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FIRE INTENSITIES AND SURFACE TEMPERATURES DURING PRESCRIBED BURNING

HARRI VASANDER and TAPIO LINDHOLM

Seloste

TULEN VOIMAKKUUS JA MAANPINNAN LÄMPÖTILA KULOTUKSEN AIKANA

Saapunut toimitukselle 15. 10.1984

Surface temperatures during two prescribed burnings were measured in 1983 in Evo, southern Finland. Surface temperatures in relation to the amount of slash burned, energy released during the fire, and fire intensities were studied. The fire intensity was also measured during a third burn. The Lake Nimetön site was burned in the end of May. Due to the uneven distribution of slash, colonization by *Calamagrostis arundinacea* and the spring moisture, the burning was very uneven. Surface temperatures varied between 410–809°C and the intensity of fire was low (range 0–900 kW/m).

The fire intensity on the other site burned in May was also low (880 kW/m). During the burn conducted in August, the surface temperatures varied between 701–869°C and the intensity of fire was moderate (1170 kW/m). Slash was burned more evenly and more thoroughly. This was caused by the dryness of the site and slash and also due to the fact that grasses and other herbs were not abundant.

INTRODUCTION

In prescribed burning slash, ground vegetation and part of the humus are burned. The aims are 1) to improve the nutrient, temperature and humidity conditions in the soil for the growth and regeneration of trees; 2) to facilitate artificial regeneration of forest; 3) to decrease competition between tree seedlings and the ground vegetation; 4) to decrease the propagation of pathogenic fungi and insects; and 5) to create a natural starting point for the regeneration and development of the whole forest ecosystem (Kulotustoimikunnan mietintö 1980, Ruuhijärvi et al. 1983). In southern boreal forests c. 40 % of organic matter in needles is still left after three years' decomposition (Mikola 1960, Berg & Staaf 1980). Five-six years after logging even the thinnest branches are left in spruce branch litter (Nyyssönen 1956). During burning at least part of the nutrients are released as oxides and carbonates increasing the pH of the soil, which is noticeable even decades after burning (Viro 1969, 1971). A part of the nutrients, especially volatile N-oxides, may disappear with fly ash but this fraction has usually no practical importance (e.g. Knight 1966, Viro 1969).

Due to the many practical difficulties in prescribed burning, it is not very popular in Finnish silviculture nowadays. The area burned was at its greatest between 1955–1965 when 30 000 ha were burned annually. Since then the area burned decreased to some hundred hectares. Because of new attitudes, the ecological advantages of burning and increasing costs of mechanical tillage, the area burnt began to increase slightly at the end of 1970s (Metsätilastollinen vuosikirja 1982). From the 1950s 15–35 ha have been burned annually in the state forest in Evo (H.

Hallila, Hämeenlinna district, pers. comm.).

Fire has usually been considered by biologists and ecologists as a binary event: an area burned or it did not (Alexander 1982). However, some studies of fire characteristics have been made, e.g. the intensity of fire in relation to the amount of slash, its moisture content and climatological conditions (Sparling & Smith 1966, Tunstall et al. 1976, Smith & James 1978, Trabaud 1979, Wright & Bailey 1982, Hobbs & Gimingham 1984).

In this study we determined the fire intensities and temperature conditions of burns conducted in the beginning and middle of the summer. Due to the limited number of burns, we could not, however, formulate any fire temperature model (cf. Hobbs & Gimingham 1984).

Acknowledgements

This study would not have been possible without the generous help of several people and institutes. Lammi Biological Station kindly assisted with material and personnel. The director of Evo forestry training school, Toivo Rauhala helped with fruitfull discussions and allowing students of the school to help in field work. Eero Tuuteri, Heikki Hallila and Matti Borg from the Hämeenlinna district of the National Board of Forestry were always helpfull and constructive in our calls and visits. Pirjo Kaitala from the forest workers' school at Evo gave valuable comments about the burning at Horkkajärvi site. Finally we would like to thank Antti Ahonen and Harri Kortelahti from VTT, Fire Technology Laboratory, for their help and comments with the measurements. Antti Ahonen and the referees made many valuable comments about an earlier draft of the manuscript. This study is a part of the project "Nutrient ecology and structure of plant communities of the Myrtillus type forest after prescribed burning" financed by the Foundation for Research of Natural Resources in Finland. Mike Starr kindly revised our English.

STUDY AREA

The study was made at three sites in Lammi parish in the vicinity of the forestry training school at Evo (61°12′N, 25°07′E). The area lies in southern boreal zone of the coniferous belt (Ahti et al. 1968). The effective temperature sum (>+5°C) at Evo is 1150 d.d. °C (mean for 1931–1960; Kolkki 1966). Compared to Scandinavia the climate is, in general, moderately continental (Tuhkanen 1980). The monthly precipitation in May – September is 44, 53, 69, 83 and 64 mm, respectively (mean of 1931–1960; Helimäki 1967).

The Lake Nimetön site (152–175 m a.s.l.), 6 km NE of the forestry training school, covered an area of 27 ha. The stand had been felled in late autumn 1981 and the burning was planned for summer 1982. The forest type is mostly the Myrtillus type (MT), but there are also less than two hectares of Vaccinium type (VT) and drained spruce mire (e.g. Cajander 1949). The depth of the humus layer varied between 5 and 10 cm (Vuorinen 1984). The forest had been fertilized in 1972 with calcium ammonium nitrate (600 kg/ha).

Due to difficulties with the timber harvesting and weather, the burning had to be postponed to the following year. All the preparations for measuring the temperatures had been done in May 1982 and they were therefore left in their places. Nineteen hectares were burned in 1983.

The Lake Niemisjärvi site (140–143 m a.s.l.) is situated 5 km NW from the forestry training school. An area of 4 ha had been felled in early winter, 1982.

The forest type is MT with some resemblance to VT. The average thickness of the humus layer was c. 10 cm. However, due to the stoniness of the sites, there is always much variation in the thickness of the humus layer.

The third site was situated 3 km NE from the forestry training school near the Lake Horkkajärvi, 150–160 m a.s.l. An area of 6 ha was felled in early winter of 1982. The forest type is MT with drained spruce mire in the middle of the area (Fig. 2). The site was burned at the same day as the Nimetön site, and that is why no temperature measurements could be made there.

