Acta Universitatis Agriculturae Sueciae

Doctoral Thesis No. 2020:55 • A multi-century perspective of the Sala mega-fire • Guilherme A. S. J. Pinto

SLU

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Faculty of Forest Sciences

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Understanding risks for future fire activity in Sweden

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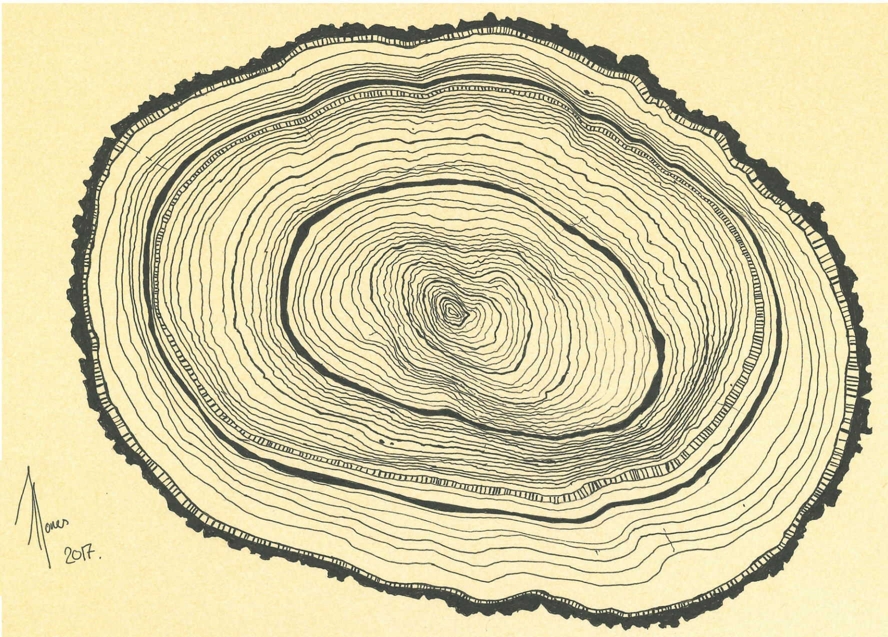

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SWEDISH UNIVERSITY
OF AGRICULTURAL
SCIENCES

DOCTORAL THESIS
Alnarp 2020

Acta Universitatis agriculturae Sueciae
2020:55

Cover: cross-section from a tree showing tree-rings
(Illustration: Sara Jones)

ISSN 1652-6880
ISBN (print version) 978-91-7760-628-4
ISBN (electronic version) 978-91-7760-629-1

Print: SLU Service/Repro, Alnarp 2020

A multi-century perspective of the Sala mega-fire: understanding risks for future large fires in Sweden

Abstract

In the summer of 2014, the Sala municipality in central Sweden registered the largest fire in modern Swedish history. The circumstances under which the fire took place highlight the complex interactions between the ignition as well as the spread of fire, and human activities along with weather. Although the role of human activities and climate are of critical importance in shaping modern fire activity, their joint effects remain largely unstudied in Northern Europe. The main aim of this thesis was to investigate the impact of landscape properties (natural and human-related) and climate patterns on forest fires at different spatial and temporal scales. Dendrochronological study (Paper II) suggested that in the past the lack of major firebreaks, homogenization of forests due to its long-term management, and a long period without fires might have contributed to the occurrence of the exceptionally large 2014 mega-fire in Sala. A study of modern fire activity (Paper I) showed that a combination of human-related ignitions, weather conditions controlling fire spread, and vegetation composition are the main drivers of fire activity in Sweden. At the scale of the European boreal zone (Paper IV), forest fire activity remains strongly connected to the annual climate variability. Predictions of the future area burned in Sweden (Paper III) indicated that changes in climate would lead to an increase in area burned, with changes in vegetation leading either to further increase or mitigation of this increase to a certain degree.

Keywords: boreal forests, landscape properties, fire prediction, fire suppression, INLA, natural hazard, climate risks, fire history, fire regime.

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A multi-century perspective of the Sala mega-fire: understanding risks for future large fires in Sweden

Sammanfattning

Under sommaren 2014 eldhärjades skogen i Sala kommun i centrala Sverige av den största skogsbranden i modern historia. Den stora branden stod i kontrast till den moderna brandaktiviteten i Sverige, som normalt kännetecknas av en stor mängd små bränder. Omständigheterna kring branden belyste de komplexa interaktionerna mellan olika mänskliga aktiviteter och klimatet och normal brandaktivitet. Även om effekterna från mänskliga aktiviteter och klimat spelar en avgörande roll i mängden antal skogsbränder, förblir de till stor del ostuderade i norra Europa. Huvudsyftet med denna avhandling var att undersöka hur effekterna av landskapet (naturliga och mänskliga) och klimatmönster påverkar skogsbränder i olika rumsliga och tidsmässiga skalor. För att förstå dessa mönster genomfördes dendrokronologiska studier (Paper II) som visade att bristen på naturliga brandgator, homogenisering av trädslagssammansättning och åldersfördelning tillsammans med en lång period utan skogsbränder kan ha varit bidragande orsaker till den stora branden 2014 i Sala Studier av modern brandaktivitet (Paper I) visade att en kombination av mänsklig påverkan i form av antändningar i kombination med väderförhållanden styr eldspridningen tillsammans i kombination med artsammansättning är de främsta drivkrafterna för skogsbränder i Sverige. På skalan för den europeiska boreala zonen (Paper IV) är skogsbrandsaktiviteten (Paper III) indikerar att klimatet kan leda till en ökning av det areal som drabbas av skogsbränder, där olika vegetationstyper kan påverkar brandintensiteten genom att öka eller minska den till en viss grad.

