from a digital elevation model from 2011 over Europe with a resolution of 25x25 meters from the European Environment Agency in the database Copernicus. Aspect was classified based on western slopes having a high fire risk due to wind induced fires and late but high solar radiation (Veena et al., 2017). East and southeast facing slopes have high risk due to early incoming radiation which dries out the fuel on those aspects (Estes et al., 2017). The aspect parameter was divided into five groups were west to southwest slopes have the highest risk, followed by south, east, northwest, and north-northeast as lowest risk (Table 2).

Slope was classified based on steeper slopes having more heating of fuel (Estes et al., 2017). Furthermore, increased slope decreases fuel moisture and air humidity (Veena et al., 2017) which indicates that steeper slopes have a higher fire risk. Slope (◦) was classified 0–5, 5–15, 15–25, 25–35 and >35 (Table 2) which is similar to the classification from Gheshlaghi (2019), Novo et al. (2020), Sivrikaya and Küçük (2022) and Veena et al. (2017).

2.3.2 Parameters with distance risk

Data of water courses originated from OpenStreetMap and were downloaded in March 2023 and water surfaces from the Swedish Metrological and Hydrological Institute (SMHI) from 2016. Fire risk was found to be lower with closer distances to rivers and water bodies as they function as a fire break even though humans might be present and inducing risk near water streams (Busico et al., 2019).

Roads with a speed limit over 70 km/h originated from OpenStreetMap and were downloaded in March in 2023. Studies have shown that closer distances to roads or higher road density increased the fire risk in Iran and Italy (Abdi et al., 2018; Ricotta et al., 2018), as well as increased fire occurrence in Sweden (Pinto et al., 2020). It is sometimes seen as the most important human induced ignition factor (Eskandari, 2017) and has proven to correlate with forest fires (Nikhil et al., 2021).

Data of agricultural areas originated from the Swedish Board of Agriculture (Jordbruksverket) from 2021 and settlements originated from the European Commission from 2015. Both data sets had a resolution of 10x10 meters. Human ignition factors, for example agricultural practices or construction work, were found to be a main reason for forest fire ignition in Sweden (Ou, 2017). Higher population density was seen to correlate with higher fire occurrence in Sweden (Pinto et al., 2020). Distance to agricultural areas was assumed to have the same risk reasoning as settlements by increasing the ignition risk closer to the agricultural area due to human activities as done by Busico et al. (2019).

These five parameters were divided into risk classes according to a distance of 50 meters for each risk class (Table 2). Closer than 50 meters was the highest risk class of very high risk except for water courses and water surfaces where there was a higher risk with further distance from the parameter. The range of 50 meters per risk class was chosen based on an empirical study of the role of distance to roads in forest fire occurrence in Italy (Ricotta et al., 2018). It is common to use larger distances, but those are not tested empirically. 100 meters interval was used by Busico et al. (2019). Slightly bigger distances of around 200–250 meters have been used in similar analyses by Nuthammachot and Stratoulias (2021), Veena et al. (2017), and Sivrikaya and Küçük (2022).

2.3.3 Forest type

The forest type data was a high-resolution layer developed by European Environment Agency in 2018 and downloaded from Copernicus with coniferous and broad-leafed forested area above 0.5 hectare based on the FAO definition of a forest. Broad-leafed and deciduous forest had a higher risk of fire than conifer trees explained by higher fuel quantity on the ground due to the accumulation of leaves on the forest floor (Estes et al., 2017; Parajuli et al., 2023; Veena et al., 2017). Vegetation type has been stated the most important factor for forest fire risk in some instances, for example in California (Estes et al., 2017).

2.3.4 Climate data

Observed climate data of average monthly precipitation and temperature from SMHI for the summer months (June, July, August) from 2001-2010 was used with a resolution of 25x25 meters. Future climate data of temperature and precipitation for summer months in the year 2041–2070 according to the emission scenario of RCP 8.5 was obtained from the SMHI Advanced climate model from 2021 which is based on an average of multiple climate models. The future climate data is a downscaling of the CORDEX (Coordinated Regional Climate Downscaling Experiment). The modelled future summer temperature according to the scenario of RCP 8.5 in Gävleborg has an average increase of approximately 2.8°C compared to the reference period of 1970–2000 and the future precipitation rate has an increase of 7 mm/month which agrees with other scenarios for precipitation (Hanssen-Bauer et al., 2005; Markku et al., 2004). The classes of the climate data parameter were determined by equal intervals from climate data in 2001-2005 similar to the method by Busico et al. (2019) and can be found in Table 2.

Climate data has been found to be the most influential for forest fire risk (Busico et al., 2019; Pourtaghi et al., 2016). Fuel moisture, derived from climatic variables such as wind, temperature, precipitation, and relative humidity, has proven to be most influential in Sweden (Cimdins et al., 2022). Historically precipitation has been the controlling factor for forest fire frequency in North America and Europe (Flannigan et al., 1998). At the same time Flannigan and Harrington (1988) found that days without rain and low humidity had strongest correlation to burnt area and the amount of rainfall had low correlation indicating that frequency of precipitation is more important than amount. Flannigan et al. (2005) stated that temperature will be the most important controlling future forest fire risk parameter since it controls fuel moisture availability and evaporation which will increase with increased temperature unless precipitation increases significantly. Furthermore, temperature seemed to be the controlling factor of fire risk in Sweden (Krikken et al., 2021). Therefore, precipitation was thought to have a slightly lower weighting coefficient on the forest fire risk score than temperature.

The RCP 8.5 was the climate scenario chosen for this analysis. It has been described as an unlikely future since more studies point towards a global warming of 3°C rather than 5°C which is expected for RCP 8.5 (Hausfather, 2020). At the same time, the effect of tipping points in the climate system has long been thought to occur after 5°C warming (following the RCP 8.5), but this might be an underestimation (Lenton & Gaffney, 2019). Tipping points could develop sooner at earlier warming stages increasing the risk for RCP 8.5 (Lenton & Gaffney, 2019) making it a suitable choice for future estimations in this analysis.

Table 2. Classes and risk score for the parameters of forest fire risk together with the reference.