The Nimetön and Niemisjärvi burnings were performed by the students of the forestry training school at Evo under the leadership of Hämeenlinna district, National Board of Forestry. The burning of Horkkajärvi site was performed by the students of forest workers' school. The burns of Nimetön and Horkkajärvi were conducted on May 24 (between 15.00–22.00 and 13.00–17.00, respectively) and that of Niemisjärvi on August 10, 1983 (between 18.00–21.30).

MATERIAL AND METHODS

Determination of the slash quantity

The quantity of natural woody fuel was determined using the line intersect fuel sampling method developed by Van Wagner (1965, 1968) and elaborated by Brown (1971) and Brown & Roussopoulos (1974). The method has been described in full detail by McRae et al. (1979). When examining a field trial of the line intersect method Van Wagner (1968) observed a standard error of ±5.2 %.

An equilateral triangle with 30 m sides was first created. Line intersect pins were located at 0, 5, 10, 15, 20, 25 and 30 m intervals along each side. These allow the reconstruction of the triangle following the burn in order to sample postburn fuel loadings and ultimately determine fuel consumption. The slope of each sample line was measured and the number of woody fuel pieces less than 7.0 cm in diameter was counted and recorded by the size class diameteres as illustrated in Fig. 1. In calculating the amount of slash, the number of slash fuel piece intersections by size class diameter for each sample triangle side was added. The average species composition values for the 0 – 0.99 and 1.0 – 6.99 cm diameter categories for sample triangles was determined. The number of pieces by species in each size class from the total was calculated and the number of intersections was multiplied by factors for species, slash age and size class. In the calculation, multiplication values for Canadian species were used for Finnish tree species as follows: *Picea mariana* and *P. glauca* for *P. abies*, *Pinus banksiana* for *P. sylvestris*, *Betula papyrifera* for *B. pendula* and *B. pubescens* and poplar (*Populus tremuloides*, *P. grandidentata*, *P. balsamifera*) for *P. tremula*. In this way the uncorrected slash fuel loadings (kg/m^2) were obtained. The slope correction factor:

$$\sqrt{1 + (\text{percent slope}/100)^2} \qquad (1)$$

was used to form the corrected slash loadings. Usually the slope correction factor was insignificant as the triangles were on rather level ground. There were eight sampling triangles at the Nimetön site, two at the Niemisjärvi site and one at the Horkkajärvi site. The triangles at Niemisjärvi were only 15 m on each side with intersect pins at 2.5 m intervals.

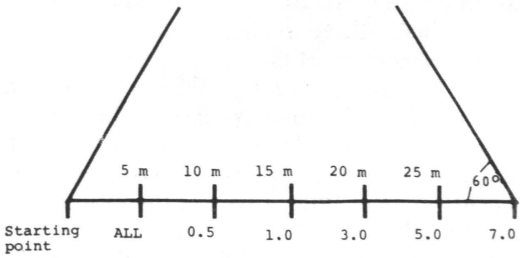

Fig. 1. Plan view of a sample line making up one side of a fuel loading triangle. The amount and composition of slash is measured along each side of the triangle. In the first five meters all intersections with slash are counted, in the next five meters the minimum diameter of slash counted is 0.5 cm and so on untill the end of the sides.

Kuva 1. Hakkuutähdekolmion mittausperiaate. Kuvassa yksi sivu kolmiosta, johon on merkitty mustattavien hakkuutähderankojen minimiläpimittarajat. Hakkuutähteen runsaus ja koostumus mitataan kultakin sivulta aloituspisteestä alkaen. Ensimmäisellä viiden metrin matkalla mitataan kaikkien mittalangan poikki menevien risujen lukumäärä. Seuraavan viiden metrin matkalla laskettavien risujen määrän minimiläpimitta on 0.5 cm. Minimiläpimittarajoja noudattaen edetään kunkin sivun loppuun.

Weather monitoring

Air temperature was recorded continuously during the summer with a Lambrect thermohygrograph located at a height of 2 m and shielded with a standard meteorological screen. The readings were corrected with a mercury thermometer, being checked about twice a week.

Precipitation was recorded with a Russian S 2 pluviograph and the wind velocity and direction with a Lambrect anemometer situated near the meteorological screen. All these measurements were made beside Lake Nimetön.

Measurements of temperature during the burns

At the Nimetön site, experimental plots were used in order to study the relationship between surface temperatures and the amount of slash burned. All the slash present in 6×12 m area was removed and eighteen plots (2×2 m) were marked out. The slash was weighed and placed back on the plots in accurate amounts (0, 1, 2, 4, 6 and 8 kg/m^2 of fresh slash, three replicates of each). The moisture content of the slash was 32 % (measured by taking c. 2 kg of fresh slash in a plastic bag, weighting, drying for 48 h at 60°C and reweighting). When putting the branch slash back onto the plots (trunks were neglected) in May 1982, a part of the needles fell during the procedure. When the site was actually burned (May 1983), all the needles had fallen forming a mat-like layer on the moss and humus.

A thermocouple was inserted in the middle of every plot. The thermocouples were of copper (+) — constantine (−) type T 9B1C4 (Ø 0.5 mm) supplied by Honeywell Ltd. The thermocouple junction was made by tightly twisting the ends of wires and covering the twist with soft solder. The thermocouple junctions were inserted in the moss layer. In two plots thermocouples were also inserted into the humus to different depths. Temperatures were measured every 10 seconds for each thermocouple with portable field data logger dug into the soil and properly insulated about 15 m away from the plots. The measurements were done in cooperation with the Technical Research Centre of Finland (VTT), Fire Technology Laboratory. Maximum temperatures and duration of temperature above 100°C and above 400°C were analysed. The latter is above the ignition point of wood material (346±40°C, Anderson 1970).

Temperatures were also measured on the Niemisjärvi site using the same wires and data logger as on Nimetön site. However, it was not possible to use similar slash plots. The thermocouples were inserted along the sampling lines of the two fuel loading triangles, 15 for both triangles, i.e. five for each side. The wires and the data-logger were protected with silicate wool. The amount of slash around each thermocouple junction was classified using the categories 0 (no slash), 1 (little slash), 2 (moderately slash) and 3 (much slash). The category 2 was the most heterogeneous one. The amount of slash in general was obtained with the fuel loading triangles. Wires insulated with silicate wool were inserted on the soil.

During the burns on the Nimetön and Niemisjärvi sites, an attempt was made to use integrating devices to measure the energy released and absorbed during the fire (Beaufait 1966). One litre metal paint cans were filled with water (1000 ml in Nimetön, 300 ml in Niemisjärvi) prior to fire and the water loss due to evaporation was measured immediately after the fire. Two cans were inserted beside each thermocouple junction on the soil surface. Only the data from the Niemisjärvi site could be used because at Nimetön the cans fell or there was no evaporation at all. In the calculations 620 cal (2595 J) was assumed to transform one gram of 20°C water into vapor.