Keywords: boreal skog, landskapsegenskaper, brandförutsägelse, brandbekämpning, INLA, naturliga risker, klimatpåverkan, brandhistoria, brandregim.

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Dedication

To Wiebke and my family (Oslei, Edna, Cecília, Walmar and Walter).
To Walda (R.I.P.)

Nature is not cruel, only pitilessly indifferent. This is one of the hardest lessons for humans to learn.

Richard Dawkins

Never, never quit.

Grand-master, Kwon, Jae-Hwa

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I. Pinto, G.A.S.J., Rousseu, F., Niklasson, M., Drobyshev, I., 2020. Effects of human-related and biotic landscape features on the occurrence and size of modern forest fires in Sweden. Agric. For. Meteorol. 291, 108084. DOI: 10.1016/j.agrformet.2020.108084

II. Pinto, G. A. S. J., Niklasson, M., Ryzhkova, N., Drobyshev, I. A 500-year history of forest fires in Sala area, central Sweden, shows the earliest known onset of fire suppression in Scandinavia. (In review)

III. Pinto, G.A.S.J., Rousseu, F., Eden, J., Niklasson, M., Drobyshev, I. Future trends of forest fires in Sweden: a joint analysis of climatic and human-related factors. (Manuscript)

IV. Drobyshev, I., Ryzhkova, N., Kitenberga, M., Eden, J., Pinto, G.A.S.J., Lindberg, H., Krikken, F. Trends and patterns in annually burned forest areas and fire weather across the European boreal zone in the 20th and early 21st centuries. (Manuscript)

Paper I is reproduced with the permission of the publishers.

The contribution of Guilherme A. S. J. Pinto to the papers included in this thesis was as follows:

I. Collected all the data. Developed the research idea, conducted the statistical analysis, and wrote the manuscript in collaboration with the co-authors.

II. Participated and planned the fieldwork, conducted the statistical analysis, and wrote the manuscript in collaboration with the co-authors.

III. Collected all the data. Developed the research idea, conducted the statistical analysis, and wrote the manuscript in collaboration with the co-authors.

IV. Participated in the data collection, in the statistical analysis, and in the writing of the manuscript in collaboration with the co-authors.

List of figures

1. Introduction

Forest fires are a major disturbance factor common throughout the boreal zone. Fires shape successional pathways in vegetation, biodiversity, and the biogeochemical cycles, e.g. the rate of carbon emissions (Granström 2001; Amiro et al. 2001; Ryan 2002; Zhang et al. 2003; de Groot et al. 2009). Within the boreal zone between five and 20 million ha of forest is burned every year (Stocks et al. 1998; Zhang et al. 2003; Wooster and Zhang 2004; Flannigan et al. 2013). Fires are mainly driven by climatic conditions (Stocks et al. 2002; Drobyshev et al. 2012, 2016; Flannigan et al. 2013). Forest composition controls the distribution and abundance of forest fuels, creating variability in fire risk across the landscape and affecting the pattern of fire spread (Larsen 1997; Niklasson and Granström 2000; Ryan 2002; Hellberg et al. 2004). Longer drought periods result in fuel drying over large portions of the boreal landscapes, resulting in forests preconditioned to larger fires (Ryan 2002).

In Scandinavia today forest fires are common; however, there are very few records of the occurrence of mega-fires (i.e. fires larger than 10 000 ha). In the summer of 2014, a fire in the municipality of Sala, Västmanland county in central Sweden, burned an area around 14 000 ha (MSB 2015). This was one order of magnitude larger than the previous largest fire in Sweden, a fire that occurred in the Norrbotten county in 2006 and burned ~1 900 ha (Bodens kommun 2006). As a result of the Sala mega-fire, one person was killed, and the large forested area burned caused tangible economic losses for the municipality and forestry operations. In Sala, the ignition was human-related, but the fire spread was driven by a prolonged drought and strong winds (MSB 2015). Homogenous vegetation due to long-term forestry monoculture may have facilitated the fire spread (Ryan 2002). Although the relationships between human activities and climate are of critical importance in shaping modern fire activity, they remain largely unstudied in Northern Europe.

Annual reconstructions of past fire activity rely on the use of dendrochronological (i.e. tree ring-based) methods to date fire scars and provide annually resolved multi-century fire chronologies. Dendrochronological studies indicate large temporal and spatial variations in fire activity in Sweden during the last 500 years (Niklasson and Granström 2000; Niklasson and Drakenberg 2001; Drobyshev et al. 2014). These studies used the fire cycle concept (FC), which is the period that would be required for the total study area to be burned (Johnson and Wagner 1985). For example, before the 1700s the FC was approximately 200 years in northern Sweden and 64 to 156 years in southern Sweden (Niklasson and Granström 2000; Niklasson et al. 2010), while in the modern times the FC is around 10^4 years across the country (Drobyshev et al. 2012).