Risk parameter	**Risk score parameter**	**Classes**	**Forest fire risk and value of risk score parameter**	**Reference (adapted from)**
Slope (◦)	SLO	>35	Very high (5)	Estes et al. (2017), Veena et al. (2017)
		25–35	High (4)	
		15–25	Medium (3)	
		5–15	Low (2)	
		<5	Very low (1)	
Aspect	ASP	216–288 (SW, W)	Very high (5)	Estes et al. (2017), Veena et al. (2017)
		144–216 (SE, S)	High (4)	
		72–144 (E, SE)	Medium (3)	
		288–360 (NW, N)	Low (2)	
		0–72 (Flat, N, NE)	Very low (1)	
Distance to water courses (m)	WCO	>200	Very high (5)	Ricotta et al. (2018)
		150–200	High (4)	
		100–150	Medium (3)	
		50–100	Low (2)	
		<50	Very low (1)	
Distance to water surfaces (m)	WSU	>200	Very high (5)	Ricotta et al. (2018)
		150–200	High (4)	
		100–150	Medium (3)	
		50–100	Low (2)	
		<50	Very low (1)	
Distance to main roads (m)	ROA	<50	Very high (5)	Ricotta et al. (2018)
		50–100	High (4)	
		100–150	Medium (3)	
		150–200	Low (2)	
		>200	Very low (1)	
Distance to settlements (m)	SET	<50	Very high (5)	Ricotta et al. (2018)
		50–100	High (4)	
		100–150	Medium (3)	
		150–200	Low (2)	
		>200	Very low (1)	
Distance to agricultural areas (m)	AGR	<50	Very high (5)	Ricotta et al. (2018)
		50–100	High (4)	
		100–150	Medium (3)	
		150–200	Low (2)	
		>200	Very low (1)	
Forest type	FOR	Broadleaf	Very high (5)	Estes et al. (2017), Parajuli et al. (2023), Veena et al. (2017)
		N/A	High (4)	
		Conifer	Medium (3)	
		N/A	Low (2)	
		N/A	Very low (1)	
Precipitation (mm/month)	PRE	<78.4	Very high (5)	Busico et al. (2019)
		78.4–85.2	High (4)	
		85.2–92.1	Medium (3)	
		92.1–98.9	Low (2)	
		>98.9	Very low (1)	
Temperature (◦C/month)	TEMP	>15.4	Very high (5)	Busico et al. (2019)
		14.6–15.4	High (4)	
		13.8–14.6	Medium (3)	
		13.0–13.8	Low (2)	
		<13.0	Very low (1)	

2.4 Summary: Description of the FFRS model

In summary, our constructed FFRS model in present study predicts the total risk score of forest fire over an entire summer at a given location from risk score parameters (TEMP, PRE, ASP, SLO, ROA, SET, AGR, WCO, WSU and FOR) according to Equation 1. Each risk score parameter represents a risk parameter (temperature, precipitation, aspect, slope, distance to roads, distance to settlements, distance to agriculture, distance to water courses, distance to water surfaces and forest type). These risk score parameters are evaluated with Table 2 based on a literature review (Section 2.3). This FFRS model has been constructed by the procedure outlined above (Section 2.2.2) with coefficients estimated in Section 3.1 (Table 3).

2.5 Validation of the model

The validation of the model was done with a predicted present-day FFRS in 2006-2010 which was compared to the observed fire data in the same region for the same time period. The observed fire data consists of observed point fires from the MODIS satellite downloaded from NASA Fire Information for Resource Management System for the summer months June, July, and August of 2006-2010. The validation data was not used in construction of the model, as different years were used.

2.6 Delineation

Only fire risk in forested areas was evaluated and it is assumed that all forested area have at least a minimum fire risk of ‘very low’ risk. Hence, there was no forest with no fire risk in this model. The term forest fire risk score (FFRS) always indicates the average summer forest fire risk score in June, July, and August.

Elevation has previously been included in these types of analyses for example in Abdi et al. (2018), Nuthammachot and Stratoulias (2021), Pourtaghi et al. (2016), and Wu et al. (2015). It was considered redundant in this analysis since it is incorporated in the climate data, following the same reasoning as Busico et al. (2019).

Wind data was not considered as a direct factor of forest fire in this analysis since it is incorporated in the aspect parameter. Westerly situated slopes are of highest risk of fire due to the wind flow (Veena et al., 2017). Furthermore, wind was not found to be a regulating factor for fire risk in Sweden (Krikken et al., 2021).

There has long been a consensus on lightning increasing in a warmer world, but this is challenged in the latest years and the effects of a global warming on lightning are more complex than thought before due to the effect of cloud ice in updrafts (Finney et al., 2018; Murray, 2018). However, several projections show an increase in lightning in Scandinavia by 2100 (Finney et al., 2018). Lightning is excluded in this analysis due to the complexities of obtaining and processing suitable data.

Historical fire spots were not used as an input parameter for fire risk, but rather as data for fitting the model and validation since the model was applied to a risk region (Gävleborg county) where fire has not occurred much.

3 Results

3.1 Construction and fitting of the FFRS model

As noted above (Section 2.2.2), the values of the weighting coefficients (c_{TEMP} …) were determined by two steps:

(1) Comparing the occurrence of observed forest fires with the predicted risk score for each risk parameter (TEMP, …) to infer the relative importance of that parameter individually. The year used for fitting was 2001-2005.