The procedure of prescribed burning

The planning of prescribed burning is usually made simultaneously with felling. The area is bordered by topography, forest truck roads or water systems. Trees in the borderline are felled towards the centre. A protection zone is left on the border by removing slash. A firebreak is created by wetting heavily and by removing the humus layer (cf. Fig. 2). The size of the area to be burned should be limited to that what can be burnt during half a day. In Evo the size of the burning areas varies from a few hectares to c. 20 ha.

Burning is usually started in the afternoon when the dew has dispelled and the wind force and direction are the most stable. The area is burned against the wind starting with a horse-shoe shaped line. The two ends of the fire line are gradually brought together a little before the border of the area to form a circle. The heat produced draws the fire inwards resulting in an even burning over the entire area.

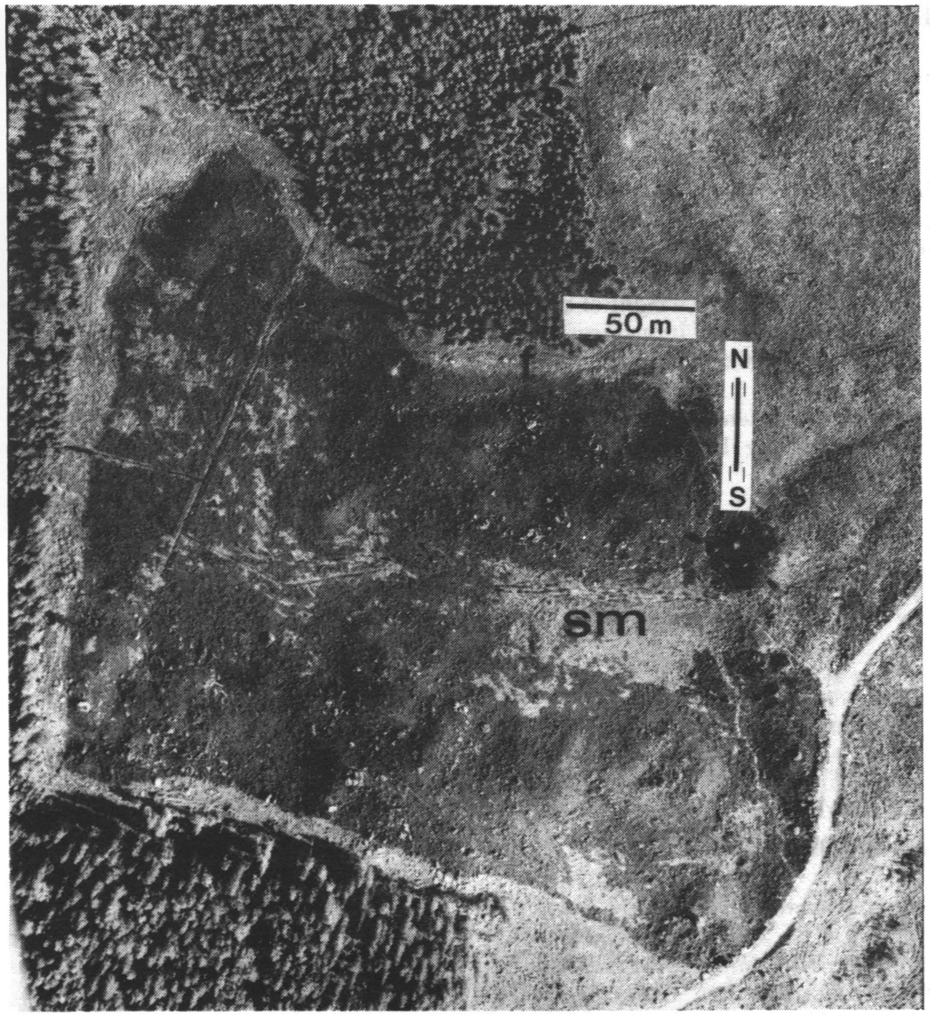

Fig. 2. Horkkajärvi after burning. Notice the protection zone and firebreak (f) between forest and burned area. In the middle there is a depression where the soil is paludified (spruce margin mire, sm) and drained. There the soil was wet and thus the burning was incomplete. Aerial photo from the height of 500 m. Photo: Keijo Kääriäinen.

Kuva 2. Ilmakuva Horkkajärven kulotusalueesta välittömästi kulotuksen jäkeen. Metsän ja kuloalan välillä suojavyöhyke (f). Keskellä kuloalaa ohitettu korpinotkelma, missä palaminen on ollut epätäydellistä (sm). Kuvauskorkeus n. 500 m. Kuva: Keijo Kääriäinen.

Postburn procedures

After the burns the fuel loading triangles were remeasured in order to study the amount of slash burned. At Nimetön the amount of slash unburned excluding needles which had fallen between springs 1982–83, was gathered from the slash plots as the mean of five replicates (20×20 cm) on each plot. The amount unburned was measured in oven-dry weights The dry weight of branches was calculated by the relationships between wood weight and needle weight presented by Hakkila (1971).

The frontal fire intensity of the three burns was calculated using Byram's (1959) equation:

$$I = Hwr \qquad (2)$$

where I is the fire intensity (kW/m), H is the fuel low heat of combustion (kJ/kg, values after Hakkila 1978), w is the weight of fuel consumed per unit area (kg/m^2) and r is the rate of spread (m/s). The rate of spread was either calculated from the difference of the time between the rise of temperature of different thermocouple junctions (their distance was known) or from the field observations (Horkkajärvi site).

The fuel loading triangles at the Nimetön site were situated all over the site, at Niemisjärvi in the middle of the site and at Horkkajärvi near the end point of burning.In surveying the sites after burning the triangles were noted to have been situated in representative places as far as the nature of burnings was concerned. At the Nimetön site the burning of the fuel loading triangles was very uneven, but more even at the Niemisjärvi and Horkkajärvi sites. The fact that some triangles were nearer the starting and end points of the burnings than others had no effect on the results.

RESULTS

Weather conditions for burning

Spring and summer 1983 were warm and rather dry (Fig. 3). According to the observations recorded in Lammi Biological Station, the effective accumulated temperature sum for 1983 was 27 % greater than on average (1460 vs. 1150 d.d. °C). Precipitation in May, June, July, August and September was 61, 45, 53, 36 and 112 mm, respectively. Thus the precipitation for June – August was only 134 mm compared to the average of 200 mm.