Dendrochronological reconstructions in Northern Sweden have shown that prior to 1550 fire activity was dominated by a small number of fires of much larger magnitudes and from 1800-1850 numerous smaller fires dominated (Niklasson and Granström 2000; Niklasson et al. 2010). This difference in fire activity was driven by the introduction of fire suppression policies and changes in land-use around the 18th-19th centuries (Niklasson and Granström 2000; Niklasson et al. 2010; Drobyshev et al. 2012; Rolstad et al. 2017). Nowadays, fires are quickly suppressed after its ignition, with many but small fires events characterizing the annual fire record. In modern Sweden between 3 000 and 4 000 fires are recorded annually, burning on average ~3600 ha, or around 0.008% of the country's forested area (MSB 2019; Sjöström and Granström 2020). The main ignition causes are human-related (e.g. campfires, mechanical failures, or arson) with only ~4% being due to lightning (MSB 2019; Sjöström and Granström 2020). Human-related ignitions are more common in the vicinity of densely populated areas (Pinto et al. 2020).

The analyses of fires since 1875 (Drobyshev et al. 2012) and reconstructed historical fire activity since the 1400s (Drobyshev et al. 2014) suggests there are two well-defined zones of characteristic fire activity in Sweden, the boundary between the zones being approximately 60º N. In the north, fire regime appears to be controlled by the summer aridity, whereas in the south the spring drought conditions are important, with a large proportion of fires occurring in late spring to early summer (Drobyshev et al. 2012).

In the last decade, the total area burned increased by over 30% in comparison to the previous decade, mostly due to the fires recorded in the years 2014 and 2018. The total area burned in each year was one order of magnitude larger than the 1996-2018 average, with over 14 000 ha burned in 2014 (mostly from the Sala mega-fire alone) and over 24 000 ha of the area burned in 2018 (from multiple fires) (MSB 2019). However, it is important to realize that the modern levels of forest fire activity in Sweden are very low from a historical perspective, mostly due to effective fire suppression.

Modeling is an important tool for forest fire managers tasked with integrating fire-related risks into long-term forest planning. A number of properties of fire regimes have been subject to such modeling work, including fire occurrence (Syphard et al. 2008; Rodrigues and de la Riva 2014), fire spread (Rodriguez-Aseretto et al. 2013; Haas et al. 2013), and overall fire risk (Gudmundsson et al. 2014; Turco et al. 2019). For Scandinavia, models predict an increase in forest fires risk associated with either an increase in temperature or in the length of the fire season (Kilpeläinen et al. 2010; Flannigan et al. 2013; Yang et al. 2015). Models further predict an increase of ~20% in the annual frequency of forest fires, mostly in the southern Scandinavia (Kilpeläinen et al. 2010; Yang et al. 2015).

Fire prediction models commonly use climate and landscape variables as predictors (Kilpeläinen et al. 2010; van der Kamp et al. 2013; Barbero et al. 2014; Yang et al. 2015; Hernandez et al. 2015; Tardivo et al. 2017). Joint analyses of these factors with human-related factors are uncommon and to the best of my knowledge, no joint analyses have been undertaken for Sweden. My project has been intended to fill in this knowledge gap.

2. Objectives

The main aim of this thesis was to investigate the impacts of landscape (natural and human-related) and climate patterns on forest fires at different spatial and temporal scales. I present a multi-century perspective of the fire activity in Sweden. The study is an analysis of fire history in the area where the Sala mega-fire took place, a site with a legacy of forest management and with the most common type of forested land currently in Sweden, i.e. a coniferous-dominated landscape managed for wood production. It is presented a Sweden-wide study of the relationship between the occurrence and size of modern fires versus human-related and natural/semi-natural landscape features. I also present an overview of the fire activity within the European boreal zone (EBZ). Lastly, predictions are made of future total area burned in Sweden using climate and landscape variables.

The specific research questions that guided this work were:

I. What are the impacts of climate, biotic, and abiotic landscape features on fire occurrence and fire size in modern Sweden?

II. How does the history of a landscape influence modern fire activity?

III. How does variability in climate and landscape properties affect the fire risk?

IV. What are the spatio-temporal patterns of fire activity across the European boreal forest?

3. The structure of the thesis

Forest fires were studied at local (Paper II), national (Papers I and III), and sub-continental (Paper IV) scales and on three temporal scales - years, decades, and centuries (Fig 1).

