

Climate and forest fires in Finland
– influence of lightning-caused ignitions
and fuel moisture

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Academic dissertation

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ABSTRACT

The objectives of this research were to examine how lightning characteristics influence ignition probability of a lightning stroke, to study the distribution of lightning-ignited forest fires and to examine fuel moisture variation.

This research utilized the comprehensive forest fire records collected by the Finnish Ministry of the Interior. Individual fires were systematically linked with individual lightning strokes to compute probabilities that a stroke has ignited a fire. A method of grouping lightning flashes into thunderstorms was developed in order to compare the ignition probability of a stroke and the characteristics of the thunderstorm to which the stroke belongs. To examine fuel moisture variation, the spatial and temporal variation in ignition probability was studied based on meteorological data, ignition experiments and Finnish forest fire risk index model.

The results supported the hypothesis that a stroke in a small thunderstorm is more likely to result in ignition than a stroke in a large thunderstorm. However, the results contradicted theories predicting that positive strokes or flashes of high multiplicity would more likely result in ignition than negative strokes or flashes of low multiplicity. Positive and negative strokes were equally likely to ignite a fire and that the ignition probability of a stroke decreases with increasing multiplicity of a flash.

Fuels were at their driest in late May and June in southern Finland and in late June in northern Finland. Lightning-caused ignitions were most frequent in July. Fuels were significantly dryer and lightning strokes are more frequent in southern Finland than in northern Finland. As a result, the density of lightning caused forest fires was twenty times higher in southern Finland than in northern Finland. Assuming that the natural fire cycle in southern Finland is at least 100 years, the results suggest that in northern Finland the natural fire cycle is several thousand years. If natural disturbance dynamics are mimicked in forest management and restoration, this south-north difference in natural fire regime characteristics, and consequently in forest disturbance dynamics in general, should be taken into account.

Keywords: fire regime, weather, thunderstorm, moisture content, ignition probability

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LIST OF ORIGINAL ARTICLES

This doctoral thesis is based on following articles which are referred to by their Roman numerals:

- I. Tuomi, T.J. & Larjavaara, M. 2005. Identification and Analysis of Flash Cells in Thunderstorms. *Quarterly Journal of the Royal Meteorological Society* 131: 1191–1214.
- II. Larjavaara, M. Pennanen, J. & Tuomi, T.J. 2005. Lightning that Ignites Forest Fires in Finland. *Agricultural and Forest Meteorology* (in press).
- III. Larjavaara, M. Kuuluvainen, T. & Rita, H. 2005. Spatial Distribution of Lightning-ignited Forest Fires in Finland. *Forest Ecology and Management* 208: 177–188.
- IV. Larjavaara, M., Kuuluvainen, T., Tanskanen, H. & Venäläinen, A. 2004. Variation in Forest Fire Ignition Probability in Finland. *Silva Fennica* 38(3): 253–266.

Study I was initiated by Larjavaara and planned jointly with Tuomi. Tuomi had the primary responsibility for all other stages of the research process of study I. Larjavaara participated in all other stages of the research process except data processing and calculation of flash-cell area and publishing of the corresponding chapter (Appendix) of study I. Larjavaara was responsible for all stages of studies II, III and IV except analysing lightning data in study II, carrying out ignition tests and computing estimated fuel moisture values in study IV. Tuomi was responsible for analysing lightning data and participated in the publishing of the corresponding chapters in study II. Pennanen participated in all stages of the research process of study II except data processing. Rita participated in the development, analyses and publishing of the statistical model for estimating unreported lightning-ignited forest fires in study III. Kuuluvainen participated in all stages of the research process of studies III and IV except data processing. Tanskanen was responsible for carrying out ignition tests and participated in the publishing of the corresponding chapters in study IV. Venäläinen was responsible for computing estimated fuel moisture values and participated in the publishing of the corresponding chapters in study IV.

CONTENTS

Abstract.....	3
Acknowledgements.....	4
List of original articles.....	6
Contents.....	7
Terminology.....	8
Introduction.....	9
Climate, vegetation and forest fires.....	9
Forest fires in Finland.....	10
Objectives.....	14
Direct influences of weather and climate on fires.....	14
An analysis of weather influences on forest fires.....	14
Lightning.....	15
Fuel moisture.....	16
Wind.....	17
Relative importance of lightning, fuel moisture and wind for forest fires.....	18
Material and methods.....	18
Lightning location data (I, II).....	18
Grouping flashes into thunderstorms (I).....	18
Forest fire records (II, III).....	19
Linking lightning with fires (II).....	19
Estimation of unreported lightning-caused forest fires (III).....	20
Derivation of ignition probability from weather data (IV).....	20
Results and discussion.....	21
Thunderstorm life-cycle, precipitation and ignitions (I, II, IV).....	21
Flash types and ignition probability of a stroke (II).....	21
Annual climatic variation and forest fires (II, III, IV).....	23
Spatial climatic variation and forest fires (III, IV).....	25
Natural, historic, modern and future fire regimes (III, IV).....	27
Suggestions for future research.....	29
Conclusions.....	29
References.....	30

TERMINOLOGY

Climate = Weather averaged for long periods.

Fire cycle = The length of time necessary for an area equal to the entire area of interest to burn (Wildland fire ... 1986).

Fire regime = Set of fires and their characteristics (e.g. intensity, severity, size and regularity) that have occurred within a defined area over a given period.

Flash = A lightning discharge (Rakov and Uman 2003).

Fuel = Combustible material (Wildland fire ... 1986).

Fuel moisture = Water in fuels. The moisture content is normally expressed as water per dry mass.

Historic fire regime = Fire regimes before active mechanised fire suppression

Ignition probability = The probability that a burning standard match will ignite a fire when it is placed on forest floor. Climate-caused fuel moisture variation is measured in IV as ignition probability.

Ignition probability of a stroke = Likelihood that a stroke ignites a fire.

Lightning = An electrical discharge caused by the separation of positive and negative discharge in clouds (Latham and Williams 2001). Lightning is a general word lacking the clarity of terms stroke and flash.

Modern fire regime = Fire regimes after the start of active mechanised fire suppression.

Multiplicity = Number of strokes in a flash.

Natural fire regime = Fire regime assuming the total absence of the influence of humans (only a theoretical concept in Finland, as humans have been present throughout the Holocene (Huurre 2001))

Negative flash/stroke = Transfers negative electric charge to the ground.

Polarity = Determines the direction of the transfer of a negative charge in a flash/stroke (negative versus positive flash/stroke).

Positive flash/stroke = Transfers a negative electric charge to the cloud.

Stroke = One component of cloud-to-ground flash. A stroke is composed of a downward leader and an upward return stroke. (Rakov and Uman 2003)

Thunderstorm = Cluster of flashes. NB that in study I this signifies a widespread instance of thundery weather and the word "cell" or "flash cell" is used to signify a cluster of flashes.

Weather = Short-term physical atmospheric conditions (e.g. temperature, wind, moisture and lightning)

INTRODUCTION

Climate, vegetation and forest fires

Climate influences forest fires directly by controlling lightning, fuel moisture and wind conditions. However, the influence of climate on fires is more complex, as climate is also a key factor influencing vegetation, the burning fuel (Bonan 2002). For example, in general a dryer weather period means dryer fuels and increases the impact of forest fires. However, in dry climates with sparse vegetation, increasing rainfall enhances growth in the wet season, which increases the spatial continuity of the fuels and causes more intensive fires in the dry season (e.g. Viegas 1998). In boreal forests, precipitation rarely limits vegetation growth (Jarvis and Linder 2000; Bonan 2002) and in general, less rainfall during the growing season (which is also the fire season) leads to more fires during the same year (Flannigan and Wotton 2001).

The most reliable climatic estimates of the past from boreal regions concern temperature, not precipitation (Pitkänen et al. 2003; Moberg et al. 2005). Temperature influences drying of fuels, but, more importantly, it is often correlated with precipitation. However, the results of paleoecological studies linking temperature, precipitation and forest fires do not reveal a clear pattern. Increasing temperature has been reported to correlate positively with precipitation and negatively with forest fires (e.g. Bergeron 1991; Carcaillet et al. 2001; Pitkänen et al. 2003). However, temperature and precipitation have been also shown to be negatively correlated, and in this case an increasing temperature can either increase fires (e.g. Johnson and Larsen 1991; Hallet and Walker 2000; Hallett et al. 2003) or decrease them (e.g. Lynch et al. 2004).

