Variation in Forest Fire Ignition Probability in Finland

Markku Larjavaara, Timo Kuuluvainen, Heidi Tanskanen and Ari Venäläinen

Larjavaara, M., Kuuluvainen, T., Tanskanen, H. & Venäläinen, A. 2004. Variation in forest fire ignition probability in Finland. Silva Fennica 38(3): 253–266.

We examined climate-caused spatio-temporal variation of forest fire ignition probability in Finland based on empirical ignition experiments and 37 years of meteorological data from 26 meteorological stations scattered across Finland. First, meteorological data was used in order to estimate the variation in forest fuel moisture content with the model of the Finnish forest fire risk index. Second, based on data from empirical ignition experiments, fuel moisture content was linked with forest fire ignition probability. In southern Finland average forest fire ignition probability typically peaks in late May and early June, whereas in the northern part of the country the peak occurs at the end of June. There was a three-fold difference in the average annual ignition probability between the north-eastern part (3%) and south-western part of the country (9%). The observed differences in fire ignition probability suggest that the characteristics of the natural fire regime also vary considerably in the southern versus the northern part of the country.

Keywords ignition, forest fuel moisture, forest fire, fire regime
Authors´ address University of Helsinki, Dept of Forest Ecology, FI-00014 University of Helsinki, Finland
E-mail markku.larjavaara@helsinki.fi
Received 21 July 2003 **Revised** 27 April 2004 **Accepted** 4 June 2004

1 Introduction

Forest fire ignition and spread potential is largely determined by weather (Pyne et al. 1996, Johnson and Miyanishi 2001). Climate influences fire regime via three factors: lightning, wind, and forest fuel moisture.

In a natural forest, i.e. in conditions that are not influenced by human activity, lightning is practically the only possible cause of fire ignition. Even nowadays lightning plays substantial role in fire ignition in many areas, such as in Russian or Canadian boreal forests (Kourtz and Todd 1991, Gromtsev 2002). However, in Finland lightning ignites about one hundred forest fires annually, which is only 13% of all forest fires (Larjavaara et al. submitted). The mean size of a lightning-ignited forest fire is also very small, only 0.4 hectares, thanks to effective countrywide fire suppression. The seasonal trend of lightning-ignited forest fires is similar to that of lightning flashes, peaking in early July (Tuomi 2002, Larjavaara et al. submitted).

Wind influences forest fire ignition and behaviour through two separate mechanisms. First, wind increases smouldering spread rates (Frandsen 1991) and thus the probability of the transition from a smouldering to a flaming fire (Kourtz and Todd 1991). Second, wind also increases the spread rates of heads of flaming fires (Rothermel 1972), which has substantial practical importance for fire suppression (e.g. Pyne et al. 1996). There is little spatial variation in the wind regime in Finland (Tammelin 1991). The existing variation is mostly due to differences in surface friction caused by variations in topography and vegetation. Thus, similar forest landscapes have similar wind regimes across the country (Tammelin 1990). The average wind speeds are typically highest in autumn and lowest in summer (Alalammi 1987).

Moisture in forest fuels decreases the rate of combustion, as the evaporation of water requires additional energy (Nelson 2001). Forest fuels typically contain a significant amount of water (Heikinheimo et al. 1996). For example, even when relative humidity of the air is only 50%, a dry fuel particle absorbs water until it reaches an equilibrium moisture content fraction of ca. 0.1 (water / drymass of the fuel) (Kunkel 2001). Precipitation, dew, temperature, wind and radiation also control forest fuel moisture content. In Finland, seasonal and spatial variations of temperature and radiation are pronounced (Alalammi 1987) and thus supposedly also variation in forest fuel moisture content. On the other hand, as mentioned, intra-annual and especially spatial variation in wind regime is relatively small and the importance of lightning as a source of ignition has been small in latest centuries (Niklasson and Granström 2000) and remains so. Therefore variation in forest fuel moisture content is presumably the most important climate dependent factor influencing spatial variation of fire regimes.

The surface to volume ratio is of critical importance in determining the rate of change in the moisture content of fuel particles following changes in weather conditions (Nelson 2001). This is because changes in the moisture content of a fuel particle take place through its surface. Large particles with small surface to volume ratio respond to the wetting and drying forces of the weather slower than small particles. Since vascular plants can control their transpiration, the variations in their moisture content are more in accordance with those of larger particles than is indicated by their surface to volume ratio (Nelson 2001). In a forest fire, the moisture content of slowly reacting large fuel particles is critical to the depth of burn (mm) or amount of energy released in a fire (J/m^2), while the moisture content of small particles determines largely the fireline intensity (W/m) and especially the rate of fire spread (m/s) (Rothermel 1972).

The aim of this study was to describe the level and variation of forest fire ignition probability in time and space in Finland. In addition, we developed a simple statistical method for generating daily ignition probabilities in order to better account for intra-annual variation in ignition probability.

2 Material and Methods

Our method of generating spatio-temporal estimates of ignition probabilities was based on combining an extensive spatio-temporal meteorological dataset and the results of ignition experiments (Fig. 1). First, meteorological data was used to estimate the geographical variation in forest fuel moisture content in Finland. Second, forest fuel moisture content estimates together with the results of an ignition experiment were used to derive spatio-temporal estimates of ignition probabilities throughout Finland. In addition, a method for generating ignition probabilities was developed.

2.1 Estimation of Fuel Moisture Content

Estimates of the spatio-temporal variation in forest fuel moisture content were based on long-term records of weather data from 26 meteorological stations spread across Finland. Weather data was recorded from 1961 to 1997 at three-hour intervals. Some weeks of data for a particular year were missing for a couple of stations. The missing data was substituted with the data from the nearest station.