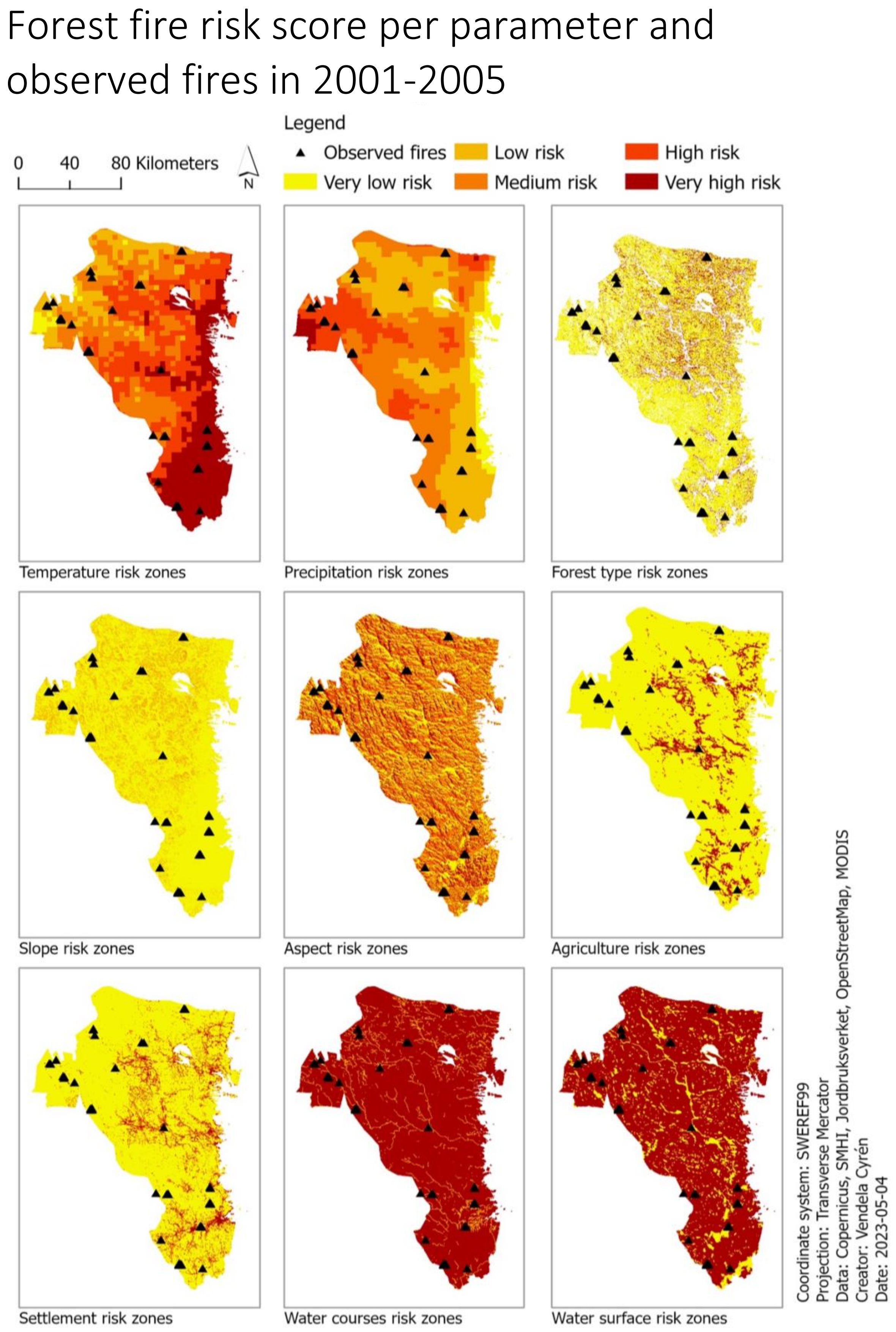
(2) Determining the value of the coefficients (c_{TEMP} …) by varying the values of all coefficients manually and selecting the permutation of values with the best fit between the map of predicted total FFRS and the observed fires for the same region (Gävleborg county) and period (2001-2005). The weighting coefficients of the risk score parameters were boosted or lowered depending on which deemed most and least influential from step (1).

Regarding step (1), Figure 2 shows the qualitative inspection for the individual risk score parameters. This reveals that the risk score parameters of temperature, precipitation, distance to water courses and water surfaces, forest type and aspect were more important, because their spatial patterns have high risk coinciding with concentrations of observed fire. By contrast, slope, distance to agriculture, roads and settlements were seen to be almost insignificant. Distance to roads is not illustrated in any figure.

Regarding step (2), Figure 3 shows the final comparison of total FFRS (Equation 1) after the adjustment of weighting coefficients (Table 3). (This comparison is not a validation as the observed data in Figure 3 was used in construction of the model. The results of the validation can be found in Section 3.3) The final weighting coefficients are shown in Table 3.

Table 3. Risk parameters with their assigned weighting coefficient after fitting the model to the years 2001-2005. High value indicates high importance for forest fire risk. *Sums up to 1.*

Risk parameter	Risk score parameter	Weighting coefficient	Value*
Temperature	TEMP	c_{TEMP}	0.18
Distance to water courses	WCO	c_{WCO}	0.17
Distance to water surfaces	WSU	c_{WSU}	0.17
Precipitation	PRE	c_{PRE}	0.16
Aspect	ASP	c_{ASP}	0.16
Forest type	FOR	c_{FOR}	0.12
Slope	SLO	c_{SLO}	0.01
Distance to agriculture	AGR	c_{AGR}	0.01
Distance to roads	ROA	c_{ROA}	0.01
Distance to settlement	SET	c_{SET}	0.01