The inconsistency of these results regarding the relationship between precipitation and frequency of forest fires has been attributed to the indirect influence of climate on fires. Increasing precipitation can for example lead to the dominance of easily flammable conifers and therefore to a higher incidence of fires (Lynch et al. 2004). Also the possible role of human-caused ignition is often ignored in these studies.

The estimation of influence of future climate change on forest fires is also challenging. Similarly as in the case of historic, also for the future, changes in temperature are more reliably predicted than those in precipitation (Johannesson et al. 1995). Studies of the recent or expected warming suggest that forest fires will become more numerous, assuming however no climate-triggered change in vegetation (Stocks et al. 1998; Flannigan et al. 2000; Gillett et al. 2004). Another approach to the study of the impact of future warming on fires is to make deductions based on past shifts in temperature. Pitkänen et al. (2003) and Carcaillet et al. (2001) claim that because previous warming in the areas they studied did not increase fires, no future increase should be expected. Others claim the opposite for their study area (Hallet and Walker 2000). However, the history-based approach is problematic, as future periods of warming may not change climate in the same way as they did in the past.

Fires, on their part, influence climate both directly and through changes in vegetation. Smoke blocks some of the radiation (Davies and Unam 1999), and the carbon dioxide and other greenhouse gases released in a fire contributes to the greenhouse effect (Ward and Hardy 1991; Amiro et al. 2001). The changes that occur in the vegetation as a result of forest fires affect the albedo and the microclimate of the burned site significantly (Yoshikawa et al. 2002).

In general, the interactions between climate, vegetation and forest fires are complex and area-specific and remain poorly understood (Larsen and MacDonald 1998; Drobyshev 2004). In a short time scale, weather influences fires mainly directly by regulating lightning, fuel moisture and wind conditions. Over longer periods of time, climate influences fires also indirectly via forest fuels i.e. live and dead plant material, first by altering decomposition and fuel accumulation, then by shifting species composition and, in a very long time scale by causing extinctions (Thomas et al. 2004) and immigrations of new species. Because of these indirect influences of climate on fires, increasing precipitation can increase fires in certain conditions even in the boreal forest (e.g. Lynch et al. 2004).

Forest fires in Finland

After having been exposed by the retreating ice sheet or having risen from the sea, Finland's land mass has been mainly covered by boreal forests, which were first dominated by *Pinus sylvestris* L. and *Betula sp.* (Pitkänen et al. 2002). Between 7000 and 3000 before present *Picea abies* (L.) Karst. colonised Finland (Giesecke and Bennett 2004), and now dominates moist and nutrient-rich sites and accounts 34% of the total growing stock (Peltola 2003). *Pinus sylvestris* still dominates dry and nutrient-poor forest types and accounts 47% of the total growing stock (Peltola 2003). The undergrowth is dominated by mosses and draft shrubs, especially *Vaccinium* spp. (Reinikainen et al. 2000). Lichens are common in the driest and most nutrient-poor sites and herbaceous plants in the most nutrient-rich sites (Reinikainen et al. 2000). When dry, the ground vegetation is easily flammable (Tanskanen et al. 2005). When either lightning or humans provide ignition and the weather has been dry enough to dehydrate the fuels, a forest fire spreads until fuels moisten due to precipitation, the fire reaches unsuitable fuels or people put out the fire.

The climate in Finland is warm compared to other regions at the same latitudes. Average temperatures in continental Finland in July vary between +17°C in the south-east and +12°C in the north (Drebs et al. 2002). In January, the corresponding range is from -6°C in the south-west to -16°C in the north (Drebs et al. 2002). The annual rainfall varies between 500mm–700mm in the south to 400mm–500mm in the north (Drebs et al. 2002). The lowest monthly rainfalls are recorded from February to May (20mm–40mm) and the highest generally in August (60mm–90mm) (Drebs et al. 2002). The relative humidity of air has its minimum in spring and early summer and maximum in autumn and winter (Johannessen 1970).

Changes in the historic fire regimes from one period to another are considered to be caused mainly by climatic shifts in boreal North America (Bergeron 1991; Johnson and Larsen 1991) and by changes in human behaviour in boreal Eurasia (Goldammer and Furyaev 1996; Niklasson and Granström 2000). One approach to evaluate the human influence on forest fires is to outline the means of livelihood and assess the harmfulness or utility of fires to people. If fires are useful, forests can be burned in a controlled manner or ignited intentionally and allowed to burn freely. On the other hand, if forest fires are considered harmful, human-caused ignitions are accidents and efforts are usually made to suppress fires.

In the past hunting has been an important subsistence strategy of people living in Finland (Taavitsainen 1987). Important game species have been moose (*Alces alces*) and wild reindeer (*Rangifer tarandus*) (Ukkonen 2004). Moose favour early successional stages with deciduous trees and herbaceous plants (Siivonen and Sulkava 1994) and therefore

benefit from fires (Wright and Bailey 1982). Reindeer also benefit from early successional vegetation, but on the other hand subsist during the winter mainly on *Cladonia* spp. lichens (Siivonen and Sulkava 1994), which are typically consumed in a forest fire and are most abundant in old-growth forests (Auclair 1983). Thus, fires can have opposing effects on game species depending on their ecology. Overall, it has been shown that people have significantly influenced forest fires to increase and manage game populations in North America (Vale 2002) and this has very probably taken place also in Finland in some extent.

The importance of livestock husbandry and agriculture developed late compared to other European countries (Taavitsainen 1987). Cattle were important and the forested summer pastures were often burned to promote the growth of Poaceae and other herbaceous plants (Massa 1987). Slash and burn agriculture of cereals and root crops peaked in the 16th and 17th centuries, and was common still in the 19th century in eastern Finland (Sarmela 1987). Escapes of fire from the slash burns to the forest were presumably common.

Table 2. Examples of various historic Fennoscandian forest fire intervals or fire cycles (III).

Mean fire interval or cycle (years)	Period of time	Latitude (° north)	Method	Reference
20	1401–1998	58	dendrochronology	Niklasson and Dradenberg 2001
80	3000–2000 B. P.	60	peat deposits	Tolonen 1985
45	300–700			
130	300–1020	62	peat deposits	Pitkänen et al. 2001
35–45	1020–1845			
32–49	1403–1994	63	dendrochronology	Lehtonen and Huttunen 1997
37–59	1412–1994	63	dendrochronology	Lehtonen et al. 1996
79 (median)	1232–1650	64	dendrochronology	Niklasson and Gransröm 2000
52 (median)	1650–1999			
120	1712–1974	64	dendrochronology	Haapanen and Siitonen 1978
80	1300–1975	65	dendrochronology	Zackrisson 1977
62	1406–1998	65	dendrochronology	Lehtonen and Kolström 2000
63	1551–1850	65	dendrochronology	Wallenius et al. 2004
110	1413–1982	67	dendrochronology	Engelmark 1984
longer than 500 years	1400–2001	69	dendrochronology	Wallenius unpublished

Cause	Proportion (%)
Camp-fire or the like	31
Matchstick or the like	11
Lightning	10
Cigarette or other form of tobacco	8
Burning trash/litter	6
Prescribed burning	5
Miscellaneous	12
Unknown reason	17

Table 3. Causes of forest fire ignition in 1996–2002 (Pronto database unpublished).

Forest fire history can be studied from peat (e.g. Pitkänen et al. 2002), lake (e.g. Pitkänen and Huttunen 1999) or alluvial sediments (e.g. Pierce et al. 2004) for the latest millenniums, from fire scars in trees for the latest centuries (e.g. Niklasson and Granström 2000) and from historical records for modern times (e.g. Malamud et al. 1998). These studies based on biological and other archives show significant changes in fire regimes in Fennoscandia during the last millennium. At first, the fire cycle decreased until the latter half of the 19th century to less than a century in southern Fennoscandia probably due to the increasing density of human-caused ignitions (Niklasson and Granström 2000). From the latter half of the 19th century the fires rapidly started diminishing because of fire suppression (e.g. Zackrisson 1977) or because of a decrease in the density of human-caused ignitions (Wallenius et al. 2004). The average fire size decreased throughout second half of the last millennium (Niklasson and Granström 2000, data from northern Sweden). The fire cycles have been shorter in southern Finland than in northern parts of the country (Table 2).