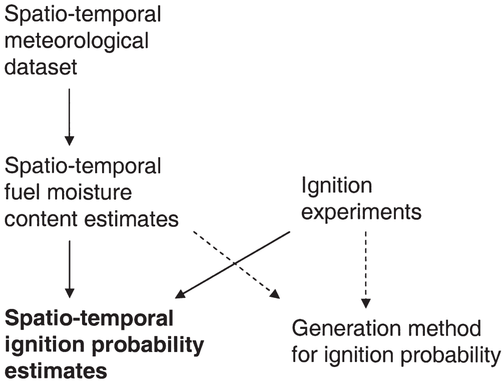

Fig. 1. Derivation of ignition probability based on meteorological and ignition experiment data. In addition, a generation method for ignition probability was developed.

Based on the weather data, the fuel moisture content estimates were calculated using the model of the Finnish forest fire risk index (Heikinheimo et al. 1996, Venäläinen and Heikinheimo 2003). In this model the fuel bed is assumed to constitute a uniform layer on the forest floor. However, even if this theoretical location and form of the fuel bed corresponds to that of ground fuels, the model is capable of representing both ground and surface fuels (terminology from Johnson and Miyanishi 2001). Due to the assumed form of the fuel bed in the model, both gain and loss of water are possible only through the upper surface of the fuel bed. A fuel bed thickness of 60 mm is used in the calculation for the Finnish forest fire risk index. However, in this study we used a thickness of 30 mm, which resulted in moisture content data that better explained ignition test results. The moisture content of this thickness corresponds probably (no data-based comparison has been done) best to the Duff Moisture Code or fine fuel moisture code in the Canadian system (Van Vagner 1987) and to the 100-h fuel class moisture content in the classification of the United States (Kunkel 2001) in terms of the speed the fuel approaches a new moisture equilibrium.

When computing the Finnish forest fire risk index, moisture content of the fuel can be increased only due to rain. The increase in water content in the fuel due to rainfall depends on daily rainfall, and the sub-model describing this process was parameterised empirically (Heikinheimo et al. 1996). Potential evaporation is modelled based on air temperature, air humidity, wind speed and surface net radiation. The proportion of water evaporating is dependent on the moisture content of the fuel, and the model describing this relation was also parameterised empirically (Heikinheimo et al. 1996). The fuel moisture content fraction is arbitrarily truncated between 0.67 and 3.33 (water / drymass). From the beginning of October until the melting of the snow cover the fuel is assumed to be saturated with water (fuel moisture content: 3.33). In this study the estimated fuel moisture at 9 p.m. was used to represent the daily moisture level, because it is congruent with the 24 hour average and to simplify data processing only one daily value could be used.

In the model of the Finnish forest fire index the lower moisture limit (0.67) is set to an unnaturally high level. In most boreal European forest fuels the moisture content must be below 0.4 to permit ignition (Schimmel and Granström 1991). As a consequence, it is evident that the Finnish forest fire index model estimates are systematically biased and the actual moisture contents are lower than what the model estimates (Tanskanen unpublished). However, this supposedly systematic error did not bias our results on the temporal and spatial variation of ignition probability because we derived ignition probabilities based on the moisture content estimates given by the Finnish model for the experimental site. This was also the reason why in the fuel moisture experiments (see next chapter) the model estimations of fuel moisture content were used instead of the fuel moisture contents measured at the site.

For the spatial data analysis, values of average ignition probability, based on weather records from the 26 meteorological stations, were interpolated throughout Finland. A contour map (Fig. 6) was generated based on kriging interpolation with a linear variogram and no drift or nugget effect (Bailey and Gatrell 1995).

2.2 Linking Estimated Fuel Moisture and Ignition Probability

A major difficulty in analysing spatial and temporal variation of forest fuel moisture concerns the choice of the time period over which the fuel moisture is averaged for spatial or inter-annual comparisons. If annual moisture content averages are used, the portion of the year outside the fire season influences the averages even though moisture levels outside the fire season are irrelevant with regard to forest fires. Comparing the averages of the fire season eliminates this problem, but the beginning and the end of the fire season are difficult to determine and are spatially variable. In addition, in some days during the season, fuels are “wet” and in others “very wet”. Even though in both cases forest fires cannot exist, these differences in moisture content influence the fire season averages. To eliminate the problem concerning the choice of the period over which the fuel moisture is averaged, the fuel moisture data can be linked to variables that more directly represent fire potential, i.e. variables related to fire ignition or behaviour. In this study we used ignition probability.

The dependency of ignition probability on fuel moisture content was modelled based on empirical data from ignition experiments. The experiments were carried out by placing burning standard matches on the forest floor. No more than five burning matches were placed on top of the bottom layer. If fire spread over 0.3 m away from its source within 5 minutes from the start, ignition was considered to have occurred. These experiments were carried out each day in 17 stands in the municipality of Lammi in southern Finland near Lahti (see Fig. 6 for the location of Lahti). The stands represented well typical managed Finnish forests. They were dominated by *Pinus sylvestris* or *Picea abies* and they were moderately dense, managed according to the normal Finnish practice and aged from 30 to 60 years. The *Vaccinium* spp. dominated field layer also gave some shade on the forest floor, where the burning matches were placed and which was covered in a continuous layer of mainly mosses but also lichens. The most common species were *Pleurozium schreberi*, *Dicranum* spp. and *Hylocomium splendens*. The experiment was repeated on 39 days between 5 June 2001 and 31 July 2001 between 12 a.m. and 4 p.m. The summer of 2001 was relatively normal in terms fire weather. The results of the ignition experiment will be published extensively elsewhere (Tanskanen et al. submitted). Because the experiments were conducted in coniferous middle-aged stands the obtained ignition probabilities describe the probability of ignition in such stands over a given period of time and not in average forest types of a certain region.

