Soil temperatures under a catchment scale experimental fire

MSc Thesis

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Abstract

"Soil heating in a catchment scale experimental fire"

Within the Desire project a Portuguese catchment area of 10 hectares was burned by experimental fire, to see the impact of fire on soil temperature. Soil temperature beneath the fire was measured at 57 sites with thermocouples at soil surface, 1cm and 3cm depth. This study is among the first to study soil temperatures during a catchment scale fire.

The fire was started with low intensity, but half way the fire fronts were combined into a climax fire with high intensity.

Maximum soil temperature and derived variables: delay before maximum temperature, heating velocity, heat index above 30°C, if temperature exceeded threshold values and delay before heating propagation were interpolated and mapped over the whole catchment. By means of regression analysis relations between soil temperatures and factors determined before the fire were sought.

Average soil temperatures were low: 104°C at soil surface, 27°C at 1cm and 13°C at 3cm depth, while average flame temperature was 735°C. High intensity fire did not increase soil temperatures more than low intensity fire. At soil surface temperature was affected by the fire, but at 1cm depth it was no higher than as can be expected on a hot day, and at 3cm depth fire effects on soil heating were even smaller.

Although the air was very dry, vegetation at the north facing slope was still wet and was burned to lesser extent than vegetation at the south facing slope. Vegetation and litter on the north facing slope were therefore not completely consumed by the fire, and restricted soil heating.

Soil temperatures had some weak correlations with soil properties, vegetation characteristics and topographical factors. Soil moisture content, vegetation height, vegetation cover, rock cover inclination of slope, aspect of slope and organic matter content were significant regressors in maximum temperature.

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1. Introduction

1.1. Background

1.1.1. Fires

Wildfires can pose a threat to humans, while fires are an important step in succession and rejuvenation of the vegetation (Bradstock and Auld, 1995). Fires also increase erosion rates by deteriorating vegetation cover (Martin and Moody, 2001) and by lowering the cohesive forces in the soil, but only when the soil is heated to sufficiently high temperatures (Shakesby and Doerr, 2006). To prevent growing risks for wildfires, prescribed burning is used as a measure to reduce the fuel load (Fernandez *et al.*, 2008). Risks for dangerous and destructive crown fires are lowered by taking dead biomass and understory away.

1.1.2. Soil heating

This study focuses on soil heating by an experimental fire in Portugal. A limited number of authors reported soil temperatures, measured at certain depth during a fire. (Penman and Towerton, 2008) reported a mean temperature of 40°C at 2cm depth and a mean of just 25°C at 5cm depth under prescribed fire. Giovannini reported about two experimental fires; ´light fire´ resulted in 180℃ at the surface, 50℃ at 2.5cm and no significant rise at 5cm, while in ´severe fire´ the surface reached 475℃ , at 2.5cm 90℃ was reached and at 5cm 40℃ (Giovannini, 1994). Soil temperatures at several depths were measured under eucalypt woodland on fire, maxima of 252°C and 152°C were reported at 1 and 2cm depth respectively (Howell *et al.*, 2006).

Soil temperatures vary in time and across the soil profile. When soil is burned temperatures rise and a steep gradient is set in depth. This means a high temperature at the surface will cause a relatively small elevation of the temperature in underlying soil. Due to the gradient in soil temperature, the effect of fire on the soil is more pronounced in the upper soil layer (DeBano, 2000). High temperatures alter properties of the soil which determine its structure. Changes in soil properties can increase the vulnerability of the soil for erosion (DeBano, 2000; Keizer *et al.*, 2005). Consequences of burning depend on fire severity, which integrates soil temperatures and duration of the burn; in belowground systems this duration is the most important factor (Neary *et al.*, 1999; Doerr *et al.*, 2004). The majority of seeds buried in the soil can be found in the upper 5 cm; therefore most studies focus on this upper layer (Penman and Towerton, 2008).