Conditions at Nimetön and Horkkajärvi sites

The middle of May was dry. There had been no rainfall during the three days before the burns at Nimetön and Horkkajärvi (24th May). Days before burning were sunny and warm with the maximum temperatures about 20°C (Fig. 3). On the burning day wind was blowing mainly from NW-W with the rate of 4–5 km/h.

On 17th May the moisture content of loose slash on the slash plots was 15 %. Fallen needles had formed a layer on humus preventing it from drying effectively. However, there are no absolute figures for the moisture percentage of humus or slash at the time of burning.

Conditions at Niemisjärvi site

As the summer was dry and warm, the conditions for prescribed burning were very favourable in the beginning of August. The four days before the burning were rainless and the precipitation during the period 1.–5. 8. was only 2.5 mm. Maximum daily temperatures in the beginning of August were 25–30°C (Fig. 3). On the day of burning the moisture content of slash was 9 %, that of ground layer (mostly very dry *Pleurozium schreberi*) 11 % and that of the humus (0–2 cm) 57 %. Because of the dryness the burning could only have gone ahead with calm weather. On 10th August the wind was from NW-N with the steady velocity of 3–4 km/h.

Table 1. The amount of slash (dry weight without needles) on different fuel loading triangles separated into fractions under and over 7 cm in diameter. The percentage of slash burned is also presented.

Taulukko 1. Hakkuutähteiden määrä (neulaseton kuivapaino) mitattuna hakkuutähdekolmioiden avulla. Mitattaessa on erotettu alle ja yli 7 cm läpimitaltaan olevat fraktiot. Myös hakkuutähteiden palamisprosentti on esitetty.

Site and no. of triangle *Kohde ja hakkuutähdekolmion numero*		Slash kg/m^2 *Hakkuutähdettä kg/m^2*		Total *Yhteensä*	Percentage burned *Palamisprosentti*		Total *Yhteensä*
		< 7 cm	≥ 7 cm		< 7 cm	≥ 7 cm	
Nimetön	1	1.34	0.05	1.39	5.9	0	5.7
"	2	1.81	0.16	1.98	29.4	5.2	27.4
"	3	1.72	0.15	1.87	49.8	2.6	45.9
"	4	2.04	0.27	2.31	57.9	3.8	51.4
"	5	1.55	0.51	2.06	11.5	0	8.7
"	6	1.77	0.30	2.07	62.1	23.9	56.6
"	7	1.02	0.22	1.24	40.8	8.6	35.1
"	8	1.77	0.11	1.88	13.1	0	12.3
Niemisjärvi	1	1.63	0.06	1.69	80.6	33.9	78.9
"	2	1.40	0.19	1.69	72.2	30.9	67.3
Horkkajärvi	1	1.32	0.31	1.63	83.7	8.0	69.2

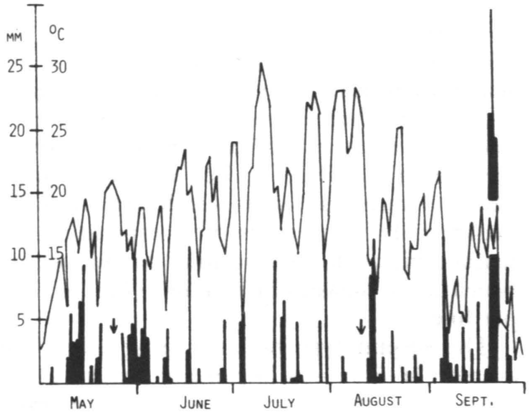

Fig. 3. Climatic conditions at Evo during summer 1983. Columns denote the daily precipitation and the curve denotes the daily maximum temperatures. Arrows denote the days of burning.

Kuva 3. Sääolosuhteet Evolla ja niiden suhde kulotusajankohtiin. Murtoviiva kuvaa päivittäisiä ilman huippulämpötiloja ja mustat pylväät vuorokautisia sateita. Nuolet osoittavat kulotusajankohdat.

The burning of slash

The quantity of slash measured with the fuel loading triangles varied rather little between the sites (Table 1). However, at the Nimetön site the slash was more attached to the soil and there was much more *Calamagrostis arundinacea* growing than at the other sites.

Approximately 70 % of the slash was burned on the evenly burned Niemisjärvi and Horkkajärvi sites. On the Nimetön site only 30 % (S.D. 20 %, n = 8) of the slash was burned. The burning there was the most even and thorough on the eastward steep slope (27°, triangle 6, Table 1). The unevenness of the burn was caused more by the distribution of slash and grasses than the situation of the triangles on the border or in the middle of the area. Triangles 1–3, 5 and 8 as also 6 and 7 were situated rather close to each other but their burning efficiency differed (Table 1).

The experiment with slash plots on Nimetön site partly failed as only half of the plots burned. The amount of slash burned was negatively correlated (r = –0.71, n = 8) to the maximum temperature recorded during the fire. This was caused by one plot were the needles has fallen. The more slash had been put on the plot the more there were needles which had been only charred during burning. If the one plot was excluded from the analysis, then there was no relationship (r = 0.03, n = 7). The amount of slash burned varied rather little (0.58 – 1.30 kg/m^2) compared to the maximum temperatures (97 – 740°C).

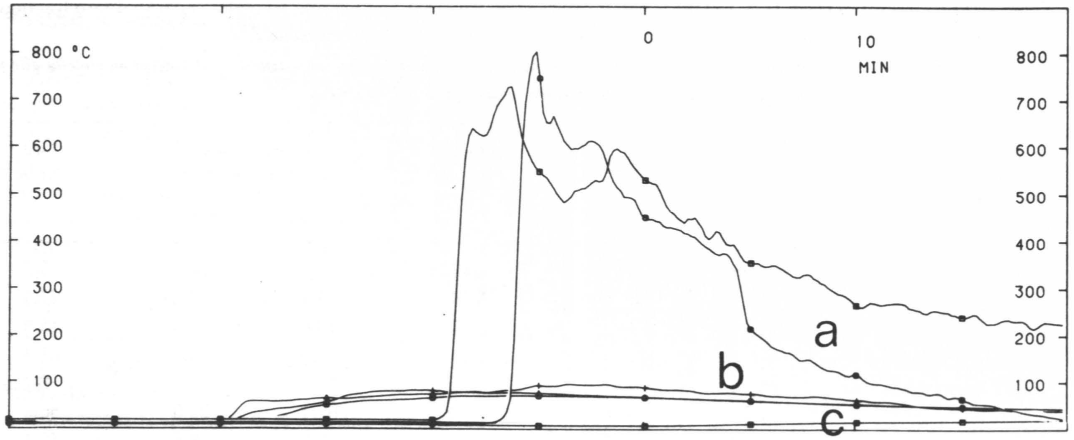

Fig. 4. Temperature curves for the Nimetön burn. Curve a from area of moderate slash. Curve b measured inside of needle mat. Curve c measured in the upper humus layer (1–2 cm).