The fuel moisture content for the area where the ignition experiments were carried out was estimated based on the model of the Finnish forest fire risk index (Heikinheimo et al. 1996) for a fuel layer of 30 mm. The fuel moisture estimates were calculated for 12 a.m. and based on data from the nearest meteorological stations. Some rain gauges were also set up near the experimental conifer stands, but this data was not used, as it did not differ significantly from the data obtained from the nearest meteorological stations.

The relationship between the estimated fuel moisture and the results of the ignition test was described using a piece-wise linear model (Fig. 2) consisting of two parts. The two parts joined at the threshold moisture content of the fuel. On the wet side of the threshold moisture content the ignition probability was determined to be zero, but on the dry side it increased linearly with decreasing moisture content. The model was fitted to the data by the standard technique of minimising the squares of the residuals. The fitting process gave values for two important parameters, viz. the threshold moisture content and the slope of the line in conditions where ignition is possible.

Other models than a piece-wise linear model could have been used, probably with similar coefficients of determination. However, the ease of interpretation of the piece-wise linear models is an obvious advantage compared with non-linear models (Moore and Deiter 1992).

The ignition experiments showed that ignition probability was always zero when the estimated moisture content fraction was more than 2.2 (Fig. 2). In the driest conditions modelled by the Finnish forest fire risk system (0.67) between 1 and 15 ignitions were observed out of 17 attempts. The “dry” part of the piece-wise linear model fitted to data had a slope of –0.70 and it conjoins

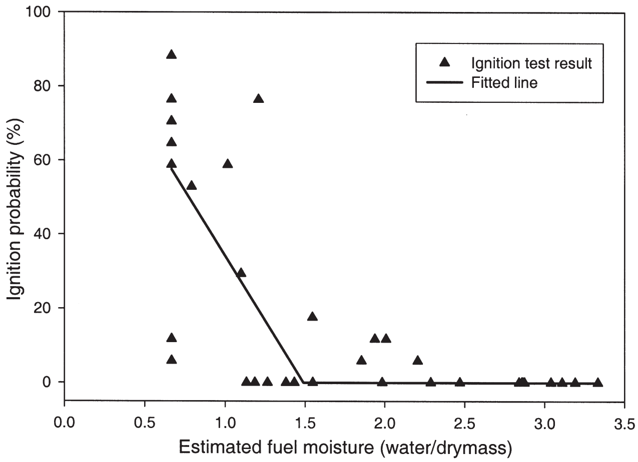

Fig. 2. Dependency of ignition probability on the estimated fuel moisture. A two-part straight line was fitted to the data. Seven ignition test results overlap in the extreme right triangle.

the "moist" part at the moisture content fraction of 1.49 (Fig. 2). Thus, the estimate for the ignition probability in the driest conditions given by the Finnish forest fire risk model (0.67 water per drymass) was 58%. The large variation in ignition probability for a given fuel moisture value is probably due to spatial variation of fuel characteristics in the experimental areas.

Table 1. Definitions of days of fuel moisture drying, wetting and equilibrium. m_t is the estimated moisture content the day in question at 9 p.m., and m_{t-1} is the estimated moisture content on the previous day at the same time.

Day of fuel drying	$m_t - m_{t-1} < 0$
Day of fuel wetting	$m_t - m_{t-1} > 0$
Day of fuel moisture equilibrium	$m_t - m_{t-1} = 0$

2.3 Generation of Ignition Probability Values

The generation of the data on intra-annual variation in ignition probability was based on estimated fuel moisture content in the Kajaani region (see Fig. 6) for the years from 1961 to 1997. Thus, the generated ignition probability variation is applicable only to the region of Kajaani.

The generation of these values was based on classification of fire season days into three categories: 1) days of fuel drying, 2) days of fuel wetting and 3) days of fuel moisture equilibrium (see Table 1 for definitions). For each day, the probabilities of these three day categories were calculated based on the fuel moisture content difference between consecutive days at 9 p.m (Fig. 7). In addition, the average proportion of drying (%) in days of fuel drying and the average amount of wetting due to precipitation (mm) in days of fuel wetting were calculated for each day of the fire season (Fig. 8).

The generation of the data on fuel moisture content was carried out by setting the beginning of the fire season at the beginning of April, when the fuel is saturated with water (moisture content fraction of 3.33) as it is assumed to be covered by snow. The generation of the data proceeded day by day by choosing a day category randomly based on their occurrence probabilities (Fig. 7) and by computing the corresponding change in the fuel moisture content (Fig. 8) for the particular day of the fire season. In this process, the moisture content is truncated between 0.67 and 3.33 (moisture content fraction), as in the original data of fuel moisture content estimations. The generated fuel moisture content values were converted to ignition probabilities based on the fitted piece-wise linear model (Fig. 2).

3 Results

The average fire season intra-annual variation in ignition probabilities in Lahti in the south and Sodankylä in the north are shown in Fig. 3 (see Fig. 6 for locations of Sodankylä and Lahti). In Lahti in the south, the ignition probability increases rapidly in late April and early May, peaks early in the fire season and stays high nearly to the end of June. In Sodankylä in the north, the ignition probability starts to increase nearly one month later than in the south, due to later snowmelt, and also increases more slowly, peaking at the end of June. From the beginning of July to the end of September both locations have approximately equal probabilities of ignition. At the end of the study period both locations have an average ignition probability of 0.6%. This means that in order to obtain a complete picture of the full length of the fire season, October should be included in the analysis. However, already at the end of September ignition probabilities are at a very low level and do not have much practical importance.