To the authors' knowledge, this study is one of the first to record soil temperatures at different depths, during a fire, at the scale of an entire catchment. Because we measure soil temperatures at three depths in high temporal resolution we can characterize the penetration of heat into the soil profile. In the study area we have several transects to cover all catena positions on the slopes, at different altitudes. With this network of measurement points we capture the spatial variation of soil temperatures throughout the catchment.

1.2. Problem description

Extended research has been done on the effects of fires in terms of soil properties (Boyer and Miller, 1994; Giovannini, 1994; Giovannini and Lucchesi, 1997; Kennard and Gholz, 2001; Certini, 2005; Hubbert *et al.*, 2006). Fire effects in the soil, such as changes in chemical and physical soil properties and in mortality of plant roots and soil dwelling fauna, depend on the temperature level and on how long temperature thresholds are exceeded (Neary *et al.*, 1999). Fire severity is a qualitative measurement which can be defined as the effects of fire on resources that control ecosystem sustainability (Hartford and Frandsen, 1992). Fire intensity is part of fire severity and refers to the rate at which a fire is producing thermal energy (DeBano et al., 1998 cited in (Neary *et al.*, 1999)). Therefore fire intensity is indicated by soil heating velocity, while severity considers two parameters: temperature level and the duration of high temperature levels. Duration of elevated temperatures depends on fire intensity (mainly determined by fuel characteristics), soil properties and duration of the fire. It was suggested that damage to belowground ecosystems is mostly determined by duration of the fire (Neary *et al.*, 1999). Soil temperature levels form thresholds for biological and chemical processes, and for changes in physical soil properties. Root mortality for example starts at 48°C and seeds get killed in the 70-90°C range (Neary *et al.*, 1999). On the other hand seeds can be triggered to sprout by elevated temperatures. Some seedbeds need temperatures up to 80°C in order to break dormancy (Bradstock and Auld, 1995). Temperatures exceeding 40°C proved to be lethal for all groups of microarthropods (Malmstrom, 2008) and many studies considered 60°C to be the lethal threshold for plants (Schimmel and Granstrom, 1996; Busse *et al.*, 2005; Malmstrom, 2008). Soil hydrophobicity, or water repellency, was found all over the world (DeBano, 2000; Doerr *et al.*, 2005; Keizer *et al.*, 2005), and changes when the soil is heated above temperature thresholds (Debano *et al.*, 1976; Debano, 1981) (Simkovic *et al.*, 2008). To be able to calculate heating velocity and the time for which temperature exceeded threshold values, temperature changes need to be monitored over time. In this study thermocouples were used to capture changes in soil temperature over time.

Soil heating can affect biological, chemical and physical soil properties (Neary *et al.*, 1999; Wikars and Schimmel, 2001; Doerr *et al.*, 2005). But how much is the soil heated? What is the variability in soil heating at the catchment scale? How deep penetrates the heat into the soil? And what is the role of soil properties in soil heating? By answering these questions the present study will help to gain insight in soil temperatures and their explaining factors. For land managers who use fire as a tool, more knowledge on the factors that influence soil temperature will help to predict the ecological impact of fires.

1.3. Research objective and research questions

The research objective of this study is:

Visualize and explain the extent and the patterns of soil heating during a catchment-scale experimental fire

To reach this objective the following questions will be answered:

- How much heating is found at the soil surface?
    - What spatial patterns are found in surface heating at the catchment scale?
- To what extent does soil heating penetrate into the soil?
    - What spatial patterns are found in soil heating at 1cm depth at the catchment scale?
    - What spatial patterns are found in soil heating at 3cm depth at the catchment scale?
- Which factors determine soil heating?
    - What is the effect of fuel load variability?
        - Vegetation height
        - Vegetation cover
        - Soil depth
    - What is the effect of topographical differences?
        - Altitude
        - Slope aspect
        - Slope inclination
    - What is the effect of different soil properties?
        - Soil moisture content
        - Soil organic matter content
        - Bulk density
        - Stoniness
        - Rock cover

An overview of soil properties that might influence soil heating by fire is presented in Appendix 2.