Kuva 4. Lämpätilakäyriä Nimettömänmaan kulotuksesta. Korkeat lämpötilat (a) mitattu alueelta, jossa keskinkertaisesti hakkuutähdettä. Käyrä b kuvaa lämpötiloja neulasmaton sisällä ja c humuksen yläosassa (1–2 cm).

Surface temperatures during burning

Nimetön site

The burn was not effective at the Nimetön site. On those slash plots where the needles formed an insulating layer on the soil surface, temperatures on the surface did not reach 100°C (Fig. 4, case b). On those plots where the quantity of slash was moderate (4–6 kg/m^2 of fresh slash with needles, which corresponds to 1.7 – 2.5 kg/m^2 dry slash without needles), the maximum temperatures varied between 410–809°C. Two such examples are presented in Figure 4, cases a. The duration of temperature above 100°C was 14.9 ± 8.5 min. (n = 10, range 0–30 min.) and that of above 400°C was 4.0± 3.9 min. (n = 10, range 0–12 min.). In the humus layer (1–2 cm from the surface) temperature increased only 15°C (Fig. 4, case c).

Niemisjärvi site

The mean maximum surface temperature reached was 779°C (S.D. 49°C, n = 30, range 701 – 869°C). The mean duration of temperature above 100°C was 20.7 ± 9.2 min. (range 11–45 min.) and above 400°C, 11.6 ± 4.2 min. (range 6–22 min.).

Three different types of burning could be identified. The first type (Fig. 5a) occurred where there was a moderate amount of slash around the thermocouple junctions (cases 2 and 1, cf. methods). Maximum temperatures were high (> 800°C), but lasted for only about 8 minutes, after which they rapidly declined. In some cases the temperature remained higher for a long time due to a stone beneath the measurement point (Fig. 5a, upper line).

The second type of burn arose when the amount of slash was low or not present at all around the thermocouple junction (cases 0 and 1) and the ground layer and the upper layer of humus had effectively dried out. Maximum temperatures were c. 780°C (Fig. 5c), but the burning was relatively even. After that the ground layer and the upper humus layer had burnt, the temperatures rapidly declined. If the thermocouple junction was near a stump, the cooling was slower (Fig. 5c, upper line).

The third type of burning occurred when the amount of slash was great (Fig. 5b). Maximum temperatures were rather similar to those previously described but remained high for a long time. Temperatures did not return to their original level until c. 35 minutes later. The burning was not, however, as even as in the previous type of burning.

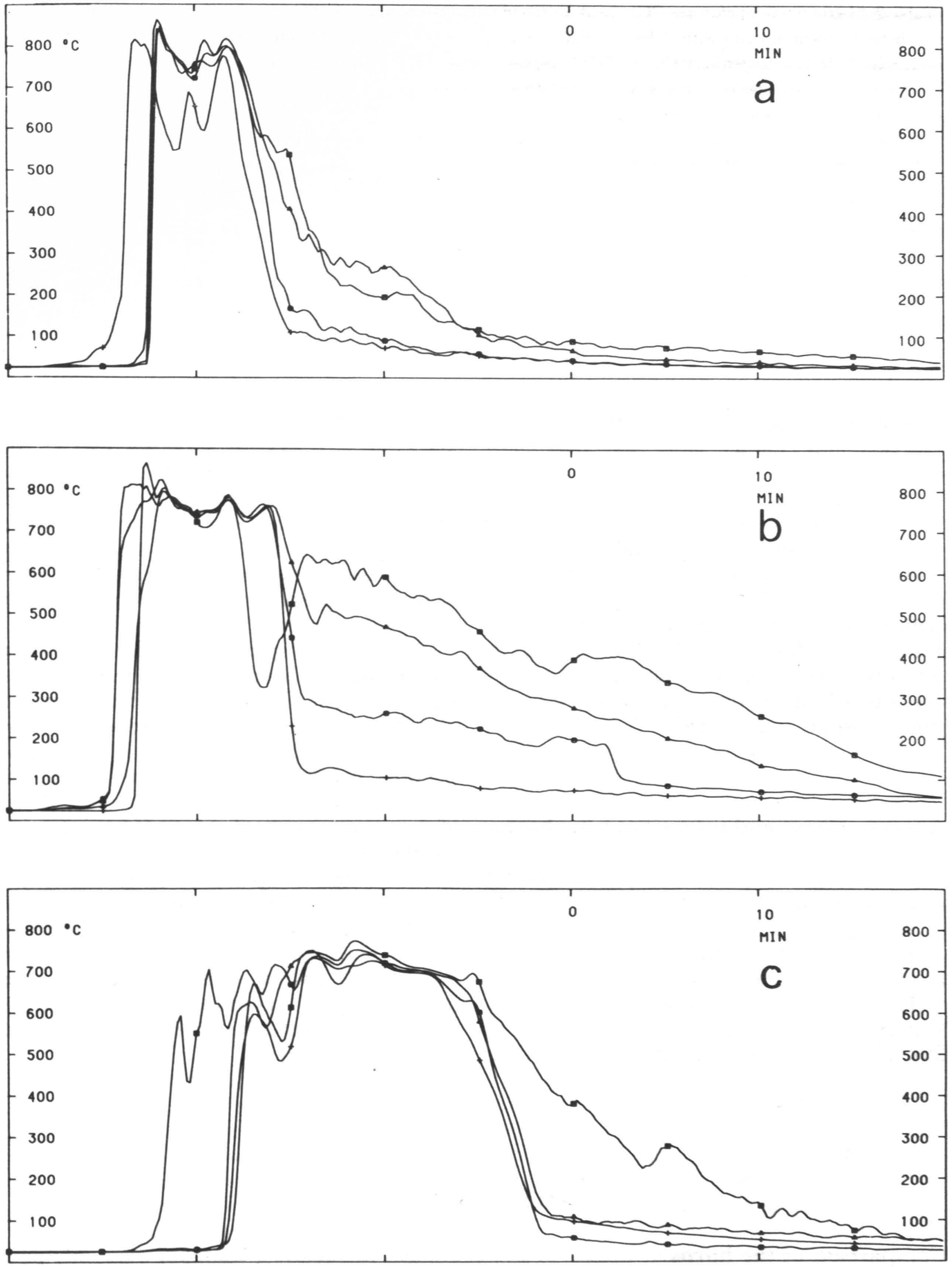

Fig. 5. Temperature curves for the Niemisjärvi burn. a. cases with a small amount of slash, b. cases with a lot of slash, c. cases with no slash (only ground layer and upper humus burned).