In the 20th century both forest fires (Wallenius 2004) and prescribed burnings (Heikinheimo 1987) had a minor role compared to the previous centuries. Worth mentioning is a period of intense use of prescribed burning after clear-cutting to enhance *Pinus sylvestris* regeneration in the 1950s and 1960s (Parviainen 1996; Västilä 2003). At present (1996–2002) on average 1300 forest fires have been reported annually (excluding the archipelago of Åland in the south-west) (Pronto database unpublished). Only 5.7% of these fires have been estimated to be larger than one hectare (Pronto database unpublished). Because of their small average size, forest fires burn annually only 485 hectares (Pronto database unpublished). This leads to a theoretical average fire cycle of 54,000 years in Finland. South of 62° N the fire cycle is 18,000 years and north of 67° N it is 609,000 years. Half of the fires are ignited by people who are not careful with campfires, matches or cigarettes (Table 3). The reported fires only seldom burn the majority of living needles. Typically, the fire remains a surface fire and possibly kills small trees and a portion of larger trees.

The small size of forest fires can probably mainly be attributed to a dense road network, which causes fast detection and initial attack and creates firebreaks for spreading surface fires. To describe and inform the public about the fire risk the Finnish Meteorological Institute operates a fire danger rating system (based on Finnish forest fire risk index model; Venäläinen and Heikinheimo 2003). The scaled estimated fuel moisture content is provided for fire suppression authorities. When the estimated fuel moisture content is below a fixed

limit a forest fire warning is given to general public in the media and igniting campfires becomes illegal.

Towards the end of the 20th century, the virtual absence of fire in the forests and the interest in biodiversity conservation led to concern about the fate of organisms dependent on fire-created substances (Lindberg and Vanha-Majamaa 2004; Ahlroth and Lehesvirta 2004). This concern influenced forest management guidelines and practices. Prescribed burning after clear cutting and the use of restoration burnings with principally non-commercial aims have been promoted (Rassi et al. 2001; Kuuluvainen et al. 2002; Lindberg and Vanha-Majamaa 2004). Restoration to create “natural” stand structures has also increased the need for knowledge about natural fire regimes.

Often natural and semi-natural fire regimes for a given location are discussed without specifying the level of human influence (e.g. Slocum et al. 2003). However, because even a sparse hunter-gatherer population can substantially influence fire regimes by igniting fires (Pyne et al. 1996), it is advisable to make a clear distinction between natural and historic fire regimes.

Modern fire regimes can be studied based on forest fire records (e.g. Table 3), while historic regimes can be examined using paleoecological methods or forest structure (Kuuluvainen et al. 2002). However, natural fire regimes are also of interest from a general interest point of view (even discussed in Finnish school textbooks (Raekunnas et al. 1999)) and as a reference for forest ecosystem management and restoration (Perera et al. 2004). Some indication of natural fire regimes can be obtained by studying historical periods of low human influence or sparsely populated but ecologically areas similar to those in Finland. However, all boreal regions have at least occasional hunters who can ignite fires and Finland has been inhabited throughout the Holocene (Huurre 2001). Therefore, the “natural fire regime” is ultimately more of a theoretical concept; nevertheless, it is possible to try to define the main features of the natural fire regime indirectly based on climate and fuel characteristics. This approach together with assumptions on human influence can also shed additional light on historic fire regimes to support studies based on paleoecological methods.

Forest fires have been traditionally studied in Finland from the point of view of natural hazard reduction (e.g. Saari 1923). Studies of the influence of weather on forest fires included lightning-caused ignitions (Keränen 1929) and estimation of fuel moisture based on weather data (Franssila 1959).

Forest fires are nowadays successfully controlled in Finland but additional knowledge on the influence of weather on forest fires may be used to increase the cost-effectiveness of fire suppression and may help to predict necessary improvements in fire suppression as a result of the global climate change. Another reason for the increasing demand for information about the influence of weather on forest fires is the recent increase in prescribed burning in Finland (Västilä 2003). This is because its technical implementation is weather sensitive. In addition, some characteristics of natural or even historic fire regimes can be estimated based on climatic data, and these estimates can be used to set guidelines for prescribed burning. Knowledge of the characteristics of natural or historic fire regimes can also be valuable for other forms of forest management than prescribed burning. For example, recommendations on rotation periods in even-aged forest management aimed at restoration and biodiversity conservation could be based on natural fire cycles (Angelstam 1998; Bergeron et al. 2002).

OBJECTIVES

The main objective of this thesis was to study the influence of weather on forest fires and that of climate on fire regimes in Finland. The three more specific objectives were:

1. to examine the influence of thunderstorm and flash characteristics on ignition probability of a stroke (II)
2. to study the spatio-temporal distribution of lightning-caused forest fires (III)
3. to examine the level and variation of ignition probability to understand climate-caused variation in fuel moisture (IV)

To reach these three main objectives, some intermediate goals had to be met. A method of grouping flashes into thunderstorms (I) was developed in order to examine the influence of thunderstorm characteristics on ignition probability of a stroke. A statistical method was developed to describe the spatial variation in the density of all lightning-caused forest fires, assuming that the proportion of reported lightning-caused forest fires of all lightning-caused forest fires was dependent on population density. (III).

DIRECT INFLUENCES OF WEATHER AND CLIMATE ON FIRES

An analysis of weather influences on forest fires

According to the scientific literature (e.g. Viegas 1998) and fire-fighters' handbooks (e.g. Heikkilä et al. 1993), the occurrence of forest fires and their behaviour depends on fuels, weather and topography. However, Finland is relatively flat and topography can often be ignored. On the other hand, the possible human action (ignitions and suppression of fires) can be listed. The influence of weather can also be divided into three separate factors (lightning, fuel moisture and wind) (Figure 11 in IV) on the basis of the different mechanisms by which they affect forest fires. Lightning causes ignition. Fuel moisture influences both ignitions and fire behaviour and is influenced by the weather before the fire. Wind during a fire affects fire behaviour. The three weather factors are shown in Figure 1, and I use this novel typology throughout this thesis.

Knowledge of the influence of lightning, fuel moisture and wind on ignition and fire behaviour can be useful when analysing fires in different spatial and temporal scales. Weather before and during a fire influences its ignition, spread and extinction. This topic has been widely studied (e.g. Fuquay et al. 1967; Rothermel 1972) and this knowledge is of significant importance for forest fire control. On the other hand, as a fire regime is composed of individual fires over space and time, influence of long-term weather factors, i.e. climate, can be studied to understand variations in fire regimes (Figure 1).

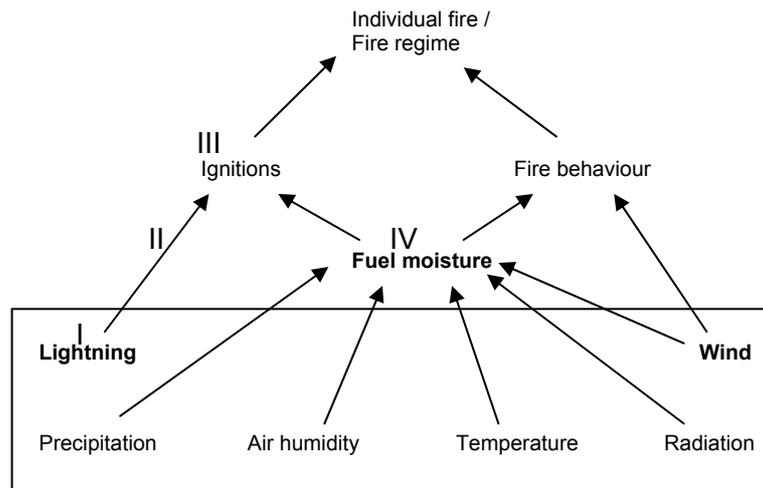


Figure 1. Influence of weather on an individual fire and influence of climate on fire regimes. The scope of weather or climate is represented by a rectangle. The three weather factors examined and compared in this thesis, lightning, fuel moisture and wind, are given in bold print. The Roman numerals from I to IV refer to the four research articles.