This research is carried out within the framework of the PhD research of Ir. Cathelijne Stoof (WUR), 'Fire effects on soil water movement' which is part of the Desire project (FP6-2005-global-4).

2. Materials and methods

2.1. Study area

The experimental fire was conducted in Valtorto (40°06'21 North and 8°07'05 West), a catchment of approximately 10 hectares, in the municipality of Gois (Coimbra, Portugal). Annual precipitation in this region is around 1000 mm. The catchment of Valtorto was burned before, by wildfire in 1990 and by prescribed fire in 1996. Elevation varies within the catchment, which is situated 600-730 meter above sea level. Two slopes make up the area, one slope facing north and the other one facing south, on top of schist bedrock. Vegetation is homogeneous shrub land dominated by *Calluna vulgaris*, *Erica cinerea, Erica umbellata* and *Pterospartum tridentatum* with few pine trees, some grass and moss and few rocky outcrops. Soils are loamy, rich in organic matter and shallow due to the steep slopes. The higher parts have only 5-10 cm of soil with many schist stones on top and in the soil profile, while the lowest part has deeper soils with less stones, which support a higher shrub layer.

2.2. Pre-fire data

In this study we try to determine the influence of soil properties, topographical differences and differences in fuel characteristics on soil heating in depth. Soil properties monitored before the experimental fire were stoniness, organic matter content, bulk density soil moisture content and rock cover. Organic matter content was analysed in soil samples taken at 200 sites. Soil moisture content, stoniness and bulk density of the soil were determined before the experimental fire as well. (refer to Appendix 1 for protocols). Topographical characteristics registered before the fire were altitude, slope aspect and inclination of slope for all measurement points. Before the fire, vegetation height and soil depth were measured, and vegetation cover was estimated to characterize the vegetation, the potential fuel for the fire.

2.3. Experimental fire

In order to be able to measure what level soil temperatures reach under fire we had a catchment burned by fire fighters who are used to conduct controlled fires. The fire was experimental in the sense that the first part was burnt with low intensity (Fig. 48 in Appendix 3) like a prescribed fire. A low intensity fire in combination with the steep vertical gradient of elevated soil temperatures means that the alteration of soil properties is expected to be very small under prescribed fires. After the upper slopes were burnt enough security space was created to burn the lower part with fast raging, high intensity fire caused by several colliding fire fronts. This climax fire was a simulated fire storm with very high intensity (Fig. 49 in Appendix 3), similar to wildfire. The vegetation next to the streams was burnt as well, unlike in a prescribed fire. The fire was ignited all around the catchment at the edge, starting with fire lines from the highest point in both directions and ending at the lowest point. Also the only path into the catchment was used to send a fire front downwards in the direction where the climax fire was planned (Fig. 50 in Appendix 3).

As pre-fire sampling is impossible before a wildfire because the fire was not planned, it is interesting to simulate wildfire in a controlled way, which gave the possibility of installing equipment before the fire started. We installed thermocouples to record soil temperature changes over the whole time span of this experimental fire.

2.4. Temperature measurements during the fire

In this study we measured soil temperatures during the experimental fire using two methods. Type-K thermocouples (50 mm long, 1.5 mm in diameter) were connected to data loggers (EL-USB-TC, Lascar electronics) and installed at 0 cm, 1 cm and 3 cm at 57 locations in the catchment. Data loggers were buried at a depth of 12 cm. Temperatures were recorded every two seconds for a period of 18 hours. The majority of measurement points were distributed along topographical catenas: five transects of two to seven points along each slope. For the exact place to install the thermocouples we selected sites with continuous vegetation along the slope, to be sure the fire would not be interrupted close to the thermocouples due to unnaturally disturbed vegetation. Soil temperatures were monitored at the soil surface and at 1 cm and at 3 cm depth. All thermocouples were excavated the day after the fire and the exact depth of the probe tip was recorded. During tests in prescribed fires in Portugal we found no significant elevation of soil temperatures below 3 cm. Under low intensity fire the heat pulse is not expected to affect soil temperature deeper than 5 cm (Miranda *et al.*, 1993). Another study under fire on shrub land found no significant rise in temperature at 5cm depth (Floyd, 1966).