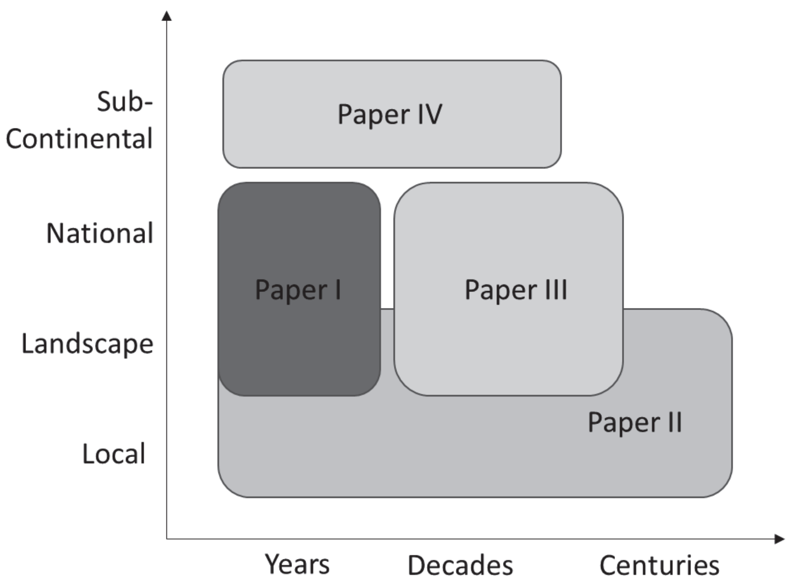

Figure 1. Spatial and temporal coverage of the papers included in this project.

Paper I used data from fires in Sweden between 1998-2017, obtained from the Swedish Civil Contingency Agency (in Swedish Myndigheten för Samhällsskydd och Beredskap, MSB) (MSB 2019). The paper studied the effects of landscape properties (road density, population density, firebreaks, vegetation zones) and climate (Buildup Index – BUI, and Initial Spread

Index – ISI) on fire occurrence and fire size. The analysis of the data used a Bayesian approach aiming to reduce the effects of spatial-auto-correlation.

Paper II used dendrochronological methods to reconstruct the history of fires in the area where 2014 Sala mega-fire took place. Samples were collected from within the burned area in the Sala municipality, Central Sweden, during the summers of 2016-2018. The analysis of the samples used a range of statistical methods to identify changes in the fire regime and to analyze the relationship between the fire, climate and humans.

Paper III presents future predictions of the area burned by forest fires in Sweden. The analysis used future estimates for population density, two climate projections and three vegetation scenarios (more fire-prone, less fire-prone, and no changes in vegetation). The analysis also considered the effects of urban areas, water bodies, road density, and vegetation zones on the predictions. Similar to Paper I, the data from fires originated from the MSB and the analysis used a Bayesian method.

Paper IV used data from the annual area burned (ABA) from different administrative units within the European Boreal Zone (EBZ). The source of the data was either the statistics maintained by the respective state authorities or from the Global Fire Emission Database (Giglio et al. 2013). The analysis used several statistical methods to reconstruct long-term ABA chronologies at a regional level. Later, the analysis investigated the relationships between the ABA and climate (MDC, monthly drought code) at a sub-continental level.

I direct the reader to the respective papers for a detailed presentation of the material and methods for each study.

4. Main results and discussion

4.1 Human influence on fire activity in the past (Paper II)

The long-term analysis in Paper II showed a dramatic decline of fire activity in the Sala municipality in central Sweden around the 1700s, observed both in terms of fire occurrence and area burned (Figure 4). The onset of the fire free period occurred in 1756 and the 2014 fire marked its end. The decline in fire activity followed a transition in land-use practices away from the use of fire as a land management tool and has been commonly observed in Scandinavia during the 1800s (Niklasson and Granström 2000; Pitkänen et al. 2003; Niklasson et al. 2010; Storaunet et al. 2013; Rolstad et al. 2017). The regime shift identified in Sala occurred almost half-century earlier than other regions in Northern Europe (Page et al. 1996; Niklasson and Granström 2000; Niklasson et al. 2010; Wallenius et al. 2010; Rolstad et al. 2017; Ryzhkova et al. 2020). It was speculated that human-activities related to agriculture and mining were the drivers for such an early shift. Slash-and-burn and charcoal production were important drivers of fire activity during 1480-1690 (Segerström and Emanuelsson 2002; Bindler et al. 2009). By the turn of the 18th century, changes from slash-and-burn to permanent fields were the likely drives for the regime shift (Emanuelsson and Segerstrom 2002; Segerström and Emanuelsson 2002). An increase in timber value further facilitated the abandonment of fire-related activities (Groven and Niklasson 2005; Storaunet et al. 2013). Superimposed epoch analyses indicated climate change played a role in the forcing of large fire years (LFY) in the pre-decline era, indicating that the reconstructed fire chronology is a product of both human impacts and climate variability.

Figure 2 View of the area burned in the Sala fire two years after the event (top) and six years after the event (bottom). The consumption of ground vegetation by the fire is evident in the area (photos: Guilherme Pinto (top) and Igor Drobyshev (bottom).

Figure 3 Top-left: example of a charred stump in the Sala burned area. Top-right: cross-section of a charred stump that was sampled in the area affected by 2014 Sala mega-fire. Bottom: dated sample from Sala with fire scar (photos: Guilherme Pinto).