Kuva 5. Lämpötilakäyriä Niemisjärvenmaan kulotuksesta. a. hakkuutähdettä niukalti, b. hakkuutähdettä runsaasti, c. hakkuutähdettä ei ollenkaan (pohjakerros ja humuksen pintakerros palaneet).

Table 2. Maximum temperatures (°C), the duration of temperature above 400°C (min.) and the correlation coefficient between them in cases with different relative amounts of slash during the burning at the Niemisjärvi site.

Taulukko 2. Maksimilämpötilat (°C), yli 400°C lämpötilan kesto (min.) ja näiden välisen korrelaatiokertoimen arvo erilaisilla suhteellisilla hakkuutähteen määrillä Niemisjärvenmaan kulotuksen aikana.

Case number *Hakkuutähteen määrä*	Mean max. temperature and its range *Maksimilämpötilan keskiarvo vaihteluväleineen*	Duration of the temperature above 400°C and its range *Yli 400°C lämpötilan kesto vaihteluväleineen*	Correlation coefficient *Korrelaatiokertoimen arvo*
0	741 (689–769)	8.2 (7.0–8.5)	−0.228
1	767 (706–866)	11.7 (7.0–14.9)	−0.927***
2	790 (712–869)	13.0 (7.7–21.0)	−0.443
3	810 (775–843)	14.0 (6.5–22.0)	−0.106

The more slash around the thermocouple junction, the higher were the maximum temperatures and the longer the temperatures remained above 400°C (Fig. 6, Table 2). The duration of temperatures were above 400°C was greater in cases 2 and 3 (moderate and much slash) than in the cases 0 and 1 (no or little slash). The correlation coefficients between maximum temperatures and the duration of hot fire (above 400°C) were higher when the amount of slash was little or moderate (cases 1 and 2) than when it was none or great (cases 0 and 3) (Table 2, Fig. 6).

Energy release and intensity of the burns

The energy absorbed by the integrating cans during the burn at Niemisjärvi was 162 ± 122 kJ (range 17–394 kJ, n = 26). The relationships between the energy and temperature data were rather weak.

The highest correlation was achieved with maximum temperature (r = 0.543***, n = 26). There was no significant correlation with the time the temperature remained above 100°C (r = 0.295) or with the area of the time-temperature curve (r = 0.132). The direct relationship between the maximum temperature measured by the thermocouple and the energy absorbed by the measuring cans is due to the fact that the exchange of radiation is proportional to the fourth power of the temperature.

As the rate of spread of the fire was rather low during all burnings, the fire intensities were not high (Table 3). The value for the Nimetön site has been calculated as the mean of the burned slash plots only. If the corresponding fire intensity value was calculated from all slash plots, it would have been 50 % of the value given in Table 2. If fire intensity for the Nimetön site was calculated by the fuel loading triangles excluding triangle 6 situated on the slope, the mean value of 107 ± 81 kW/m (range 12–228 kW/m) was obtained. The fire intensity of triangle 6 was the highest, 893 kW/m. This is about the same intensity as at the Horkkajärvi site and about three fourths of the fire intensity measured at the Niemisjärvi site.

DISCUSSION

Comparison of the burns

The burns at Nimetön and Niemisjärvi differed in many respects. At Nimetön half of the slash plots remained unburned and three of eight fuel loading triangles were only partially burnt (fire intensities 12–44 kW/m, percentage of slash burned 6–12 %). Burning at Niemisjärvi, on the other hand, was rather even. Differences in burning could be directly

Table 3. The fire intensity of the three burns. The intensity of the Nimetön burn relates only to those slash plots which were burned.

Taulukko 3. Tulen voimakkuus kolmessa kulotuksessa. Nimettömänmaalla voimakkuus mitattiin palaneista hakkuutähderuuduista, mikä yliarvioi koko alan tilannetta (kts. teksti).

Site *Kohde*	Date *Aika*	H (kJ/kg)	W (kg/m^2)	r (m/s)	I (kW/m)
Nimetön	1983–05–24	19100	1.20	0.008	183
Niemisjärvi	1983–08–10	19500	1.20	0.05	1170
Horkkajärvi	1983–05–24	19400	1.13	0.04	877

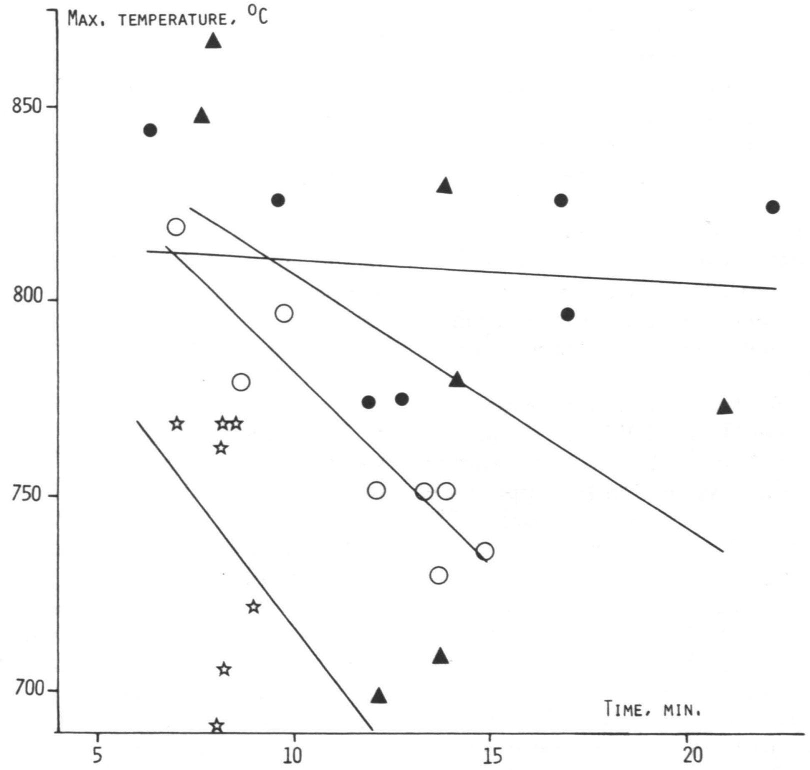

Fig. 6. The relationship between maximum temperature of burn and the duration of the most intense phase of the fire (above 400 °C) with different amounts of slash. Line A with stars denotes the situation without slash, y = 846.2–12.9x. Line B with open dots denotes the situation with a small amount of slash, y = 878.0–9.5x. Line C with black triangles denotes the situation with moderate slash, y = 872.5–6.5x. Line D with black dots denotes the situation with a lot of slash, y = 817.0 – 0.5x.