Lightning

In Finland, about 130,000 cloud-to-ground flashes are detected annually (Tuomi 2004). One flash is on average composed of 1.8 strokes (Tuomi 2004). Both in northern and coastal Finland fewer flashes are detected than in inland parts of southern Finland (Figure 2). Most flashes occur between June 25 and August 5 (Tuomi 2004).

Thunderstorm systems can be classified based on the spatial pattern of cloud-to-ground strokes. Dense coverage of flashes over a large area is often associated with thunderstorms related with frontal systems (e.g. Figure 1 in I) (Tuomi and Mäkelä 2003). Sometimes individual thunderstorms are clearly separated by areas in which no strokes are detected. These thunderstorms can be either moving (e.g. Figure 2 in I) or stationary (e.g. Figure 3 in I) and often occur on warm afternoons of sunny days (Tuomi and Mäkelä 2003).

Weather influences ignition via lightning and fuel moisture (Figure 1), the latter being largely determined by precipitation. Both lightning and precipitation are always associated with thunderstorms (although it is possible all raindrops evaporate before reaching the ground) (Schroeder and Buck 1970; Ahrens 2003) and therefore the relationship between lightning and precipitation is a key issue for understanding lightning-caused ignitions. Already in the late 1920s, Keränen (1929) hypothesised that convective “warm afternoon thunderstorms” play a key role in lightning-caused forest fire ignitions.

A long-continuing current is a low-level current following a stroke. It is associated only with a small proportion of cloud-to-ground flashes (Rakov and Uman 2003). Previous research has shown that a long-continuing current between strokes in a flash is necessary for forest fire ignition (Fuquay et al. 1967) and that this long-continuing current is more likely to be

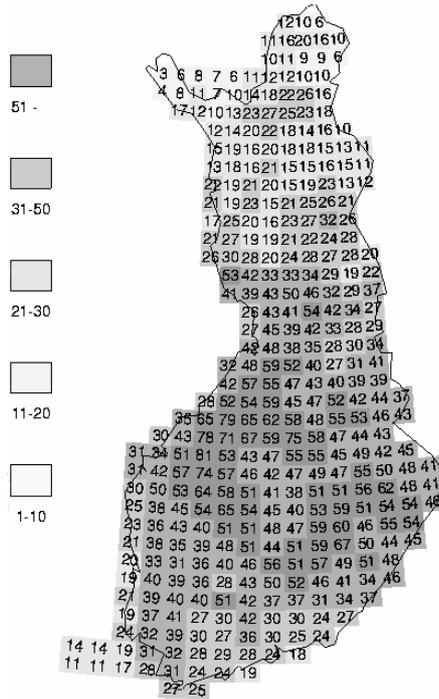


Figure 2. Density of located lightning flashes (per year and per 100 km² of water and land) based on data from 1998–2004. Most strokes were not detected in northern Finland before 2002, when new sensors were added. The corresponding density for the region north of Sodankylä (location of Sodankylä in Figure 6) calculated based on years 2002–2004 is 20–30 flashes. (Tuomi 2004)

attached to a positive stroke (Fuquay 1980). The multiplicity of flashes and the polarity has been shown to correlate similarly with the occurrence of a long-continuing current. High multiplicity has been demonstrated to increase the probability of a long-continuing current (Shindo and Uman 1989) and therefore ignition probability of a stroke (Flannigan and Wotton 1990).

Lightning is an important ecological factor (Komarek 1969). In many parts of the world where fires significantly influence large areas, lightning is the main source of ignition and is therefore an important concern for forest fire management (e.g. Johnson 1992). Even though forest fires are currently negligible in Finland, and lightning ignites only 10% of them (Table 3), an understanding of this only possible non-anthropogenic (Pronto database unpublished; Gromtsev 2002) mechanism of ignition, is important e.g. if natural disturbance dynamics are modelled (e.g. Li 2000).

Fuel moisture

Forest fuel moisture is determined by adsorption and desorption (Nelson 2001). Adsorption is determined in Finnish conditions by precipitation and relative humidity, while desorption is dependent on temperature, relative humidity, radiation and wind (Nelson 2001; Venäläinen and Heikinheimo 2003). These determinants of fuel moisture vary considerably both spatially within Finland and temporally between seasons (Drebs et al. 2002).

Both lightning and wind are components of weather that directly influence fire ignition or fire behaviour (Figure 1). Fuel moisture directly influences fire ignition and behaviour,

but it is not a component of weather (Figure 1). Several components of weather influence fuel moisture directly, such as precipitation, air humidity, temperature, radiation and wind, but their effect is noticeable only after a time lag.

Moisture content in forest fuels is inversely related to ignition probability (Tanskanen et al. 2005). Its presence increases the time needed for preheating of a particle and its burning time (Nelson 2001) as moisture must be evaporated before the fuel temperature can exceed 100 °C (Johnson 1992). The seasonal changes in fuel moisture are so distinct in Finland that a separate fire season is often specified (e.g. from May to August in southern Finland in Heikkilä et al. 1999). Despite the spatial variation in the determinants of fuel moisture in Finland, typically no geographical distinction is made in textbooks when discussing fire regimes (e.g. Hannelius and Kuusela 1995; Raekunnas et al. 1999).

Wind

There is little spatial variation in regional scales in mean wind speeds in Finland (Drebs et al. 2002) compared to the variation in flash density and variation in most determinants of fuel moisture. However, small-scale variations caused by differences in topography and vegetation are important. At the main weather stations at nine inland airports, measured average speeds (averages of daily averages) in the fire season, (here from May to August) vary from 2.9 m/s to 4.0 m/s (Drebs et al. 2002). However, these extreme mean values were measured at neighbouring airports (less than 200 km apart) and are caused by varying altitude and friction from land surface roughness around the airport and not by actual variability in the climatic conditions (Tammelin 1991). No spatial gradients in average wind speeds during the fire season have been detected (Drebs et al. 2002). In addition, the occurrence of strong winds, needed for crown fires is relatively invariable in inland Finland (Puranen 2005). The temporal variation (seasonal scale) in wind speeds is also small (Drebs et al. 2002). There is a steady decrease in the average wind speed of only 10% from May to September (Drebs et al. 2002). The highest average wind speeds are measured in November at most stations (Drebs et al. 2002).

The influence of wind on the drying of fuels was discussed above (Figure 1). However, wind influences fire ignition and behaviour also directly. Wind influences combustion by feeding oxygen-rich air in the combustion zone and by altering the path of hot gases (Chandler et al. 1983). Wind also significantly increases the horizontal travel of burning pieces of fuel, which can help a fire spreading downwind jump over fuel breaks (spotting) such as streams (Nelson 2003). Normally a more important effect than spotting for the rate of spread of a fireline downwind is the bending of flames and plumes, thus preheating fuels effectively (Chandler et al. 1983).

Whether wind influences ignition or not depends on the definition of “ignition”. In some textbooks (e.g. Chandler et al. 1983) and in this thesis (Figure 1) wind is considered not to influence ignition. The transition from smouldering to flaming combustion is enhanced by the increased availability of oxygen due to wind (Miyanishi 2001). In some cases, burning pieces of fuel can be blown to another location and start a fire. Rather than calling these ignitions as such, these might be propagations of fire from the area in which it was intended to burn (e.g. a fire spreading from a campfire or from a prescribed area). Wind also increases the “ignition probability” of some fuel types in field and laboratory ignition tests in which a burning match is placed on forest floor and the initial spread is observed. If only the moment of the start of combustion is considered “ignition”, this

increasing “ignition probability” with wind in these experiments is caused by a change in fire behaviour, as typically some seconds have passed prior to extinction in still conditions.