When intra-annual variation of individual years were examined instead of long-term averages, rapid changes in ignition probability were discovered (Fig. 4). During the wettest year (1974) of the study period in Kajaani there was only one

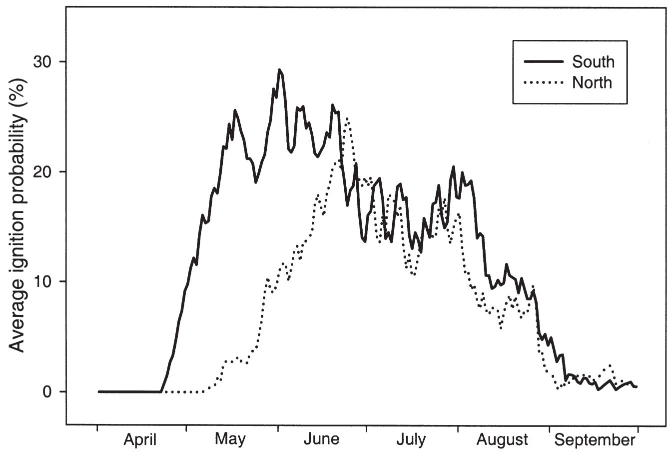

Fig. 3. Average ignition probability variation in southern (Lahti) and northern (Sodankylä) Finland during the fire season.

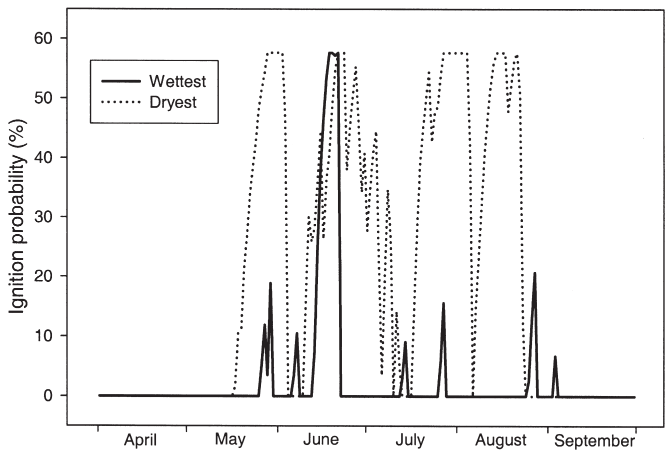

Fig. 4. Ignition probability variation in Kajaani during the wettest (1974) and driest (1969) year of the period from 1961 to 1997.

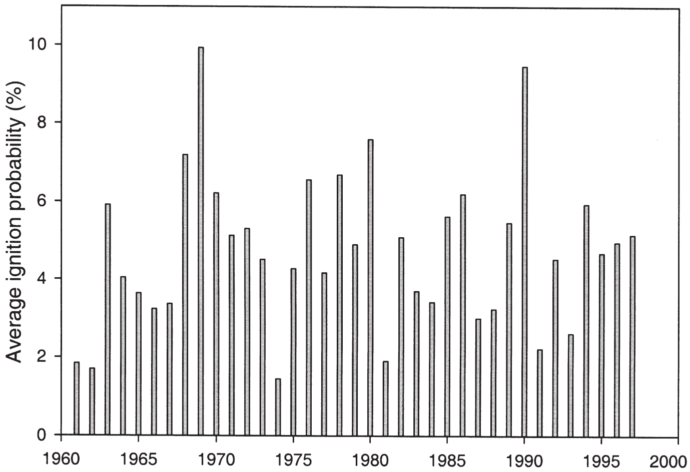

Fig. 5. Inter-annual variation of ignition probability in Kajaani.

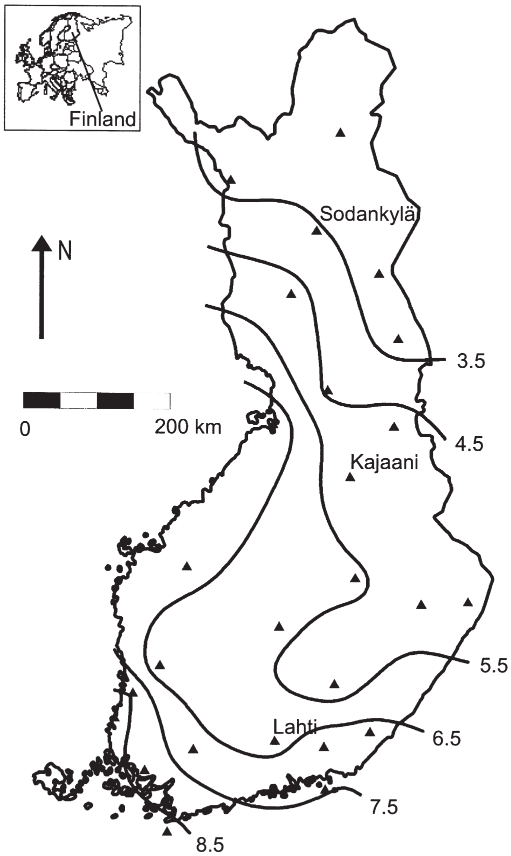

Fig. 6. Spatial variation of ignition probability in Finland based on weather data from 26 meteorological stations (▲).

short dry period, whereas the driest fire season (1969) included four longer dry periods. The rise of ignition probability from nil to more than 40% happened typically within a few days, and the decrease was even more rapid.

In addition, the inter-annual variation in the average ignition probability in Kajaani was large (Fig. 5). The wettest and driest years (also shown in Fig. 4) had average ignition probabilities of 1.4% and 9.9%, respectively. No increasing or decreasing trend could be detected for the study period from 1961 to 1997 (R^2 for an increasing trend was only 0.0064). This result is consistent with that obtained in an earlier circumboreal study by Flannigan et al. (1998).

Interpolation of the spatial variation of average ignition probability over all of Finland revealed a gradient of higher average ignition probabilities in the south-west and lower probabilities in the north-east (Fig. 6). In addition to this general gradient, coastal areas seem to be dryer than adjacent inland areas. The driest and also the southernmost meteorological station on an island south of the southernmost tip of mainland Finland had an average ignition probability of 8.8%. The wettest station was the easternmost of the northern stations (fourth northernmost) with an average ignition probability of 3.0%.