Kuva 6. Hakkuutähteen määrän vaikutus maksimilämpötiloihin ja palamisen (yli 400 °C) kestoon. Suora A (tähdet) kuvaa tilannetta ilman hakkuutähdettä, y = 846.2 — 12.9x. Suora B (avoimet ympyrät) kuvaa tilannetta vähällä hakkuutähdemäärällä, y = 878.0 - 9.5x. Suora C (mustat kolmiot) kuvaa tilannetta, jolloin on kohtalaisesti hakkuutähdettä, y = 872.5 - 6.5x. Suora D (mustat ympyrät) kuvaa tilannetta, jolloin hakkuutähdettä on runsaasti, y = 817.0 - 0.5x.

related to the amount of slash (Figs. 5, 6, Table 2). Maximum temperatures were determined by the amount of slash, vegetation and the nearness of flames to the recording thermocouples. Hobbs and Gimingham (1984) similarly found the maximum temperatures in heathland fires to be related to the stand age of *Calluna* and to the amount of distribution of fuel.

The slash and humus layer were drier at Niemisjärvi than at Nimetön. The burn at the Nimetön site had been postponed one year, which was too much for good burning to take place. The amount of slash was moderate but it was unevenly distributed and part of it was still rather moist as it was on logging roads and attached to the soil. The Nimetön site was more fertile than the Niemisjärvi site, and it had also been fertilized. Colonization by *Calamagrostis arundinacea* had therefore been vigorous at the Nimetön site while at the Niemisjärvi site the amount of grasses and other herbs was very small. The burning at the Nimetön site had to be done in the spring before the site would become too "green".

A damp humus layer is an excellent thermal insulator acting as a cold barrier where moisture is condensed. A "sweating zone" is formed below the fire zone which effectively prevents the fire from penetrating deeper into the humus layer (Uggla 1957). In the present study temperatures in humus were studied only at the Nimetön site. In the upper layer (1–2 cm) the temperature rose only 15°C indicating that the damp needle layer and humus had formed a sweating zone. At the Horkkajärvi site the fallen needles had only partly been burned and the underlying humus not at all. At the Niemisjärvi site needles and humus on the tops of stones had been burnt, but only a thin layer of humus or none at all had been burnt where it overlie mineral soil. The amount of humus burnt at any of the sites was not measurable with the aid of depth of burn measurements (T-pins) used during the burnings (cf. McRae et al. 1979).

As the temperature increase in the humus was only small, buried seeds and belowground tissues remained undamaged. Vegetation succession thus tends to be rapid after fire in boreal forests (e.g. Kujala 1926, Uggla 1949, Viro 1969). This was observed at the Nimetön site where the above-ground parts of *Calamagrostis arundinacea* tussocks that had been burned totally on the burned slash plots had regenerated by midsummer.

Temperatures during the burns

Due to the limited number of burns and the selected weather conditions, we could not formulate any equations between the fire regime and environmental conditions. At the Niemisjärvi site the maximum temperatures and durations of the fire were noted to be related to the amount of slash. The moisture content of humus and slash (Nimetön site) as well as the amount of "green" plant material (Nimetön site) were also noted to effect the burning and intensity of fire. However, their effect could not be formally described in the form of equations or fire temperature models (cf. Hobbs & Gimingham 1984).

Fuel biomass, wind velocity and fuel moisture have been noted to be the most relevant factors in explaining the fire regimes and temperatures of different burnings. The increase in fuel biomass increases maximum temperatures while the increased moisture lowers them (e.g. Tunstall et al. 1976, Trabaud 1979, Wright & Bailey 1982, Hobbs & Gimingham 1984). The effect of wind speed is more complicated. It has been noted to increase (e.g. Whittaker 1961, Daubenmire 1968, Tunstall et al. 1976, Wright & Bailey 1982) or decrease (e.g. Sparling & Smith 1966, Smith & James 1978, Hobbs & Gimingham 1984) the maximum temperatures. At Niemisjärvi the maximum temperatures were noted to increase slightly when the fire front advanced rapidly (cf. Fig. 5), and at Nimetön the burning was most effective on the steep westwards slope where the fire front advanced rapidly.

The surface temperatures recorded here were fairly high. Uggla (1957) measured 540°C in a Swedish spruce forest, i.e. a similar value as measured at Nimetön. The maximum temperatures at the Niemisjärvi site varied between 690–870°C, which is higher than temperatures measured in Canadian woodlands (e.g. Smith & Sparling 1966, Smith & James 1978) or on British heathlands (e.g. Whittaker 1961, Kayll 1966). As the amount of burning fuel was not very great and not concentrated, temperatures remained on a lower level compared to situations where large amounts of woody fuel or piles have been burned. In those situations temperatures often exceed 1000°C (e.g. Nelson & Sims 1934, Isaac & Hopkins 1937, Countryman 1964).

The duration of fire was longer than in the studies mentioned above. On burning grasslands, for example, temperatures above 200°C have been noted to last less than one minute (e.g. Pitot & Mason 1951, Tunstall et al. 1976). In boreal slash burnings, on the other hand, Uggla (1957: figs. 6–9) measured the duration of temperatures above 100°C upto 60 minutes in one burn. Thus the duration of elevated temperatures is longer in controlled northern coniferous slash burnings than wild fires in grass ecosystems where dry fuel is burned quickly, or in boreal forest ecosystems where moist living plant material is burned.