Relative importance of lightning, fuel moisture and wind for forest fires

The relative importance of lightning, fuel moisture and wind for forest fires is dependent on whether an individual fire or a fire regime in general is considered, as well as on whether the fire regime is natural or human-influenced. For example, lightning is relatively unimportant in the modern fire regime in Finland. However, as it is the only natural cause of ignition, it has a central role in the influence of weather and climate on fires in the natural regime and possibly has been in historic fire regimes.

Information on spatial and temporal variation in fuel moisture is valuable for modern fire control in time scales for both individual fires and fire regimes, and it can be used to suppress individual fires or for making strategic plans for nation-wide fire control. It can also be helpful in estimating spatial or temporal variation in historic or natural fire regimes.

Because there is little spatial (at regional scale) or temporal variation (at seasonal scale) in wind speeds in Finland (Drebs et al. 2002), wind probably causes little or no variation in fire regimes. This is also valid for historic fire regimes assuming that wind climate has been similar. On the other hand, wind is very important for explaining the behaviour of individual forest fires.

MATERIAL AND METHODS

Lightning location data (I, II)

To examine the influence of thunderstorm and flash characteristics on ignition probability of a stroke data on lightning was needed. Cloud-to-ground strokes emit electromagnetic radiation that is detected by a lightning location system (Tuomi 2004). The system reports location, exact time, peak strength and polarity of the stroke, and if several strokes are close enough in time and space, it groups them into a single flash. The current system covering Finland except the northernmost parts has been in operation since 1998 and has a location error of approximately one km (Tuomi 2004). The detection efficiency is unclear but has been estimated vary between 40% and 90%.

Grouping flashes into thunderstorms (I)

Flashes were grouped into thunderstorms using several rules. A flash was related to the nearest thunderstorm if the lag from the previous flash in the thunderstorm in question was less than 15 minutes and the distance to the centre of its latest 20 flashes was less than 15 km. In addition, if the time lag multiplied by the distance exceeded a certain limit, the new flash was not considered part of the thunderstorm (this rule was not used in II, where the grouping method was applied). The values of these rules were set subjectively but based on our best understanding of thunderstorm dimensions (e.g. McIlveen 1992; Ahrens 2003) and on extensive trials of grouping using varying values for the rules above.

Forest fire records (II, III)

To study the spatio-temporal distribution of lightning-ignited forest fires and to link strokes with fires data on forest fires was needed. The Finnish Ministry of the Interior has collected information on forest fires from municipal chiefs of fire brigades. Records prior to 1985 are not available. In 1993, a new electronic recording system, called the Pronto database (unpublished), was introduced. Because it took three years to set the system fully up, data for the period 1993–1995 is not reliable. Both forest fire databases include information on the municipality, area burned and estimated date, time and cause of ignition. In addition, the electronic database provides chiefs of fire brigades with an opportunity to comment, for example on the location of the ignition in the forest and the elapsed time from when a thunderstorm ignites a smouldering fire to the start of flaming combustion. The newer database also includes more detailed information on the coordinates of ignition. Unfortunately, this was only seldom given directly with exact coordinates but was typically based on a road address or a grid of 2km X 2km squares used by rescue services. A large proportion of fires had insufficient or unclear locating information.

Linking lightning with fires (II)

To examine the influence of thunderstorm and flash characteristics on ignition probability of a stroke a linking method was developed. First, all strokes less than 50 hours and 10 km (both subjectively chosen) from a fire estimated to be ignited by lightning were given a positive “proximity index” (A). If T is the delay from a stroke to the time of ignition (in hours) and S the distance between the stroke and the nearest fire (kilometres), the proximity index was obtained as:

$$A = \left(1 - \frac{T}{50}\right) \left(1 - \frac{S}{10}\right). \quad (1)$$

Based on proximity indices, the probability that the fire estimated to be ignited by lightning was actually ignited by lightning (B) was obtained as:

$$B = 1 - \prod_{i=1}^n (1 - A_i), \quad (2)$$

where A_i is the proximity index of a stroke surrounding a fire in question and n is the number of strokes with positive proximity index surrounding the fire.

The ignition probability of a stroke (P_k), i.e. the probability that stroke k ignited a forest fire, was computed from the probability that the fire was ignited by lightning (B), and the ratio of the proximity index of the stroke in question (A_k) to that of all strokes associated with this fire:

$$P_k = B \left(\frac{A_k}{\sum_{i=1}^n A_i} \right). \quad (3)$$

Estimation of unreported lightning-caused forest fires (III)

The proportion of lightning-caused forest fires that remain unreported to the forest fire record was estimated based on municipal population densities reported by Koskenranta and Piipponen in 2001. For this purpose, it was assumed that inhabitants of all rural municipalities are randomly distributed (or have the same level of clustering) and that each inhabitant reports all fires from a fixed area (averages of the area sizes are the same in various municipalities). In addition, it was assumed that a certain percentage of fires is reported regardless of the population density of the municipality in question (Eq. 1 in III).

With these assumptions it was possible to derive maximum likelihood estimates of the average size from which an inhabitant reports fires and the proportion of fires reported regardless of the population density in the municipality in question. For the computation we assumed that only population density influences the densities of reported lightning-caused forest fires in neighbouring municipalities.

Derivation of ignition probability from weather data (IV)

Based on standard weather station data from 26 weather stations at three-hour-intervals for the years 1961–1997 and on the Finnish forest fire risk index model (Heikinheimo et al. 1996; Venäläinen and Heikinheimo 2003) estimates of forest fuel moisture were calculated. The model assumes the fuel bed to constitute a uniform layer on the forest floor and that therefore both gain and loss of water are possible only through its upper surface. It also assumes that the fuel moisture content increases due to rain, and the potential evaporation is modelled based on air temperature, air humidity, wind speed and surface net radiation. The ratio of the actual evaporation to the potential evaporation is dependent on the moisture content of the fuel.

The fuel moisture content estimates were linked with ignition probability using data from ignition experiments. In these experiments, burning standard matches were placed on the forest floor (Tanskanen et al. 2005). Estimates of fuel moisture for the location where the experiments were conducted were plotted with the observed ignition probability and a two-part linear model was fitted to the data (Figure 2 in IV). This model was then used for estimating ignition probabilities based on moisture content estimates for the whole country.

RESULTS AND DISCUSSION

Thunderstorm life-cycle, precipitation and ignitions (I, II, IV)

The data clearly showed that the ignition probability of a stroke is higher than average in small thunderstorms of low intensity (Figure 3 f, g, h and j). This difference is probably caused by less abundant precipitation in thunderstorms with only a few flashes. The importance of precipitation is indicated also by lower than average ignition probability of strokes near the half-life of the thunderstorm (Figure 3 k) which is the most intensive phase in terms of precipitation (see Ahrens 2003).

These results are consistent with the hypotheses of Keränen (1929) that small afternoon thunderstorms are an important cause of lightning-ignited forest fires (Figure 3 b, f and j). Similar information given by Granström (1993), based on old Swedish literature in which "local thermal cells" have been related to many fires, is well supported by the results of this study (Figure 3 h). Rorig and Ferguson (2002) report that in a fast-moving thunderstorm less rain accumulates in a given location and this can increase the ignition probability of a stroke. This is also in agreement with the results of this study (Figure 3 i).

Flash types and ignition probability of a stroke (II)

Previous studies (Fuquay et al. 1967; Fuquay 1980) found that positive strokes are more likely than negative strokes to ignite forest fires. In contrast, we found that on average, positive and negative strokes were equally likely to ignite a fire. We also found significantly decreasing ignition probabilities in association with strokes with increasing multiplicity (Figure 3 e), which is clearly in contrast with results from previous research (Fuquay et al. 1967; Shindo and Uman 1989; Flannigan and Wotton 1990).

We also studied the relation between stroke peak current strength and ignition probability separately for positive and negative strokes. For both polarities, the ignition probability was very low for weak strokes and increased with increasing strength (Figure 3 c and d). An important difference in ignition probability for very strong strokes is likely. The ignition probability of negative strokes decreased at very strong peak current strength while for positive strokes the ignition probability continued to increase (Fig 3 c and d).