From 11 May, when the snow cover has normally melted, the long-term average probability of a day of fuel drying remained relatively constant

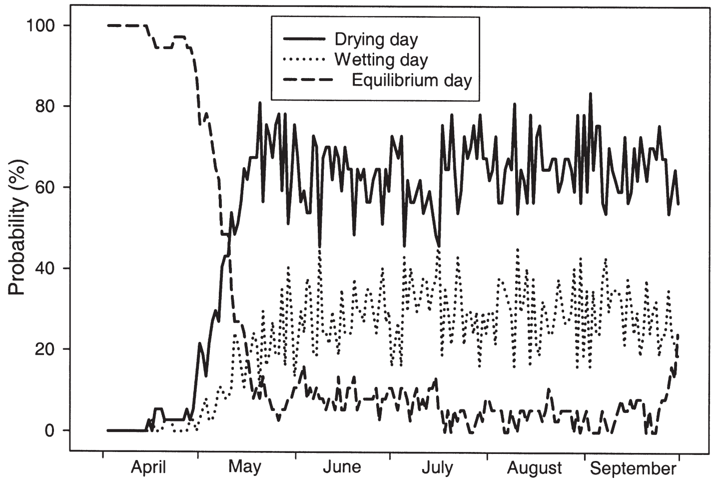

Fig. 7. Probability of having a drying, wetting or moisture equilibrium day of fuel moisture during the fire season in Kajaani.

(Fig. 7). However, there were large day-to-day variations (between 46% and 86%) in the data due to the relatively small number of years studied. The probability of a day of fuel wetting was about half of the probability of a day of fuel drying except in late May just after the snowmelt, when days of fuel wetting were rather uncommon.

As the model of the Finnish forest fire risk index (Heikinheimo et al. 1996) artificially truncates the possible fuel moisture contents within a relatively narrow range of values, the extremes were often attained. Most of the days of fuel moisture equilibrium were days when the fuel moisture content was constant because it was at one or the other extreme and could not wet or dry further because of the arbitrary limits set by the model. The probability of a day of fuel moisture equilibrium was above 85% in April as the fuel was typically under snow and thus saturated with water (assumption of the model). At the end of September the probability for a day of fuel moisture equilibrium also rose steeply, as years when fuel moisture content was at its highest value were more numerous later in the fire season. In June and during the first half of July the probability of a day of fuel moisture equilibrium was slightly elevated compared to August mainly due to frequency of minimal fuel moisture content.

The average amount of decrease of water in the fuel during a day of fuel drying (%) and the amount of increase during the days of fuel wetting (mm) cannot be directly compared because of different units (Fig. 8). The average day-to-day variability in drying was very large early in the fire season as the average is based on values of just a few years as most years the fuel was still covered by snow. After this early period of high variability, the average proportion of water lost on days of fuel drying was relatively stable until the end of July and decreased thereafter. The average increase of fuel moisture content on days of fuel wetting remained constant during the snow-free period.

Two examples of variation in the generated ignition probability during the fire season are shown in Fig. 9. Visual comparison of 37 of such generated fire season sequences of ignition probability with the same number of directly estimated variations in ignition probability did not reveal any visually noticeable differences. In addition, the temporal pattern of averages of those 37 ignition probability generations (not shown) corresponds rather well to the pattern of directly estimated ignition probability variations (Fig. 3).

The comparison of generated and estimated (observed) sequences of ignition probability in Table 2 gives information about the performance of the generation method and reveals temporal autocorrelation in observed sequence, as no

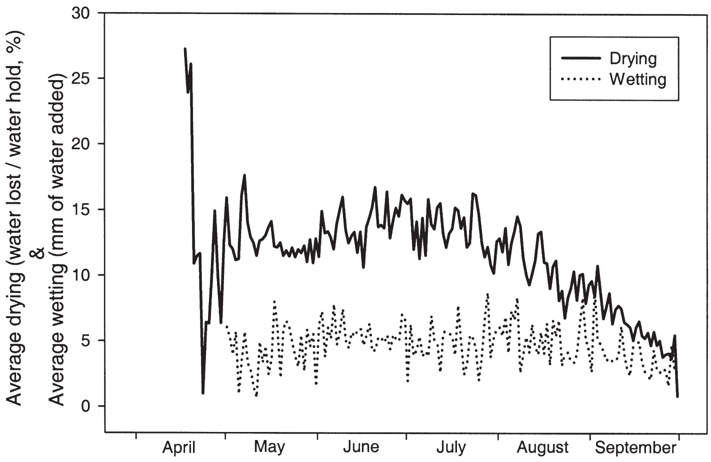

Fig. 8. Average proportion of water lost during a drying day and added to the fuel during a wetting day in Kajaani.

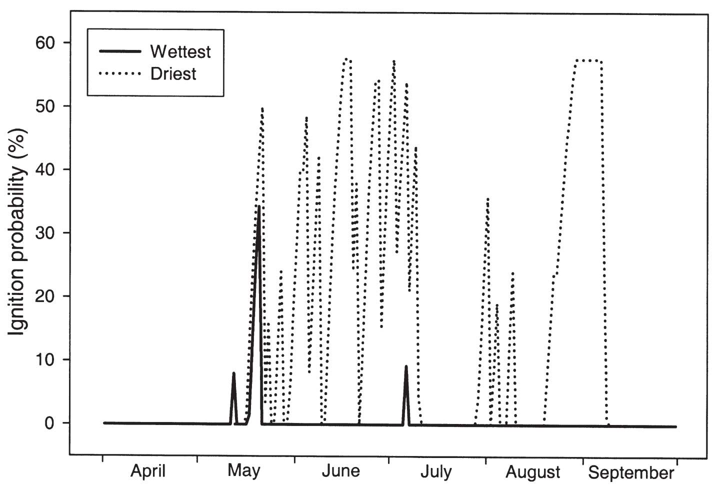

Fig. 9. Ignition probability variation during the wettest and driest fire season of the 37 years generated artificially.