Forest fire risk score per parameter and observed fires in 2001-2005

Temperature risk zones

Precipitation risk zones

Forest type risk zones

Slope risk zones

Aspect risk zones

Agriculture risk zones

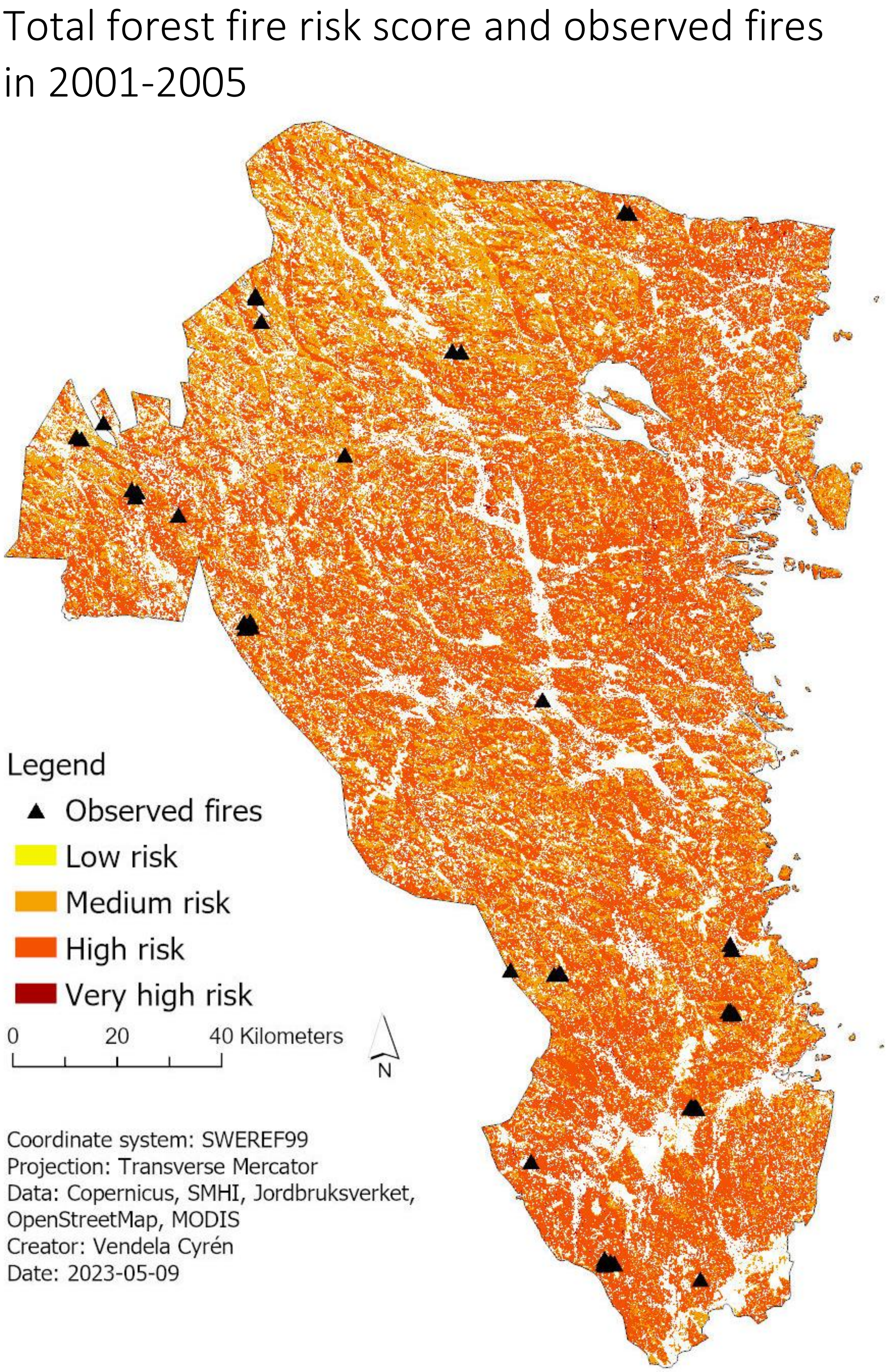
Settlement risk zones

Water courses risk zones

Water surface risk zones

Coordinate system: SWEREF99
Projection: Transverse Mercator
Data: Copernicus, SMHI, Jordbruksverket, OpenStreetMap, MODIS
Creator: Vendela Cyrén
Date: 2023-05-04

Figure 2. Predicted forest fire risk score per risk parameter in the year 2001-2005 in Gävleborg county with observed fires used for fitting the model. The map with forest type risk in the right corner has areas of no risk (white shading) due to areas with no forest. This is applied to all the risk score parameters in the total FFRS (Figure 3). The way roads are incorporated is not illustrated in this figure.



Total forest fire risk score and observed fires in 2001-2005

Coordinate system: SWEREF99
Projection: Transverse Mercator
Data: Copernicus, SMHI, Jordbruksverket, OpenStreetMap, MODIS
Creator: Vendela Cyrén
Date: 2023-05-09

Figure 3. Predicted total forest fire risk score in 2001-2005 in Gävleborg county with observed fires used for fitting the model.

3.2 Interpretation of the FFRS model

The observed number of fires is illustrated as a rough interpretation of the models' risk scores applied in number of fires. The observed number of fires per risk score per 100 km^2 per year in the summer in 2006-2010, total number of fires and total predicted number of fires are shown in Table 4.

Table 4. Observed number of fires per 100 km^2 per year in the summer for each predicted risk score value (FFRS) based on observations in 2006-2010 per yearly fire summer season in Gävleborg county using predicted regions of FFRS. Also shown is the total observed number of fires per risk score for the whole area of Gävleborg county and the predicted number of fires per year in the same time period and region.

Forest fire risk score and value for 2006-2010	**Area (%)**	**Observed number of fires per 100 km^2 per year in summer between 2006-2010**	**Total observed number of fires for the whole area per year in summer between 2006-2010**
Very low risk (1)	0	0	0
Low risk (2)	0.5	0	0
Medium risk (3)	28.4	0.04	2
High risk (4)	69.1	0.08	10
Very high risk (5)	2.0	0.15	0
Total	100.0	N/A	**12**

3.3 Validation of the FFRS model

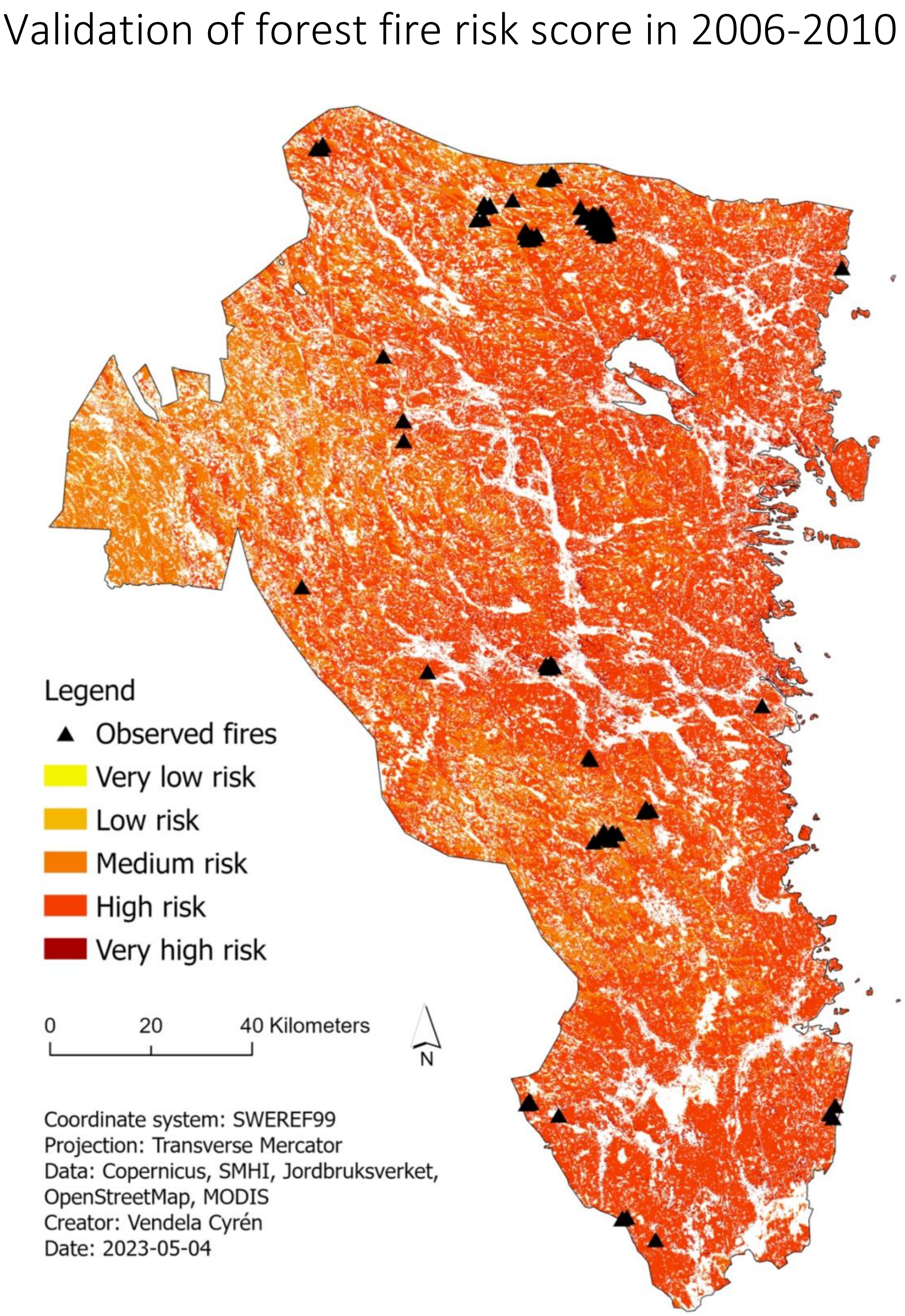
As noted in Section 2.5, the robustness of the model was tested by applying the FFRS model (Equation 1 with weighting coefficients from Table 3 and risk score parameters from Table 2; Section 2.3) to the years 2006-2010. The prediction of forest fire risk score in 2006-2010 was compared with observations of fire occurrence not used in construction of the model in the same years. 62 forest fires were observed in Gävleborg county between 2006-2010 according to MODIS data.