As mentioned, increasing multiplicity was inversely related with ignition probability of a stroke. However, multiplicity did not influence the ignition probability of a flash. Assuming that ignition probability of a stroke is dependent on its physical characteristics, ignition probability per stroke is an adequate unit for comparisons of ignition probability. However, as there are far fewer ground terminals (lower ends of lightning discharges in the atmosphere) than strokes in a flash (Proceedings of... 2004) and if ignition is dependent not on the physical characteristics of strokes but on fuels, ignition probability per flash is a more adequate unit.

The results about the influence of polarity and multiplicity contradict prevailing theory, which may be due to one or several of the following reasons: 1) Long-continuing current is not important in lightning ignitions. 2) Long-continuing current is not more often than average associated with strokes in flashes of high multiplicity or positive strokes in Finland. 3) The occurrence of positive strokes and flashes of high multiplicity is correlated with

another variable, such as precipitation, which cancels out the effect of higher probability of long-continuing current on the probability that a stroke will result in ignition.

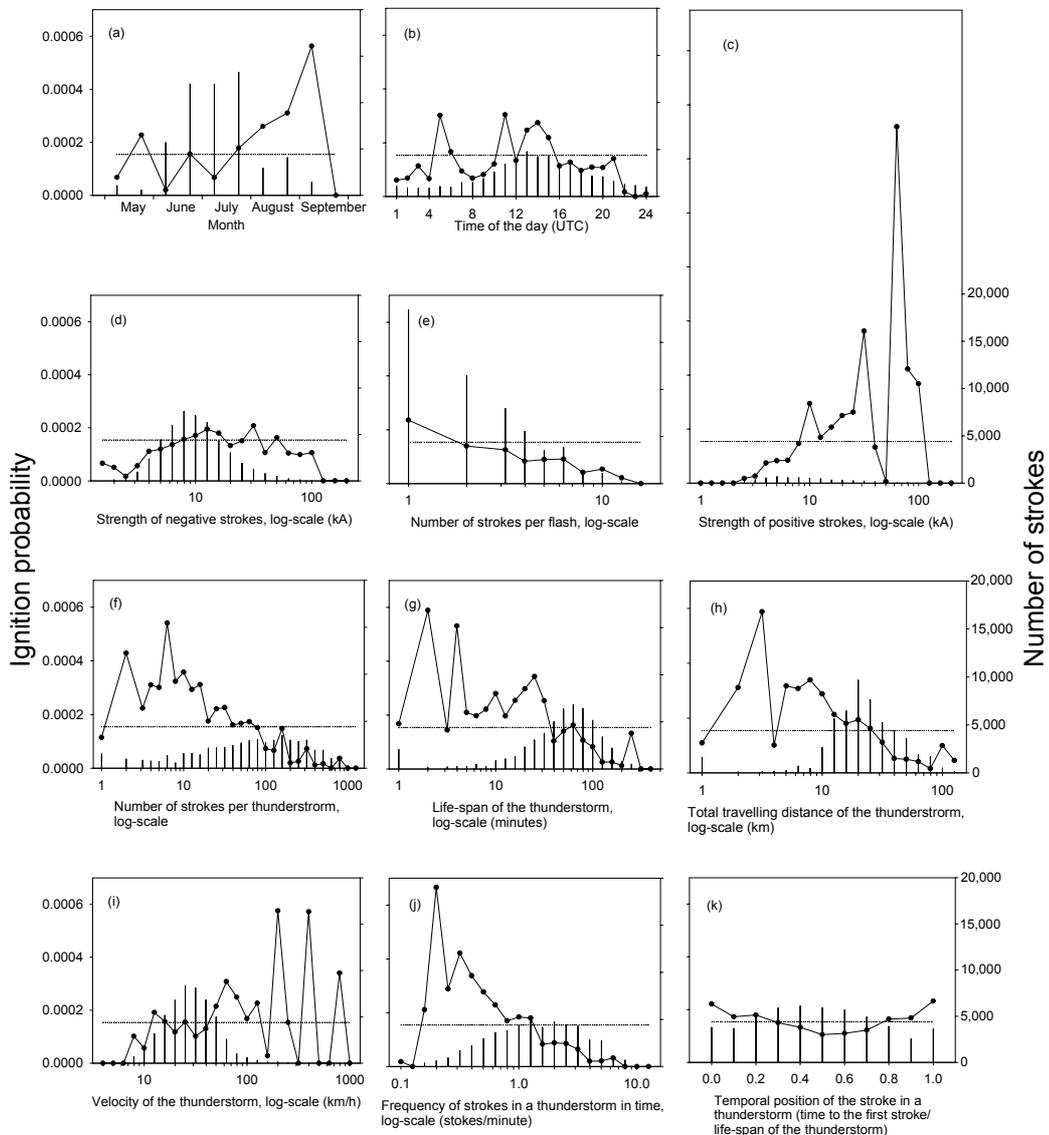


Figure 3. Dependence of ignition probability from a stroke on selected variables, (solid line with solid circles; scale on the left) and average ignition probability of all strokes (dotted line). The number of strokes in each category is shown with columns (scale on the right). Y-axis scales in all diagrams are equivalent. (II)

Annual climatic variation and forest fires (II, III, IV)

The weather factors lightning, fuel moisture and wind, all have their specific annual variation. The results of this study showed that highest ignition probability (lowest fuel moisture content) occurred in southern Finland (around Lahti; see Figure 6 for the location of Lahti) already in late May and early June, and in northern Finland (around Sodankylä; see Figure 6 for the location of Sodankylä) in late June (Figure 4). Monthly averages of wind speeds in inland Finland are relatively constant (Drebs et al. 2002). Most of the lightning occurs in late June, July and early August (Tuomi 2004).

Lightning-caused forest fires are influenced by fuel moisture and occurrence of lightning (Figure 1). As shown in Figure 3 a, ignition probability of a stroke increased during the fire season. Assumingly this trend is caused by the drying of deep duff layers during the summer. However, this increasing ignition probability of a stroke should also be detected by comparing lightning intensity (Tuomi 2004) and the number of lightning-ignited forest fires (Figure 5), both of which peak in mid-July and there is no evidence of strokes late in the season having a higher ignition probability. This contradiction may have been caused by the fact that lightning data were gathered in 1998–2004 and data on lightning-ignited forest fires were gathered in 1985–1992 and 1996–2001.

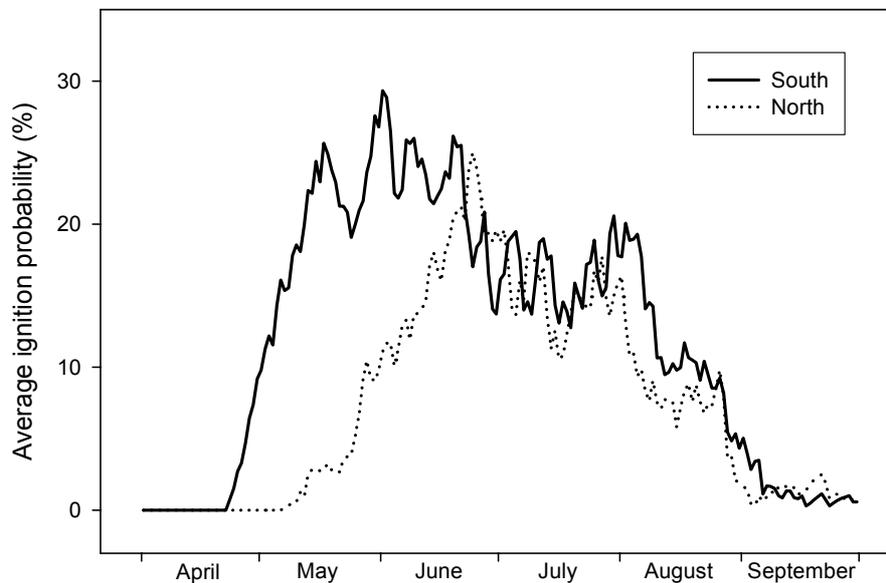


Figure 4. Average ignition probability variation in southern (Lahti) and northern (Sodankylä) Finland during the fire season. (IV)