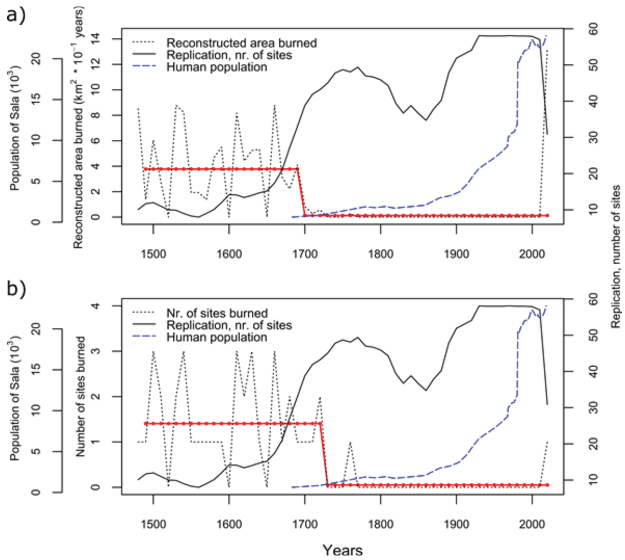

Figure 4 (a) The reconstructed area burned and (b) the number of sites burned at decadal resolution (dotted lines). Regime changes in the fire cycle (a) and the fire occurrence (b), as identified by the regime-shift analysis (line with dots in red). The population data are shown by the dashed blue line. Site replication is shown by the black solid lines.

4.2 Effects of the landscape and climate on modern fire activity in Sweden and across the European boreal zone (Papers I and IV)

Fire occurrence is strongly influenced by road density, the number of firebreaks, and population density, suggesting an important role of human-related ignitions (Figure 5). Specifically, most of the fires are human ignited and normally close to densely populated areas (Syphard et al. 2007; Catry et al. 2009; Martínez et al. 2009). A dense road network facilitates peoples' access to forested areas and increases the ignition frequencies further away from populated areas (Feltman et al. 2012). Water and urban areas are considered firebreaks, but they also have a high recreational value and human activity, which in itself could increase fire occurrence. Drought indices are strongly and positively correlated with fire size (Figure 6). The initial spread index, a drought index used as a proxy for fire spread risk, showed a stronger positive correlation with fire size than the build-up index, a proxy for the dryness of deep organic layers in the soil. Human structures, such as urban areas and roads, and firebreaks limited fire size and possibly assisted in fire suppression in the areas with a denser population.

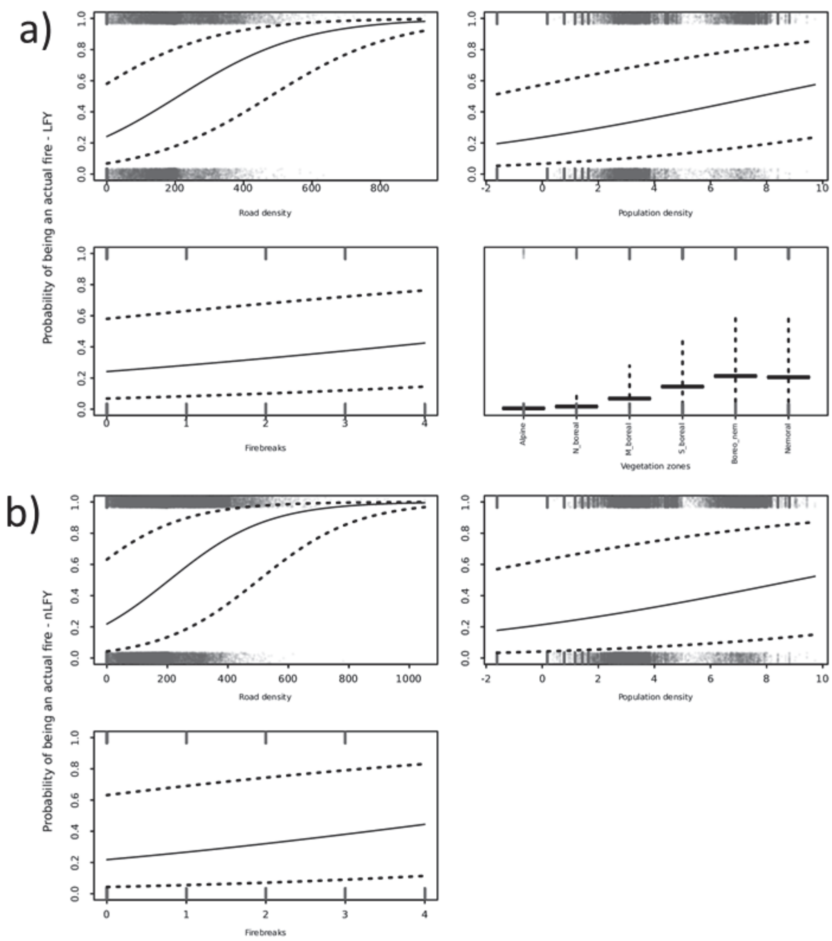

Figure 5 Relationship between fire occurrence and factors selected by the best model operating on the subset of data representing (a) large fire years (LFY) and (b) non-large fire years (nLFY). Units: road density, meters; population density, log (mean of inhabitants/km2), firebreaks, pixel count within the buffer area; and vegetation zones, predefined classes. The y-axis shows the probability of a point being a fire proportional to the density of our observations (random points (probability of 0) and fire points (probability of 1)). Each blue point represents either a random point or a fire and the dotted lines represent the credible interval (CI) (Pinto et al. 2020).