Table 2. Comparison of observed and generated fuel moisture. The observed values are based on the meteorological data of Kajaani from 1961 to 1997. The generated values are for the same location and for 3 sets of 37 years (variation is shown as an interval).

	Observed	Generated
Proportion of days when ignition probability is positive (> 0%)	15.3%	16.2%–18.6%
Annual number of periods when ignition probability is positive (> 0%)	8.8	8.7–9.1
Proportion of days when ignition probability is maximal (= 57.6%)	2.0%	1.3%–1.7%
Annual number of periods when ignition probability is maximal (= 57.6%)	2.2	1.3–1.8
Average annual ignition probability	4.7%	3.0%–3.8%

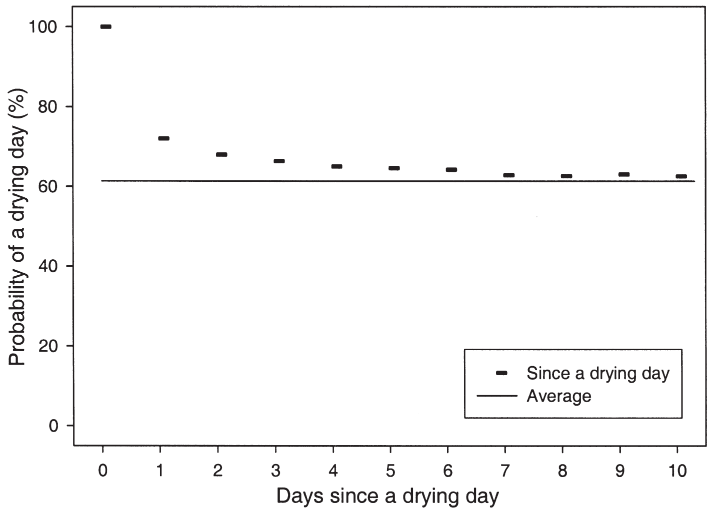

Fig. 10. Autocorrelation of the day types shown as probability of a drying day after a drying day from May to August in Kajaani.

autocorrelation was included in the generation method. Due to the relatively small number of years observed (37) relative to the inter-annual variation, most of the differences are probably not statistically significant. For an unknown reason it seems that in the generated ignition probability data the number of days with a positive probability of ignition is too high. However, this overestimation was not reflected in the annual number of periods with a positive ignition probability. This could indicate some weak negative autocorrelation of days of fuel drying in time in the sequences of observed moisture content. However, when the proportion of days with the highest ignition probability was compared to that of days with positive ignition potential, there was clear evidence of positive temporal autocorrelation of days of fuel drying. This clearly higher number of days with extremely dry fuel moisture in the observed sequence suggests a higher probability of a day of fuel drying once the ignition threshold is reached in the drying process.

The positive temporal autocorrelation in the observed sequences of ignition probability (estimated from meteorological variables) is illustrated in Fig. 10. After a day of fuel drying in May, June, July or August the probability of having another such a day was higher than the average probability of having such a day during these months. This effect decreased steadily with time and hardly existed a week after the day of fuel drying.

4 Discussion

4.1 Ignition Probability

The results of this study showed that there is a threefold difference in the average ignition probability of a forest fire between the south-western and north-eastern parts of Finland (Fig. 6). This difference can be partly explained by the general decrease in summertime potential evaporation and the later snowmelt toward the north-east (Alalammi 1987). The dryness of fuels of the coastal areas is probably mostly due to the scarcity of local convectional precipitation (related to small scale rising air currents) in May and June caused by the low surface temperature of the nearby Baltic Sea. Convection is typically triggered by warm land or water masses that heat the lowest layer of the troposphere (McIlveen 1992). The importance of convectional precipitation for forest fuel moisture variation might be greater than that suggested by its proportion of the total rainfall. Local convectional precipitation typically occurs in synoptic (large scale) conditions favourable for the drying of forest fuels. Convectional rains can thus break otherwise rainless periods that could dry fuels to their ignition threshold and dryer.

Because of the truncation of the model of the Finnish fire risk index both the absolute amount of drying (mm) and the absolute amount of wetting (mm) will be equal and relatively constant over the fire season. This expectation is logical, as after a few days of wetting or drying, the allowed extremes of fuel moisture content in the model are reached, and despite favourable weather the wetting or drying process cannot continue in the model. The drop in the amount of drying (%) late in the season (Fig. 8) is caused by the fact that we used a proportional measuring unit, as the amount of water in the fuel increases towards the end of the season. An equal amount of drying (measured in mm) is proportionally (%) less important late in the season.

The probabilities of days of fuel drying, days of wetting and days of fuel moisture equilibrium (Fig. 7) appear nearly constant in the long term (after snowmelt), because the gradual long-term changes are hidden by large short-term variation. Only when the long-term changes in probabilities and amounts of drying and wetting are shown cumulatively does the temporal variation pattern within the fire season become visible (Fig. 3).

Most of the precipitation in Finland is associated with large low pressures and frontal systems that may influence one location for several days, as a result, the days of fuel wetting are clustered, leaving periods of days of fuel drying in between. This clustering of days of fuel drying and wetting causes positive autocorrelation in time of days of fuel drying as shown in Fig. 10. Interestingly, the occurrence of local convective rains typically over warm and thus dry surfaces could cause negative autocorrelation of the days of fuel drying. However, this study shows that this effect is either non-existent or small.

4.2 Generation of Ignition Probability Values

The method of generating forest fuel moisture content values demonstrated that the observed (estimated from meteorological variables) characteristics of fuel moisture content can be generated relatively simply and realistically. However, if a higher degree of congruity is needed, the most obvious improvement would be the addition of autocorrelation in time in the generation of values on the probability of a day of fuel drying. This could be done, for example, by making the probability of different day categories (fuel drying, wetting or fuel moisture equilibrium) dependent on the day categories of previous days or on current fuel moisture content.