Table 5 shows the validation result. 10 of the observed forest fires were located in the predicted area of medium risk (Figure 4, orange shading), 50 of the observed forest fires were located in the predicted high risk area (red shading), and 2 observed forest fires were located in the predicted very high risk area (dark red shading).

A spatial representation of the comparison between the prediction of FFRS (coloured shading) and observed fire locations (black triangles) is shown in Figure 3. This revealed okay agreement between observations and the model in the way that most observed fires were located in a region with predicted high or very high fire risk.

Table 5. Observed number of fires detected in each predicted forest fire risk score class in 2006-2010

	Very low risk	**Low risk**	**Medium risk**	**High risk**	**Very high risk**
Observed number of fires	0	0	10	50	2



Coordinate system: SWEREF99
Projection: Transverse Mercator
Data: Copernicus, SMHI, Jordbruksverket, OpenStreetMap, MODIS
Creator: Vendela Cyrén
Date: 2023-05-04

Figure 3. Predicted forest fire risk score in 2006-2010 used for validation of model with observed fires.

3.4 Future forest fire risk (2041–2070) compared with present-day (2006-2010)

The validated FFRS model was applied to the projected climatic conditions for 2041-2070 estimated from available data sets (Section 2.3.4). The prediction for 2041-2070 was then compared with the present-day prediction (2006-2010). The period 2006–2010 was characterized by lower temperatures and less rain compared to the future period 2041–2070 that is predicted to be characterized by higher temperatures and more rain according to the available data sets.

Table 6 shows the area in each predicted risk score class in percentage both in present-day (2006-2010) and in the future scenario (2041-2070) in Gävleborg county. In both periods the majority of the area was classified as high risk. A greater area has a medium risk in 2006-2010 compared to the future scenario. The area with a very high risk was greater in a future scenario (2041-2070) compared to present-day (2006-2010).

Table 6. Total area (%) per predicted forest fire risk score class for 2006-2010 and future (2041-2070)

Forest fire risk/period	**Very low (%)**	**Low (%)**	**Medium (%)**	**High (%)**	**Very high (%)**
2006–2010	0.0	0.5	28.4	69.1	2.0
2041–2070	0.0	0.0	6.8	83.2	10.0

Figure 5 shows the spatial representation of Table 6 (i.e., predicted forest fire risk score in 2006-2010 and 2041-2070 in Gävleborg county). The risk score for 2006-2010 was the same risk score used in the validation (Section 3.3).

Figure 5 shows the change in predicted forest fire risk score between 2006-2010 and 2041-2070 in Gävleborg. Figure 6 is the result of the difference between the two maps in Figure 5. There was a general increase of one forest fire risk score class in a future climate or no change in risk (White shading, Figure 5). In the northern, centre, and eastern parts of the map some areas of decreasing risk can be seen (Figure 5). One area in the west had increasing risk of two classes (Figure 5).

The predicted numbers of fires per risk score in 2041-2070 are shown in Table 7. The predicted total number of fires was calculated by multiplying the observed density of fires in 2006-2010 (Table 4) by the area for each predicted forest fire risk score in 2041-2070.

Table 7. For 2041-2070 predicted total number of fires per predicted risk score per year in summer using prediction of FFRS and assuming fire density for each risk score category from Table 4, and the area for each risk score class.

Forest fire risk score and value	**Area (%)**	**Predicted total number of fires per year in summer (2041-2070)**
Very low risk (1)	0	0
Low risk (2)	0	0
Medium risk (3)	6.8	1
High risk (4)	83.2	12
Very high risk (5)	10.0	3
Total	100.0	16