Related to the controlled burning practice and the resulting slow rate of spread as also to the limited amount of slash, fire intensities were low. According to Van Wagner's (1983) five scale classification, the burn at Nimetön could be classified as class two – surface backfires (burning against the wind, 100–800 kW/m), or even that of class one – smouldering fire (< 10 kW/m). The burning at Niemisjärvi and Horkkajärvi sites could be classified as that of class three, surface headfires (200–15000 kW/m). Uncontrolled forest fires intensities seldom exceed 50 000 kW/m and most of the crown fires fall within the range of 10 000–30 000 kW/m (Alexander 1982). Hobbs and Gimingham (1984) obtained intensity values of the same magnitude from burning building and mature *Calluna* stands as we measured in the present study. Intensities less than 1 700 kW/m are considered to be possible to control with mechanical equipment (Chandler et al. 1983).

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Total of 44 references

SELOSTE

TULEN VOIMAKKUUS JA MAANPINNAN LÄMPÖTILA KULOTUKSEN AIKANA

Kulotuksen aikaista maanpinnan lämpötilan nousua, hakkuutähteiden palamista, tulen energiasisältöä ja sen voimakkuutta tutkittiin kahdessa kulotuksessa Evolla kesällä 1983. Lisäksi selvitettiin palon voimakkuus kolmannen kulotuksen aikana. Hakkuutähteiden määrä selvitettiin hakkuutähdekolmioiden avulla "linjalaskentana". Yhdellä alueista kasattiin hakkuutähteitä erisuuruiset määrät tarkoituksena selvittää palavan aineksen määrän ja lämpötilan välistä suhdetta.

Nimettömänmaalla lämpötila nousi niillä hakkuutähderuuduilla, jotka ylipäänsä paloivat, 410–809°C. Pudonneet neulaset muodostivat joillekin ruuduille eristävän kerroksen, jonka alapuolella lämpötila ei noussut 100°C:een. Tämä aiheutti palavan aineksen määrän (neulasettomat oksat) ja palon aikaisen maksimilämpötilan välisen negatiivisen riippuvuuden tässä koejärjestelyssä. Nimettömänmaan kulotus tapahtui monista syistä johtuen vuotta liian myöhään. Alue on luontaisesti rehevähkö, ja se oli lisäksi voimakkaasti lannoitettu 10 vuotta ennen päätehakkuuta. Metsäkastikan suuren määrän takia alue oli jo muuttunut "vihreäksi". Hajallaan ja osittain ajourilla olevat hakkuutähteet olivat alkaneet maatua ja neulaset olivat pudottuaan muodostaneet kosteuden haihtumista ehkäisevän kerroksen kuntan pinnalle. Palo jäi täten hyvin laikuttaiseksi. Hakkuutähdekolmioista mitaten vaihteli palon voimakkuus 12–893 kW/m ollen suurin jyrkällä länsirinteellä. Horkkajärvenmaan kulotus oli voimakkuudeltaan samaa luokkaa kuin Nimettömänmaalla hyvin palaneissa kohdissa (877 kW/m). Alue ei ollut heinittynyt, mutta kuntan kosteudesta johtuen maassa olevat neulasetkaan eivät palaneet. Kostea kuntta ja sen päällä olevat neulaset muodostivat "hikoamiskerroksen", jonka alle tuli ei päässyt pureutumaan.

Kolmas kulotus suoritettiin elokuussa 1983 Niemisjärvenmaalla. Lämpimän ja vähäsateisen kesän ansiosta alue oli kuivunut tehokkaasti ja paloi tasaisesti. Hakkuutähteiden määrä oli melko suuri, ne olivat alueella tasaisesti jakautuneina eikä alue ollut heinittynyt. Maksimilämpötilat maan pinnalla vaihtelivat 701–869°C ($\bar{x}$ = 779± 49°C, n = 30). Yli 100°C:n lämpätilan kesto oli 20.7 ± 9.2 min. ja yli 400°C:n 11.6 ± 4.2 min. Lämpötilakäyrät erosivat muodoltaan sen mukaan, mistä mittaus suoritettiin (Kuva 5).

Jos hakkuutähteitä oli melko vähän, nousi lämpötila korkeaksi, mutta tulirintama ohitti paikan suhteellisen nopeasti (Kuva 5 a). Missä hakkuutähteitä oli paljon, nousi lämpötila korkeaksi ja tulen kesto oli selvästi pidempi kuin em. tapauksessa (Kuva 5 b). Siellä missä hakkuutähteitä ei ollut mittauskohdan lähellä ollenkaan, jäivät maksimilämpötilat jonkin verran eo. tilanteita matalammiksi, mutta tulirintaman kesto oli yllättävän pitkä (Kuva 5 c). Ilmeisesti pohjakerroskasvillisuus ja humuksen pintakerros oli näissä kohdin niin kuivaa, että kuntan ohut pintakerroskin paloi. Siellä missä hakkuutähteitä oli jonkin verran, paloi myös mahdollinen pintakerros nopeammin kuin hakkuutähteettömissä kohdissa. Asiaa on tarkasteltu myös kuvassa 6. Mittauskohtien ympärillä olevan hakkuutähteen määrän mukaan tilanteet jaettiin neljään luokkaan: 0 (ei hakkuutähdettä), 1 (vähän hakkuutähdettä), 2 (keskinkertaisesti hakkuutähdettä) ja 3 (paljon hakkuutähdettä). Tilanne 0 vastaa pelkkää pohjakerroksen biomassan määrää (n. 0.05 kg/m^2) ja tilanne 2 keskimääräistä alueen hakkuutähteiden määrää (1.6 kg/m^2). Mitä enemmän oli hakkuutähdettä sitä korkeammaksi nousi lämpötila kuntan pinnassa. Palon keston suhteen suunta ei ollut yhtä selvä. Mitä enemmän oli hakkuutähdettä sitä kauemmin lämpötila keskimäärin pysyi korkeana (Taul. 2).

Maanpinnasta mittaamamme lämpötilat olivat korkeita verrattuna ruohosto- ja pensaikkopaloihin, jossa tuli etenee nopeanan rintamana. Myös palon kesto oli pidempi kuin em. paloissa. Koska tulirintaman etenemisnopeus oli alhainen ja palaneen aineksen määrä melko pieni, jäivät voimakkuudet melko pieniksi. Van Wagnerin (1983) viisiluokituksen mukaan jäivät kaikki palot kolmeen alimpaan luokkaan (0–15000 kW/m). Koska humus ei palanut juuri lainkaan, kulotus ei vaikuttanut kasvien maanalaisiin osiin eikä maassa oleviin siemeniin. Nimettömänmaalla olivat jo keskikesään mennessä useat kastikkatuppaat vironneet paikoille, jotka olivat kulotuksessa palaneet mustiksi.