As the amount of drying and wetting on a given day of the fire season is obviously variable, the use of averages of drying and wetting in the generation of fuel moisture content simplifies the reality. However, it is unclear how much this simplification biases the generated fuel moisture content sequences. The amount of drying and wetting could be randomly chosen from the distribution of their amounts in the data estimated from meteorological variables.

Most of the days of fuel moisture equilibrium in the sequences of fuel moisture content estimated by the Finnish forest fire risk model are caused by the estimated moisture content being either at its highest or lowest allowed value. The meteorological conditions would cause further wetting or drying, but the artificial limits built into the model of the Finnish forest fire risk index prevent the estimated fuel moisture content from changing, resulting in a day of fuel moisture equilibrium. The fact that days of fuel moisture equilibrium in this model are possible even when fuel moisture content is not at its extremes can create unnatural unchanging moisture content conditions (=days of fuel moisture equilibrium) and actually causes some artificial autocorrelation in the generated sequences of fuel moisture content values. If there is a need to deal with this issue in a more sophisticated fashion, days of fuel moisture equilibrium could be divided into days when fuel moisture content is at its lower limit, at its upper limit because of snow cover or at its upper limit after the snowmelt.

The need for additional development of the method of generating ignition probability values depends on how simple versus realistic it should be. If the only purpose is to better comprehend the temporal variation of ignition probability, the method presented in this study is sufficient.

Forest fires are included in some ecological spatially explicit models of forest dynamics (e.g. He and Mladenoff 1999, Pennanen and Kuuluvainen 2002). Using generated fire potential records it would be possible to model the ignition and behaviour of forest fires for example on a 24-hour time step based on the generated values of fire potential. The use of such generated records would reveal extreme drought years, which might have important ecological implications. For example, in many areas in Canada the majority of burned area is created by large fires occurring during such drought years (e.g. Johnson 1992). Because these extreme years could easily be missing from relatively short records, the use of historic data of fire potential may not give a full picture of the inter-annual fire potential variation.

If the presented method of generating ignition probability values is used in spatially explicit modelling of forest fires, the unnaturally low number of very dry days in the sequences of fuel moisture content should be corrected. This bias was caused by the absence of temporal autocorrelation in the probability of a day of fuel drying. However, the incorporation of autocorrelation is not necessary in the generation method if a coefficient is added to the function linking the generated fuel moisture values and ignition probability values to match the average ignition probabilities of observed and generated fuel moisture contents.

4.3 Implications Regarding Fire Regimes in Finland

The observed threefold difference in forest fuel ignition probability in north-eastern vs. south-western Finland (Fig. 6) is important for understanding spatial variations in current (of last decades), historic (before industrialisation) and potential natural (not influenced by human activity) fire regimes. However, regarding historic and natural fire regimes even this threefold difference in ignition probability is an underestimation of the susceptibility of fuels for forest fires. This is because boreal forest fires can easily be active for several days (Ryan 2002) and fuel moisture conditions normally change during this time. Assuming an equal fire season length and equal autocorrelation of dry days in time across Finland, dry areas have on average longer dry periods than wetter areas. Because forest fires spread two-dimensionally, doubling the time for spread quadruples the area burned (assuming that natural firebreaks do not block the spread of fire). In Finland, the length of the fire season is correlated with the average ignition probability (Fig. 3 and Fig. 6), but it nevertheless seems that dry periods are longer in the south. Thus, the fuel moisture conditions are more than three times more suitable for forest fires in the south-western compared with the north-eastern part of the country.

In addition to wind and fuel moisture conditions, geographical variations in fuel characteristics and the density, timing and type of lightning activity also influence natural forest fire regimes (Fig. 11). In the study of the distribution of lightning ignitions, Larjavaara et al. (submitted) found a strong south-north gradient in the density of lightning-ignited forest fires, with nearly 20-times more ignition in the south compared with the north of the country. The annual threefold difference in ignition probability demonstrated in this study explains much of the previously partly unexplained large difference in the density of lightning-ignited forest fires between the south and north of Finland (see Larjavaara et al. submitted).

In the case of historic or current fire regimes, the role of anthropogenic ignitions must be taken into account (Fig. 11). Southern Finland has always had a higher population density than the northern parts of the country. Probably a realistic assumption is that the importance of human-caused intentional or unintentional "acts toward ignition" (or fire brands) (Fig. 11, arrow from "Human action" to "Ignitions"; leads to an ignition (or fire arrival) only in suitable fuel type and moisture conditions) correlates positively with the population density. Thus, in addition to lower fuel moisture content, the density of anthropogenic acts toward ignition would indicate that forest fires historically were more significant in southern than in northern Finland. On the other hand, humans also influence forest fires by splitting forested areas into smaller portions on the basis of agricultural and other activities, which can create fuel breaks (Fig. 11, arrow from "Human action" to "Fuel types"). However, because this effect of

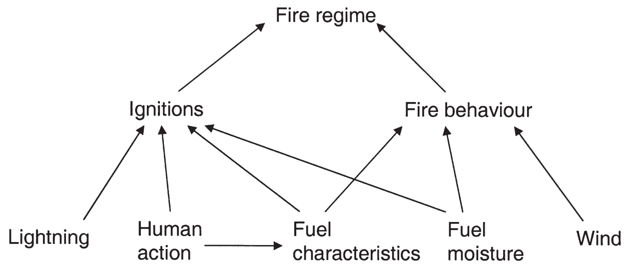

Fig. 11. Simplified representation of determinants of a fire regime. In modern times, human activity also directly influences fire behaviour by suppressing fires.

such human action is probably masked by the general increase in acts toward ignition, human action before modern fire control increased the occurrence of forest fires.