Forest fire risk score in 2006-2010 compared with 2041-2070

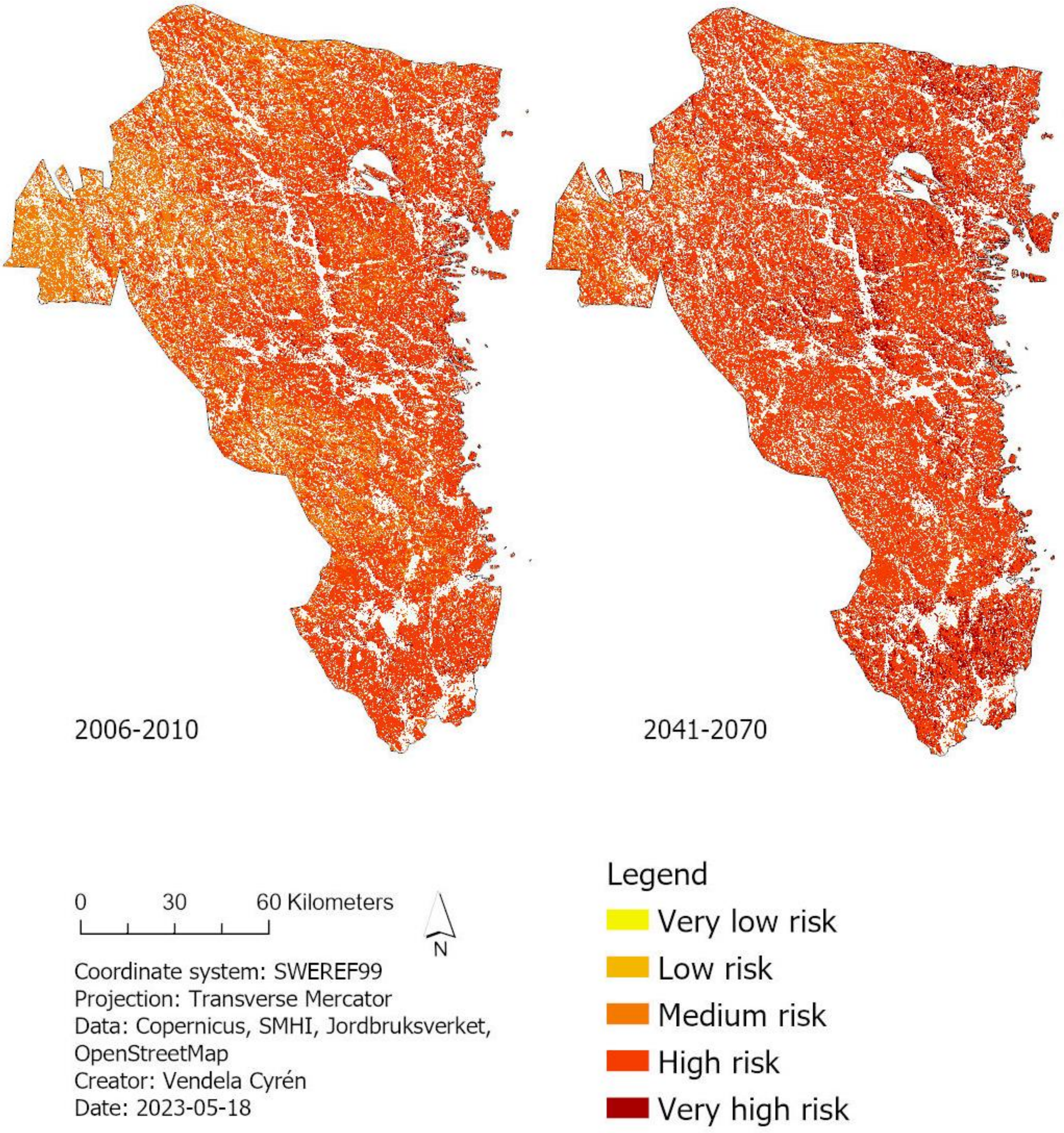


Figure 4. Predicted present-day forest fire risk score in 2006-2010 and predicted future forest fire risk score in 2041-2070 in Gävleborg county.

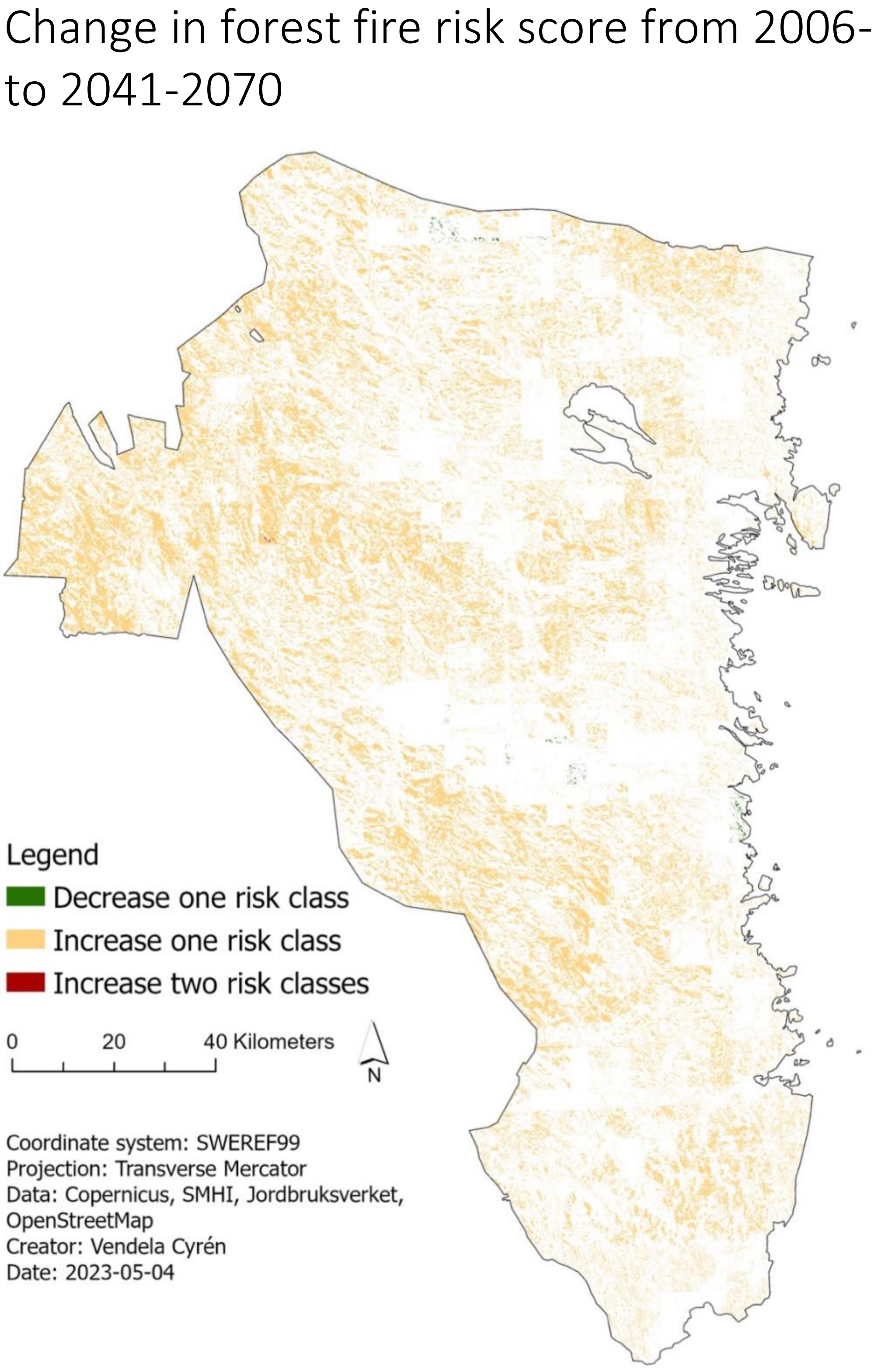


Figure 5. The change in predicted forest fire risk score between 2006-2010 and 2041-2070 in Gävleborg county.