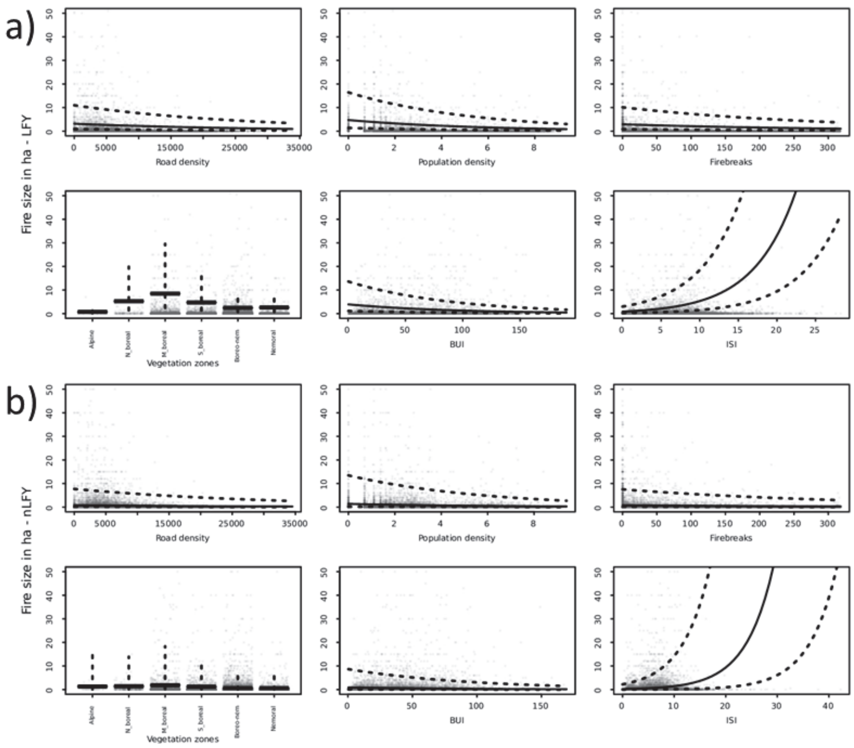

Figure 6 Relationship between fire size and factors selected in the model operating on the subset of data representing (a) large fire years (LFY) and (b) non-large fire years (nLFY). Units: road density, meters; population density, log (mean of inhabitants/km^2), firebreaks, pixel count within the buffer area, vegetation zones, predefined classes; BUI and ISI - index values. Each blue point represents a fire and the dotted lines represent the credible interval (CI).

The European boreal zone (EBZ) exhibited large variability in forest fire activity with the fire cycles varying from 1 581 (St. Petersburg region) to 37 119 years (Finland). Considering their ABA, the clustering of administrative units suggested the presence of sub-regions with synchronous annual variability in ABAs (Figure 7). LFY s in each of the clusters were associated with the development of high-pressure cells over the regions in question in July, indicating climatic forcing of LFYs. Contingency analysis indicated no long-term trend in the synchrony of LFYs observed simultaneously over several administrative units.

A trend towards higher values of MDC was observed for the months of April and May in the western section of EBZ (April) and southern-eastern sections of the Baltic Sea region and North sections of EBZ in Russia (May).

Trends in MDC during the summer months were largely absent. The geographic pattern of July MDC values analyzed through principal component analysis over the entire EBZ, indicated the presence of a dipole, i.e. alternative behavior, of the July MDC values over the Scandinavian peninsular and the eastern section of the EBZ. The dynamics of summer precipitation likely act as a "synchronizing factor" for the EBZ-wide forest fire activity. June SNAO exhibited positive but moderate (R2 = 0.17) correlation with EBZ fire activity, pointing to only partial annual synchronization of fire-prone conditions across the EBZ.