4.4 Conclusions

This study showed that when describing the inter-annual or spatial variation of fire potential a feasible approach is to link fuel moisture with a variable describing fire potential, such as ignition probability, and use this variable for inter-annual or spatial comparisons. On the other hand, describing the variation in fire potential by calculating averages of fuel moisture content may present an unacceptably biased picture of the phenomenon.

The average fire ignition probability is three times higher in south-western than in the north-eastern Finland. The spatial variation in ignition probability broadly overlaps with the gradients in densities of lightning activity and human acts toward ignition. Thus specific influences of these factors on the forest fire regime can be difficult to disentangle. For example, it may be impossible to specify whether the spatial differences of fire frequencies revealed by forest fire history studies are caused by variations in human or lightning activity, or by variations in fuel moisture content. On the other hand, this congruity of the spatial gradients of the determinants of the fire regime (Fig. 11) makes it evident that prior to the introduction of modern fire control measures, forest fires were much more important in southern than in northern Finland.

Acknowledgements

We thank Juho Pennanen, Tuomo Wallenius and two anonymous reviewers for comments and Finnish Fire Prevention Fund for funding.

References

Alalammi, P. (ed.) 1987. Atlas of Finland, Folio 131, Climate. National Board of Survey, Helsinki. 32 p.

Bailey, T.C. & Gatrell, A.C. 1995. Interactive spatial data analysis. Longman. 413 p.

Flannigan, M.D., Bergeron, Y., Engelmark, O. & Wotton, B.M. 1998. Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science 9: 469–476.

Frandsen, W.H. 1991. Smoldering spread rate: a preliminary estimate. 11th Conference on Fire and Forest Meteorology, April 16–19, 1991, Missoula, Montana.

Gromtsev, A. 2002. Natural disturbance dynamics in the boreal forests of European Russia: a review. Silva Fennica 36(1): 41–55.

He, H. & Mladenoff, D. 1999. Spatially explicit and stochastic simulation of forest landscape fire+disturbance and succession. Ecology 80: 81–99.

Heikinheimo, M., Venäläinen, A. & Tourula, T. 1996. A soil moisture index for the assessment of forest fire risk in the boreal zone. COST 77, 711 International symposium on applied agrometeorology and agroclimatology, proceedings, Volos, Greece.

Eur 18328 en, European Commission, Belgium. p. 549–556.
Johnson, E.A. 1992. Fire and vegetation dynamics studies from the North American boreal forest. Cambridge University Press, Cambridge, U.K. 129 p.
— & Miyanishi, K. (eds.). 2001. Forest fires: behavior and ecological effects. Academic Press, San Diego-San Francisco-New York-Boston-London-Sydney-Tokyo. 594 p.
Kourtz, P. & Todd, B. 1991. Predicting the daily occurrence of lightning-caused forest fires. Information report PI-X-112. Forestry Canada.
Kunkel, K.E. 2001. Surface energy budget and fuel moisture. In: Johnson, E.A. & Miyanishi, K. (eds.). Forest fires: behavior and ecological effects. Academic Press, San Diego-San Francisco-New York-Boston-London-Sydney-Tokyo. p. 303–350.
Larjavaara, M., Kuuluvainen, T., Rita, H. & Venäläinen, A. (Submitted). Spatio-temporal distribution of lightning-ignited forest fires in Finland. Forest Ecology and Management.
McIlveen, R. 1992. Fundamentals of weather and climate. Chapman & Hall, London-Glasgow-Weinheim-New York-Tokyo-Melbourne-Madras. 497 p.
Moore, M.M. & Deiter, D.A. 1992. Stand density index as a predictor of forage production in northern Arizona pine forests. Journal of Range Management 45: 267–271.
Nelson, R.M. 2001. Water relations of forest fuels. In: Johnson, E.A. & Miyanishi, K. (eds.). Forest fires: behavior and ecological effects. Academic Press, San Diego-San Francisco-New York-Boston-London-Sydney-Tokyo. p. 79–150.
Niklasson, M. & Granström, A. 2000. Number and sizes of fires: Long-term spatially explicit fire history in Swedish boreal landscape. Ecology 81(6): 1484–1499.
Pennanen, J. & Kuuluvainen, T. 2002. A spatial simulation approach to natural forest landscape dynamics in boreal Fennoscandia. Forest Ecology and Management 164: 157–175.
Pyne, S., Andrews, P.L. & Laven, R.D. 1996. Introduction to wildland fire. John Wiley & Sons, New York-Chichester-Brisbane-Toronto-Singapore. 769 p.
Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA Forest Service. Reasearch Paper INT-115.
Ryan, K.C. 2002. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fennica 36(1): 13–39.
Schimmel, J. & Granström, A. 1991. Skogsbränderna och vegetationen. Skog & Forskning 4: 39–46.
Tammelin, B. 1991. Meteorologista taustatietoa tuulienergiakartoitukselle. Finnish Meteorological Institute, Helsinki. 332 p. (In Finnish).
Tanskanen, H., Venäläinen, A., Puttonen, P. & Granström, A. (Submitted). Impact of stand structure on surface fire ignition potential in Norway spruce and Scots pine forests in southern Finland. Canadian Journal of Forest Research.
Tuomi, T.J. 2002. Lightning observations in Finland, 2002. Geophysical Publications 56. Finnish Meteorological Institute. 47 p.
Van Wagner, C.E. 1987. The development and structure of the Canadian forest fire weather index system. Canadian Forest Service, Forest Tech. Report 35.
Venäläinen, A. & Heikinheimo, M. 2003. The Finnish forest fire index calcualtion system. In: Zschau, J. & Kuppers, A. (eds.). Early warning systems for natural disaster reduction. Springer. p. 645–648.
Total of 26 references