In summary, the future forest fire risk score in Gävleborg county was higher than the present-day risk score by generally one risk class increase (Figure 6). The FFRS model predicted an expansion of the area with a 'high' or 'very high' risk of fire from 71% in the present-day to 93% in 2041-2070 (Table 6). This could indicate an increase of total number of fires per annual summer season from 12 in present-day to 16 in a future scenario in Gävleborg county (Table 4 & 7).

4 Discussion

The results for the response to long-term climate change (present-day to 2041-2070) are partly in line with previous research in this area for Sweden. Krikken et al. (2021) showed a higher risk of forest fires in the whole of Sweden, contradicting Yang et al. (2015) that showed a higher risk in southern Sweden and a lower risk in northern Sweden. Yet Migliavacca et al. (2013) had predicted no increase over Sweden.

Migliavacca et al. (2013) made a prediction over a larger area of whole Europe and therefore used coarser data which impacts the result. Both Krikken et al. (2021) and Yang et al. (2015) used the Fire Weather Index (FWI) which is a cumulative index for daily forest fire risk developed by researchers at the Canadian Forest Service and used in conjunction with daily weather forecasts in Sweden by Swedish Meteorological and Hydrological Institute (SMHI) and the Swedish Civil Contingencies Agency (MSB).

For daily records of weather and fire occurrence, Eriksson et al. (2023) tested four different indexes performance in Sweden and found that the FWI had the best prediction capability. This could indicate that a cumulative index, one that measures risk depending on the risk on the previous day, works best in Sweden for estimating both present and future forest fire risk.

By contrast, in the present report, the context is climate-related: the model used for estimating FFRS is a non-cumulative model quantifying risk of fires over a warm season. Daily changes in forest fire risk are not predicted in our approach. The time scale of applicability is climatic rather than weather-related in the present model of FFRS.

4.1 Validation of the FFRS model

The validation of our constructed FFRS model, shows good but not perfect results. Most of the observed fires were located in a predicted high risk area (Table 5). Some were located in a predicted medium risk area, and a few in predicted very high risk area. There are predicted areas of very high risk class with no observed fires which is not ideal. This can be because the duration of the dataset used to fit the model is limited to only five years. The area investigated is also limited which would increase the need for more years of observed fire data in the fitting.

4.2 The construction and fitting of the model

The construction and fitting of the model was based on 26 points of fires in five years and validated on data of 62 fires during five other years. To develop a universal model that can be applied to the future with higher robustness, more observational fire data during several years covering a bigger area would be needed for construction and fitting of the model.

As mentioned, the FFRS model is based on forest fire risk combining ignition risk, fire spread risk and flammability risk. Distance to roads, settlements, agriculture, water courses and water surfaces are parameters of ignition risk. Slope and aspect are parameters of fire spread risk, although they also affect flammability to some degree. Temperature, precipitation, and forest type are parameters of flammability risk. Yet some of the risk parameters could contribute to both of these three types of risk, creating more complexity than is assumed when constructing our model. For example, roads (parameter distance to roads) could both have an associated ignition risk and a suppressing effect by creating a fire corridor that stops the fire from spreading possibly making it more suitable as a risk of spread parameter as Pinto et al. (2020) reasoned (This is further discussed in Section 4.3).

4.3 Alternatives to classification and weighting of risk parameters

The different parameters classification (Table 2) of ‘very low’ to ‘very high’ risk can be discussed. Roads have in this study been classified as positively correlated with fire, as the closer to roads the higher the fire risk due to human ignition. However, there were few fires detected close to roads in the construction of the model (Section 3.1). This might be explained by roads having a suppressing effect on fires by creating a corridor where the fire cannot spread, resulting in a lower risk closer to roads due to fire breaks in the environment (Pinto et al., 2020). As previously discussed in section 4.2, this could mean that roads control the risk of fire spread rather than ignition. This can explain why distance to roads was weighted with low importance despite being found to correlate with forest fire occurrence in Sweden (Cimdins et al., 2022; Pinto et al., 2020). Furthermore, the roads used in this risk prediction are main roads with a speed limit of 70 km/h. It was assumed that roads with higher speed limit have higher ignition risk due to heavier traffic. However, it could be that the risk increases with higher velocities and that 70 km/h is not the best delineation of ignition risk from roads. Ignition risk from traffic on smaller forest roads are not included in the road risk parameter which would increase the fire risk as shown by Pinto et al. (2020).

The model includes higher forest fire risk closer to settlements due to the risk of human induced ignitions such as sparks from equipment, construction work or vehicles. However, almost no fires were detected in areas with predicted ‘very high’ or ‘high’ risk score of close distance to settlement, hence that parameter was deemed to be of lower significance compared to others. One possible explanation for this observation might be that the predicted risk area of ‘very high’ or ‘high’ risk is very small due to the chosen size of the distances from the settlement (Section 2.3.3). It can also be explained by the fact that, in reality, fires that occur close to settlements are observed and suppressed in an early stage due to faster response from fire brigades, similar to the reasoning by Pinto et al. (2020). Furthermore, fires might be detected faster closer to agriculture, reducing the risk closer to the field in the same way as settlements. This could explain why distance to agriculture received a low weighting coefficient.

When considering forest type, most of the fires were surprisingly found in conifer forest, not broad-leafed forest. This can be because conifers dominated the forested area. This risk assessment is also based on that broad-leafed forests have higher fire risk since there is more fuel for the fire (i.e., leaves) available on the forest floor, but since this is a summer forest fire risk this might not be applicable until late summer or autumn when the leaves fall.

The reason why the risk parameter of distance to water courses and surfaces achieved a high weighting coefficient can be since the predicted area of high risk score is large and more fires happen to occur there. It does not mean it is a controlling factor for forest fire risk. It would be more reasonable to believe that water courses and surfaces have similar risk weight as road risk if both functions similarly as fire breaks. Pinto et al. (2020) found, in contrast to what is suggested in this thesis, that water bodies had positive correlation with fire possibly due to recreational activities close to water increasing the ignition risk.