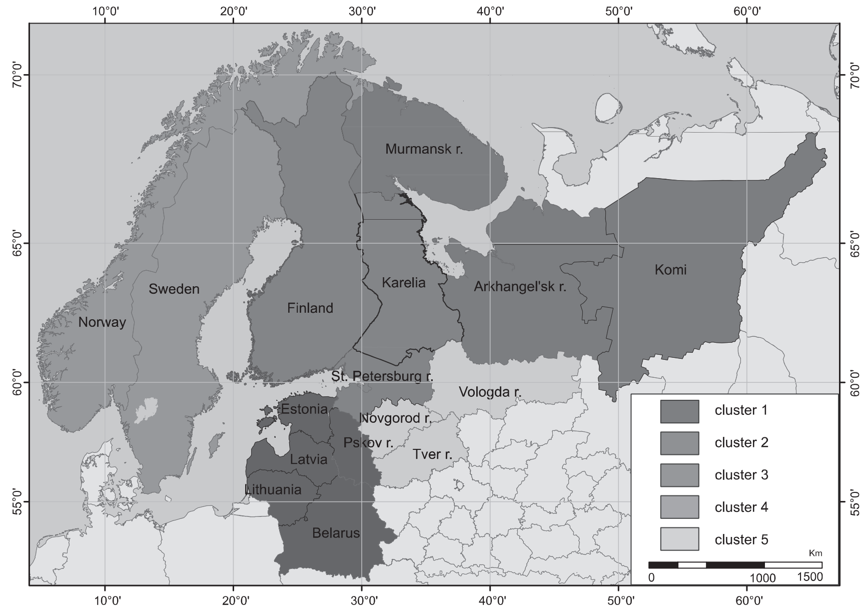

Figure 7 The geographical scope of the study with the regions providing the fire data for Paper IV. The classification is a result of clustering methods based on the between 1901-2017. Each cluster represents a group of administrative units with synchronous annual fire activity (see the colored version in Paper IV).

4.3 Future area burned in Sweden (Paper III)

Rising temperatures are expected to increase fire activity in the boreal zone until the end of the century. This study offered predictions of the forest area burned in Sweden under two climate projections (RCP4.5 and RCP8.5) and three vegetation scenarios (more fire-prone, MFP, less fire-prone LFP, and a scenario with changes in climate and population only, CPO) (Figure 8). The projections used climate data from a 20-year period centered on three time horizons: years 2060, 2080, and 2100. The MFP scenario prescribed an increase in the volume of pine, resulting from a decrease in the volumes of spruce and deciduous species. The LFP scenario prescribed an increase in the volume of spruce and deciduous, at the expense of the pine volume. Both MPF and LFP considered both climate projections (RCP4.5 and RCP8.5). The CPO scenario operated with two climate projections and changes in population. The area burned by forest fires is expected to increase by an average of 58% in the MFP and by 28% in the CPO scenarios in all time horizons, in comparison to the mean 1996-2019 levels. The LFP scenario showed an average decrease of 3% in comparison to the mean 1996-2019 levels. Changes in vegetation between scenarios seemed to considerably affect the future area burned. The small differences observed in area burned between the time horizons in all scenarios indicate fire activity shows a certain level of resilience to small changes in climate. There were observed regional differences, with southern Sweden (the region below 60º latitude) having a larger increase in area burned compared to northern Sweden, possibly due to a larger increase in precipitation for northern Sweden in comparison to the southern portion of the country, especially over summer (Kilpeläinen et al. 2010; Nikulin et al. 2011; Yang et al. 2015). The results suggest that vegetation has a strong impact on fire activity, with possibilities to mitigate the increases in area burned expected due to climate change.

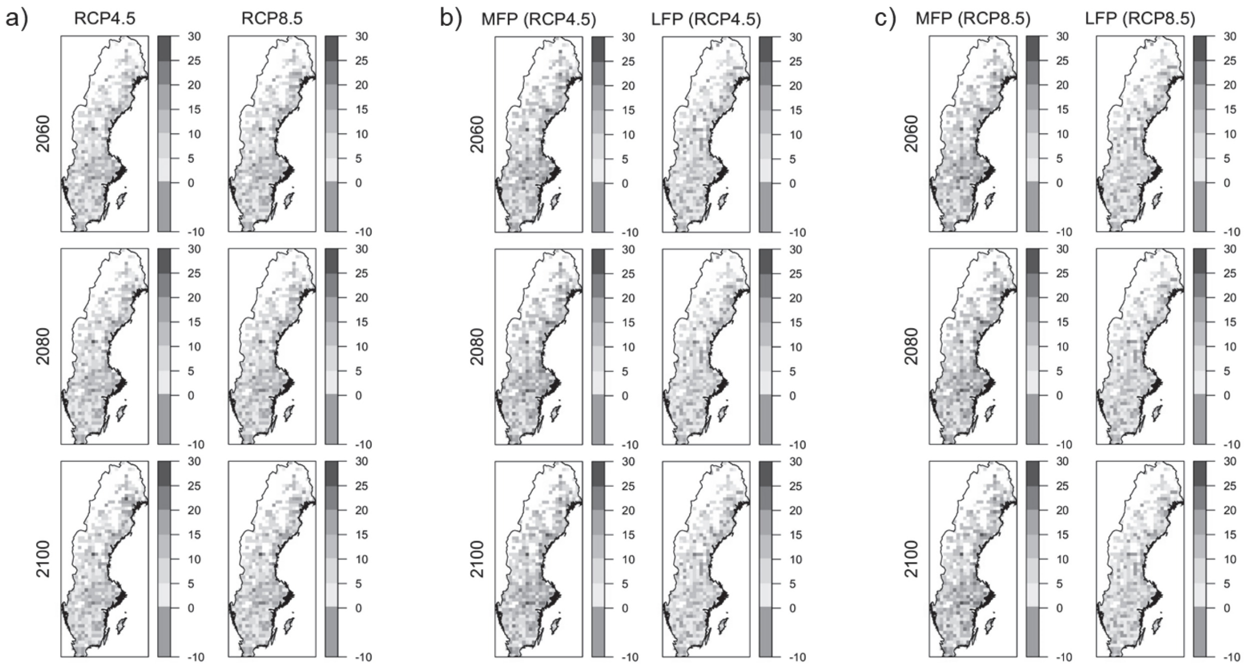

Figure 8 Predicted area burned for (a) CPO scenario, (b) both MFP and LFP scenarios and under the RCP4.5 projection, and (c) both MFP and LFP scenarios and under the RCP8.5 projection. All the figures show the predictions for three time horizons (2060, 2080, and 2100) (see the colored version in Paper III).