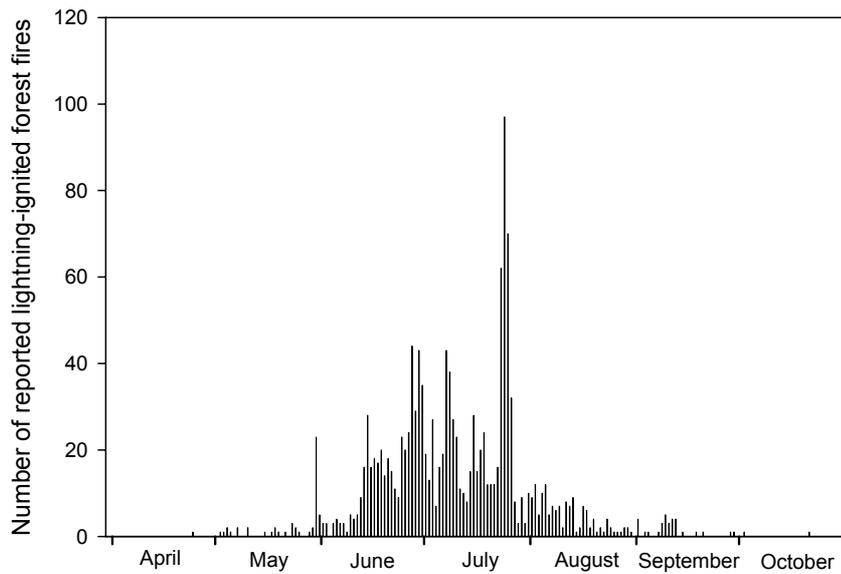


Figure 5. The total number of reported lightning-ignited forest fires for each day of the fire season during the 14 years included in the data. (III)

Another contradiction was the increase of the ignition probability of a stroke from July to August (Figure 3 a; points represent half month averages) despite a considerable increase in fuel moisture content (Figure 4). A probable cause for this is that fuel moisture was computed only for the 30-mm top organic layer of the soil on open location, while ignition probability of a stroke is also dependent on the moisture of deeper layers at sheltered sites near the tree bole that has conducted the lightning discharge. Deep and sheltered fuels dry more slowly and their dryness can peak much later than that of a 30-mm top organic layer of the soil on open location shown in Figure 4. On the other hand, to study fire spread the moisture content of probably a thinner and more rapidly drying layer should be modelled.

Based on datasets of the three climatic determinants (lightning, fuel moisture and wind) of fire regimes and forest fires, the climatic limits of the fire season can be determined independent from fire data. This can be helpful when estimating the fire seasons of historical or natural fire regimes. If forest fires are allowed to burn for a long time, their occurrence (e.g. area burned per day) peaks later than that of ignitions (Granström 1993). If anthropogenic ignitions are numerous, the climatic fire season lasts from May to August in southern Finland and from June to August in northern Finland. If lightning is the only cause of ignitions, also then the climatic fire season is from June to August in southern Finland.

The fact that there have been so few wildfires in recent decades in Finland has led to a concern that organisms that are dependent on substances created by fire, such as charred wood, are in danger (Rassi et al. 2003). This has led to recommendations to increase prescribed fires (Rassi et al. 2003). In North America, lack of congruency between the timing of prescribed burnings and the seasonal patterns of natural or historic fires has been a concern (e.g. Slocum et al 2003; Taylor and Skinner 2003). In Finland, this topic has not

been discussed. However, only seldom have burnings been conducted to produce fire-created substances during the climatic peak of the natural fire regime because of holidays in July. Despite the lack of hard evidence, it is possible that some of the fire dependent organisms are adapted to fires and new fire-created-substances during the peak of the Finnish climatic fire season.

Spatial climatic variation and forest fires (III, IV)

The results showed nearly a three-fold difference in fuel moisture conditions (measured as average annual ignition probability) between north-eastern Finland and the south-western coast (Figure 6). The coastal areas were dryer than adjacent areas inland (Figure 6). The lightning flash density is relatively constant in most of Finland except in coastal areas and northern Finland (Figure 2). Average wind speeds during the fire season are relatively invariable within Finland (Drebs et al. 2002).

The density of reported lightning-caused forest fires decreased significantly from south to north (Figure 7). There is a 17-fold difference in their density between the region of Lahti in southern Finland and the region of Sodankylä in northern Finland.

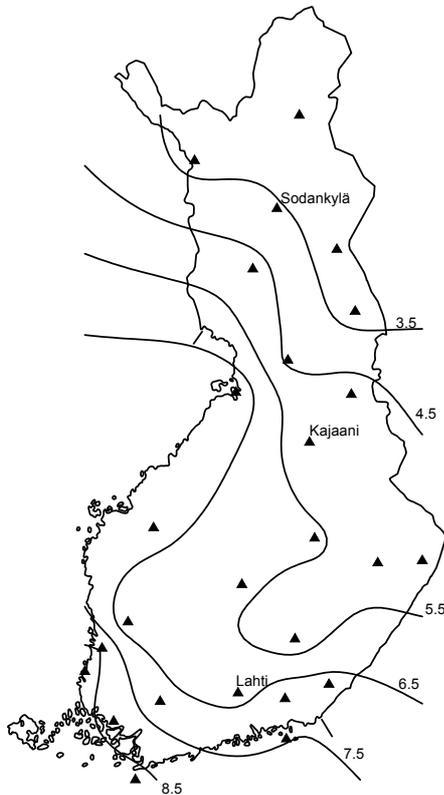


Figure 6. Spatial variation of ignition probability in Finland based on weather data from 26 meteorological stations (▲). (IV)

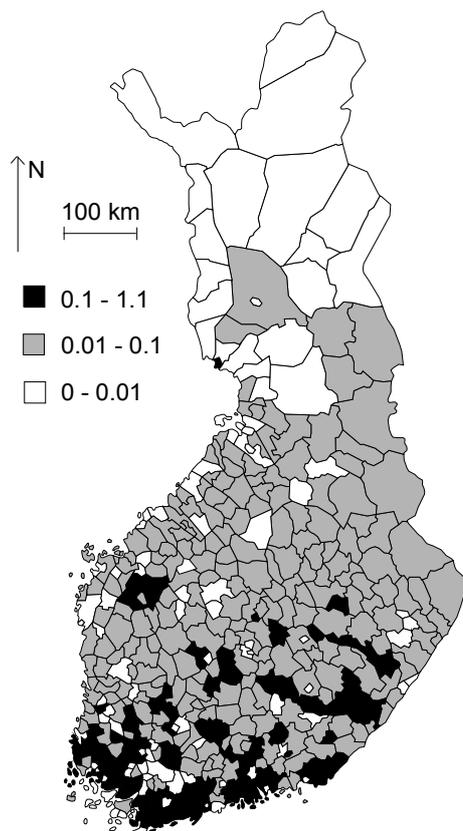


Figure 7. The mean annual number of reported lightning-ignited forest fires per 100 km² of forestry land in the 436 Finnish municipalities. Note the non-linear and non-logarithmic scale. (III)

The proportion of all lightning-caused forest fires reported was estimated based on human population density. Population density had a statistically significant influence on the proportion of fires reported (Figure 4 in III), however, differences between densely and sparsely populated municipalities were small. Therefore, the observed south-north gradient in the density of reported lightning-caused forest fires is due to a true south-north gradient in the density of all lightning-caused forest fires and is only slightly exaggerated by higher population density in the south.

Based on the lightning stroke density (Figure 2) and the density of reported lightning-caused forest fires (Figure 7), it is possible to calculate the average number of strokes on forestry land needed for one reported ignition (assuming that the proportion of forestry land is 80% (Tomppo et al. 1998)). However, this estimate is only approximate, as the datasets for lightning and ignitions are from different time periods. To partially overcome the problem caused by the non-overlapping time periods of the datasets, regional averages were computed. Along the southern coast (south of Lahti) 300 strokes on forestry land were needed for one reported ignition. The corresponding number for the westernmost coast was 500, for the easternmost Finland (North Karelia) 1400, for the region of Kajaani 2900 and for the area near the latitude of Sodankylä 7600 (computed based on lightning data for the years 2002–2004, as northern Finland was previously not well covered) (see Figure 6 for the locations of Lahti, Kajaani and Sodankylä). The order of these regional numbers is a

rather good reflection of the gradient of fuel moisture (Figure 6), which is the other determinant of lightning-ignition density.