Temperature was weighted slightly higher than precipitation in line with previous research (Flannigan et al., 2005; Krikken et al., 2021). Moreover, most fires in the fitting of the model 2001-2005 were located in an area with ‘low’ or ‘very low’ risk of the parameter slope and therefore slope was not found to have a high weighting coefficient. This is not very surprising as previous studies have not deemed slope a highly significant factor for forest fire risk in Sweden (Cimdins et al., 2022).

4.4 Uncertainties and limitations of the FFRS model

A limitation of the model is its neglect of how lightning ignites forest fires generally. Lightning was excluded from the ignition risk section due to the complexities of obtaining and processing suitable data, which brings uncertainties to the results shown here. Lightning represented 24% of the detected fires in Gävleborg county between 1998 and 2021 and the spread is uneven throughout the years ranging from 0 to 38 lightning induced ignitions per year (Myndigheten för samhällskydd och beredskap, 2018a). Therefore, it can be assumed that almost a fourth of the forest fires are not included in this risk analysis and it would be likely that the actual forest fire risk is higher than calculated. If in future, lightning increases drastically in its role in 2040s for the target region (Gävleborg), then the model has underestimated the fire risk. It has been shown that lightning will probably increase with projected temperature increase in Scandinavia due to global warming (Finney et al., 2018). Therefore, future work to develop the model could include a lightning risk parameter.

The FFRS model can be applied to other regions in Sweden where fire occur mostly without ignition by lightning. To do so, accuracy might be improved further by adjusting the weighting coefficients for each risk score parameter following the approach noted (Section 2.2.2).

According to the results for long-term climate change up to 2041-2070, an increased fire risk score can be seen even though precipitation is increasing. This prediction can seem counter-intuitive since intuitively more precipitation might be expected to lower the fire risk. An explanation may be that timing of precipitation is more important than the amount. Precipitation during the fire season will most likely have a suppressing effect but depends on the intensity and frequency. Precipitation also partly controls the amount of fuel available. High precipitation in the spring could increase the fire risk due to more growth that dries in the summer. The forest fire risk model in this analysis does not include precipitation from the spring season and could therefore under- or overestimate the amount of ground fuel making the fire risk higher or lower.

The observational data of precipitation used in this analysis are of summer average precipitation. It could be argued that, since fires respond mainly to variability in precipitation and not amount, this might somehow misrepresent the forest fire risk in the model (e.g., Flannigan & Harrington, 1988). The risk of fire is lower when a low amount of precipitation falls for many days, rather than one heavy rainfall. Days without rain, or daily precipitation might be a better indication of precipitation risk rather than average monthly precipitation.

However, in fact this is not such a limitation for our model because future projections of hydrological response of climate change show that precipitation will increase where it is already wet and decrease where it is dry due to the decrease in atmospheric circulation as a consequence of decreasing mass flux between atmospheric layers because of an increase in the lower-tropospheric water vapor (Held & Soden, 2006). The variability of precipitation is expected to increase in a warmer world (IPCC, 2023). Furthermore, Ou (2017) found that conditions of drought affect fires both on daily, monthly, and seasonal time scales in Sweden which would imply that monthly precipitation values still capture the seasonal forest fire risk. In summary, seasonally averaged increased precipitation can be assumed to work as a proxy for an increased variability in the hydrological atmospheric cycle and our model implicitly captures how more variability in precipitation accompanies more mean summer precipitation.

Some of the simplifications made in the FFRS model will lead to inaccuracies in the risk assessment. The model assumes no future change in all the risk parameters except precipitation and temperature. It assumes no change in forest cover or type, no increase of settlements, no change in road network, water courses and surfaces, and no change in agricultural areas, slope, and aspect. It is likely that the road network, water courses, water surfaces, slope and aspect will stay similar in the next 30 years and will therefore not change the result much. Forest cover could change in 2041-2070 in Gävleborg compared to the present-day, but it is unclear to what extent and how. It is also unclear if agricultural areas will expand in Gävleborg in the future, but since agriculture does not have a major land cover in this area it is reasonable to assume that it will not affect the result much. Population growth in Gävleborg is relatively low and dependent on immigration (Johansson, 2019). Since there is no expected increase in population in Gävleborg, settlements are not expected to increase significantly by 2041-2070.

In the construction of the simple model, the effects on forest fire risk from various risk score parameters were tested and evaluated individually, not in combination with each other. A limitation of the construction of the model is that in reality, it is possible that the risk would increase non-linearly when two factors are combined. This was not considered in the construction of the FFRS model. For example, combination of two medium risk score ignition factors could increase the risk score to ‘high’. However, to what extent is unclear since this is not tested.

The uncertainties of the RCP 8.5 scenario and its consequences are large and depend on the climate model used (Friedlingstein et al., 2014). However, the climate data retrieved from SMHI used in this analysis is based on 22 different climate models with an average value over 30 years to eliminate possible bias from one model.

5 Conclusions

To conclude, according to the forest fire risk score model developed:

(1) The forest fire risk score will increase in 2041-2070 in Gävleborg county compared to present-day forest fire risk score as a consequence of global warming with increased temperature and precipitation. The increase of FFRS is by one risk class which implies a rough estimated change from total 12 fires per year in the summer season in present-day to total 16 fires per summer season in a predicted future scenario.

(2) The parameters with the highest weighting coefficients (i.e., where present-day fires occurred in a predicted ‘high’ or ‘very high’ risk score) were temperature, precipitation, distance to water courses and surfaces, forest type and aspect. The parameters that received low weighting coefficients (i.e., where observed fires occurred in an area with ‘very low’, ‘low’, or ‘medium’ risk class) were slope and distance to roads, agriculture areas and settlements.

(3) The validation of the method shows okay results with a majority of observed fires located in a predicted high or very high risk area.

This answers the aim of estimating the future FFRS and fire occurrence in Gävleborg together with a present-day estimation and validation of the model. This also answers the research question ‘What is the forest fire risk in Gävleborg county in 2041–2070, relative to the present-day forest fire risk, in the context of global warming?’. The hypothesis, that the FFRS is expected to increase in Gävleborg county in 2041-2070 due to the expected rise in temperature in a future climate, is also confirmed.

Future studies could evaluate a more robust validation method for the model making the results more reliable. Furthermore, focus on making the fit for the model even better, preferably detecting more fires in a predicted ‘very high’ risk area instead of ‘high’ risk area and including lightning as a risk parameter. It would be interesting to implement this model to the whole area of Sweden.

This thesis has contributed to partly understanding forest fire risk in Gävleborg in the present-day and has provided a possible future prediction for forest fire risk score that could imply an increase of the annual number of forest fires in the summer season from 12 in the present-day to 16 in the future climate scenario.

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