5. Conclusion

To disentangle the role of human-related activities and climate upon fire activity is a complicated task, as both intimately co-interact at multiple temporal and spatial scales. These co-interactions often show various temporal lags and many cumulative and non-linear effects. The results from this project suggested that climatic annual variability and scale are two important elements to understand the individual roles of climate and human activity. Annual climate oscillation is the main factor impacting annual variability in fire activity. Throughout the year, dry weather is responsible for preconditioning forest fuels in increasingly larger portions of the forest landscape which is conducive to fires. During prolonged droughts the proportion of the forested landscape capable of carrying fire increases.

Humans and vegetation structures, however, impact the landscape on a different scale. From a societal point of view, the amount of area burned in a given time is of high importance. This is where the differences in vegetation structures and human suppression comes in. Humans are the main source of fire ignitions in Sweden, either purposeful or accidental. The difference in fuel composition in a forest makes a landscape more or less prone to fire spread. Similarly, fires closer to populated areas are subject to fire suppression. In fact, the major decline in modern fire activity in comparison with historical levels shows the effectiveness of suppression efforts, the scale of human impact on fire activity today is much reduced than it was in the past. Today at the landscape level, human activities have become one of the main drivers of fire activity, along with climate.

Future climate will likely be more fire-prone and the amount of forest area burned will increase. It is unclear if the current fire suppression framework will be sufficient to effectively address future fire risks. Difficulties in controlling today's large fires and projected increase in climatological fire hazards, call for novel strategic approaches in fire mitigation. One strategic approach could be regional fuel management, which would address the risks of fires spreading over the large areas under severe drought conditions.

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Acknowledgements

A four years' project isn't done by one person alone, but a group of people working together. Here I would like to thank all the involved ones in this thesis, either for working with the project, or for simply sharing a coffee, talk, and/or beer.

First of all, I would like to thank Igor for the patience during those years. I learned a lot and am thankful to have you as my main supervisor. I also would like to thank Mats Niklasson, because I learned a lot about fire and fire ecology from you. This work would have been way less fun without the discussions, fieldwork, chats, phone calls, and sauna sessions if you two were not involved. Also, thanks to my other supervisors for their presence and support at different stages. I would like to add here two co-authors that worked like supervisors: François and Jonathan. Thanks for your contributions.

I also would like to thank others involved in our working group either through publications, fieldwork, or fun times, that made all the work nicer and extremely enjoyable, namely Nina, Ivan, Mara, Daniela, and Tanja. Also, shout out to my good French colleagues for the good company during conferences and excursions.

A big thanks to some colleagues/friends that were very special during this time for sharing a beer, coffee, or a horror movie: **Isak, Oscar, Linda, Emma, Adrian, Mikael, Björn, Santosh, Peter, Daniela, Anaïs, Guille**, and others. You are very dear to me.

Also, thanks to everyone at the department for helping, researchers or not. Many things would not work here is it wasn't for you involved. Thanks to past and present colleagues and fellow PhDs and post-docs for fikas, beers, and nice talks.

A big thanks to my Taekwon-Do family at the **Kang Center** in Germany and to everyone that participated in my classes in Alnarp. You surely kept me sane and fit thought this time (in addition to the fun!).

Thanks to my dear friends **Sara** and **Andy** for the support and good times, you made Sweden sweeter. Also, to my friends in Germany (**Frido, Moritz, Stephan, Matthias, Florian, and Benjamin**), Poland (**Kuba**), England (**Tomek and Martin**), and Brazil (**Veto, João, Deivid, Weliton, Zé Marcio, and Nelcivan**). You all have no idea how important you all were during these times.

Last but surely not least, thanks to the people that are my life, inspiration, and motivation: **Wiebke, Oslei, Edna, Cecília, Walter, Walmar,** and **Walda** (R.I.P). This thesis was dedicated to you but I still can't thank you enough.

Acta Universitatis agriculturae Sueciae
Doctoral Thesis No. 2020:55

In the summer of 2014, the Sala municipality in central Sweden registered the largest fire in Swedish modern history. The circumstances regarding the fire highlighted the complex interactions between ignition and the spread of the fire, on one side, and human activities and weather, on the other. The main aim of this thesis was to investigate the impact of landscape properties (natural and human-related) and climate patterns on forest fires at different spatial and temporal scales.

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Online publication of thesis summary: https://pub.epsilon.slu.se

ISSN 1652-6880
ISBN (print version) 978-91-7760-628-4
ISBN (electronic version) 978-91-7760-629-1