When the steepness of the gradients of ignition probability (Figure 6) and the number of strokes needed for one ignition were compared from the south-west to the north-east, an unexplained difference was revealed. While the number of strokes needed for one ignition increased from the southern and western coast to the regions of Kajaani and North Karelia more than 5-fold, the annual ignition probability decreases only 1.5-fold. Although location-specific intra-annual comparisons of the distributions of ignition probability and stroke frequency were not conducted, it seems certain that this difference in the gradients is so great that it cannot be explained by the decreasing population density and proportion of fires reported in the north-east. Plausibly two factors explain this difference in the steepness of the gradients of ignition probability and number of strokes needed for one ignition. One is the shallow depth of the fuel layer for which moisture content was estimated (30mm), as lightning-ignitions are dependent probably also on moisture content of slowly reacting deeper layers or sheltered locations under tree canopies. The other factor is the possible spatial gradient in fuel characteristics. However, both the amount of carbon in the organic layer of the soil (Liski and Westmann 1997) and the coverage of various moss and lichen genera (Reinikainen et al. 2000) is relatively invariable between regions of Finland.

Climate and weather influence forest fire ignitions depending on the proportion of human-caused ignitions. If they are absent, southern Finland (around Lahti) has about seventeen times more ignitions than the northern part of the country (around Sodankylä). If humans cause all ignitions, the difference between the two regions is only less than two-fold, assuming no spatial variability in other fuel characteristics than moisture content and in density of “human acts toward ignition”.

If in addition to the influence of climate on density of ignitions, its influence on fire behaviour and the average area burned by one fire are taken into account, the difference between southern and northern Finland is even more drastic. The average area burned per fire is in general smaller in climates where the average annual ignition probability is lower, as the weather is suitable for fire spread for a shorter time. This effect is the stronger the smaller is the influence of fire suppression, the larger is proportion of days suitable for fire spread and the less there are natural firebreaks in the landscape. If firebreaks are absent, the fire can spread two-dimensionally and the area burned grows exponentially.

Natural, historic, modern and future fire regimes (III, IV)

As only lightning can ignite fires in the natural regime, the 17 times greater density of lightning-ignited forest fires in southern than in northern Finland (regions of Lahti and Sodankylä), can be seen as a characteristic of natural fire regime, assuming that the ratio of lightning-caused forest fire densities would be the same in northern Finland and southern Finland both in the natural and in the modern fire regime. However, this assumption is possibly incorrect because for example of current unnaturally high reindeer population in northern Finland. Reindeer have reduced the coverage (Reinikainen et al. 2000) and biomass (Mattila 2004) of easily flammable *Cladonia* spp. lichens and therefore, lightning-caused ignitions could be denser without human influence.

The average fire cycle can be computed based on the density of fires and average area burned of one fire. A more humid climate and therefore shorter dry periods would mean smaller fires in northern Finland. On the other hand, the flammability of fuels can increase

as the time since the previous fire increases (Schimmel 1993), and thus abundant fires (higher density of ignitions) would be related to smaller fires in southern Finland. It is difficult to estimate which of these opposing factors is more important. Assuming they are equally important (and therefore the average fire size is invariable) and that southern Finland receives 17 times more ignitions than northern Finland, the natural fire cycle would be 17 times longer around Sodankylä than around Lahti. The natural fire cycle in the south is at least approximately 100 years, as it cannot be shorter than any of the historic regimes, in which human ignitions are added to the natural ones (if fire suppression is negligible) (historic regimes in Table 2). Based on this reasoning, the natural fire cycle in the region of Sodankylä would be at least 1700 years. The spatially non-varying average fire size would be at most approximately 10 km² (calculation based only on reported lightning-caused forest fires). The fire size was computed by dividing the area of examination by the product of the fire cycle and annual number of ignitions in the area of examination.

The difference between reported historic fire cycles in southern Finland and northern Finland (Table 2) is too small to be caused only by climate and fuel characteristics. This suggests that the proportion of human-caused ignitions have been greater in northern Finland than in southern Finland. On the other hand, the density of human-caused ignitions has probably been greater in southern Finland where also the population has been denser.

Both data on historic fire regimes and the results of this study indicate that fire regimes are distinctively different in southern and northern Finland. As organisms have had more fire-created habitats available in the south, they may be more dependent on these substances. Therefore, more burnings could be prescribed in the south for conservation purposes. The considerable difference between fire regimes of southern and northern Finland should be taken into account in other aspects of forest and ecosystem management as well. For example, natural fire cycles have been suggested as a guide template for determining rotation periods in even-aged ecosystem based forest management (e.g. Angelstam 1998; Bergeron et al. 2001). The very long natural fire cycle in northern Finland would indicate that small-scale gap dynamics are important naturally (Kuuluvainen 1994).

It has been argued that the ongoing climate change is increasing the area burned by forest fires in Canada (Gillett et al. 2004). In Finland lightning has been predicted to increase considerably because of increasing atmospheric CO₂ (Price and Rind 1994). Fuel moisture has been estimated to remain about the same with increasing CO₂ in Finland (Flannigan et al. 1998). This perception is supported by data from 1961 to 1997 in which no rising trend in fuel moisture was observed (Figure 5 in IV). Average wind speeds are expected to increase slightly or remain the same during the summer (Tammelin et al. 2002). Overall, the changing climate will probably cause only a small increase in the risk of fires in Finland as the level of the fuel moisture, which is the key weather factor of modern and future fire regimes, has been predicted to change little.

SUGGESTIONS FOR FUTURE RESEARCH

To understand why the well-established theory that positive flashes and flashes of high multiplicity ignite most of the fires (Fuquay et al. 1967; Fuquay 1980; Shindo and Uman 1989; Flannigan and Wotton 1990) did not hold in this study, polarity and multiplicity of flashes containing long-continuing current could be studied in Finland. However, the re-examination of this theory under conditions where it was developed could have greater practical consequences. For example in Canada, flash positiveness has been used to predict the high ignition probability of a flash (Kourtz and Todd 1991; Anderson 2002), but based on the results of this study, this approach would be clearly erroneous in Finland.

The precipitation associated with the same thunderstorm that is also the source of the igniter stroke seems to be the critical factor influencing ignition probability of a stroke. Weather radars detect rainfall on a sufficiently fine spatial and temporal scale to permit the estimation of precipitation before and after an ignition (Ahrens 2003). In addition to lightning strokes, precipitation and estimated fuel moisture could be linked with fire ignitions.

The Finnish fire risk index (Heikinheimo et al. 1996; Venäläinen and Heikinheimo 2003) is based on modelled evaporation and therefore has a potential to be more realistic than purely statistical indices (e.g. Stocks et al. 1989) especially in a changing climate. However, the model of the Finnish fire risk index has some weaknesses which should be corrected. For example, the increase of moisture in the fuel should be dependent also on the amount of moisture in the fuel. In addition, the artificial lower and upper limit for the possible amount of moisture in the fuel should be removed because measured fuel moisture contents are not confined between these limits (Tanskanen et al. 2005).

CONCLUSIONS

The results of this study support the hypothesis that strokes in small non-intensive thunderstorms cause more likely fires than strokes in larger thunderstorms. On the other hand, we found that, in contrast to the predominant theory, stroke polarity did not influence ignition probability of a stroke and that an increasing number of strokes per flash (i.e. multiplicity) decreased ignition probability of a stroke in Finland. These results on the varying ignition probability of a stroke could be used to increase the cost effectiveness of locating fire ignitions by nowcasting ignition probabilities of thunderstorms for fire suppression authorities. Because the introduced methodology of linking lightning and ignition and computing ignition probability of strokes based on the linking worked well, similar methods could be applied in other countries.

The results demonstrated that climate in southern Finland is much more benign for forest fires than in northern Finland. Southern Finland receives nearly twenty times more lightning-ignited forest fires than Northern Finland. In addition, forest fuels are dryer in Southern Finland, which allows fires to burn for a longer time at a faster rate of spread assuming invariable fuel characteristics. This indicates significant differences between the natural fire regimes of southern and northern Finland.

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