The second method we used to measure soil temperature was applied only at the soil surface and consisted of metal sticks with thermo sensitive paints (Omega lacquers). Litter was removed before the sticks were laid down directly next to where the thermocouples were installed and the litter was put back over the sticks. This method was used before and showed good results (Gimeno-Garcia *et al.*, 2004).

In the fire temperatures of flames and ignited fuels were measured with a laser-gun (Omegascope).

2.5. Analysis of soil heating

The maximum soil temperatures measured at the surface during the experimental fire by means of thermocouples will be compared with temperature indications of the thermo-sensitive-paint sticks at the same points. One person will read all the paint sticks to minimise inconsistencies in determining if the paint had melted. Paint sticks' temperatures are considered as 'minimum' maximum temperatures; because when one paint has melted it indicates a temperature up to the next paint-melting temperature. Statistically both surface temperature measurements are compared with linear regression analysis and a paired t-test. With this comparison we can judge accuracy, variance and usefulness of both methods.

To visualize the extent of soil heating, we select and calculate three indicators of fire intensity: maximum temperature; duration of temperature above threshold values; and a heat index defined as the cumulative temperatures above 30°C (an arbitrary value slightly above maximum soil temperature before the fire started). These three indicators will be spatially mapped by means of ESRI ArcGIS software (ArcInfo 9.2) at the three depths where soil temperatures were measured, 0cm 1cm and 3cm. The same indicators were used earlier to characterize soil heating beneath fire (Iverson *et al.*, 2004). Proposed values for temperature thresholds are 40°C, 60°C, 100°C and 175°C. 40°C and 60°C are lethal thresholds for microarthropods and plants respectively, but can also be seen as thresholds for breaking seed dormancy in seeds. At 100°C soil moisture content changes, therefore it is taken as third threshold. Although dehydration of soil will not be completed before temperatures reach 170°C-220°C (Giovannini, 1994), temperatures exceeding 100°C indicate that soil moisture content has dropped below 2% (Campbell *et al.*, 1995). Moisture content affects vegetation growth via root length and canopy height (Gross *et al.*, 2008), and species dominance (Clark *et al.*, 2008), because the need for moisture differs between plant species. The threshold of 175°C needs to be exceeded to increase water repellency (Debano, 1981).

For each measurement point the attenuation of soil heating with soil depth is characterized by lower maximum temperature, longer duration of elevated soil temperature, lower heating velocity and the delays before soil heating starts and before maximum temperature is reached (Fig. 10 and Fig. 11). Delay of heating propagation and delay of reaching maximum temperature at 1cm and 3cm is referenced by heating propagation and time of maximum temperature at the surface. This way of calculating delays and heating rates means that we have to select the moment in time when heating by the fire starts. Because of spatial variability in soil temperature and the fact that it is increasing also before the fire (daily temperature cycle), every measurement point has to be judged separately to see when the fire starts to heat the soil surface. When temperatures start to rise continuously until maximum, and faster than before, soil heating by the fire is assumed. With this reference in time (resolution of 2 seconds) the heating velocity until maximum temperature is calculated for each thermocouple and delays of heating propagation and maximum temperature are calculated for both depths 1cm and 3cm. Both delays will be mapped over the catchment at both depths and also the heating velocity at 0cm, 1cm and 3cm will be mapped, using ESRI ArcGIS software (ArcInfo 9.2).

Expected results of the visualizing part of this study will be maps of: maximum temperature, residence time above temperature thresholds, heat index above 30°C and heating velocity at 0, 1 and 3 cm; and delay of heating propagation and timing of maximum temperature at 1 and 3 cm.

To be able to map temperature data variables over the whole catchment area spatial interpolation is needed. With spatial interpolation any variable can be estimated at locations where it was not measured, a surface is created based on data points taken at known geographic locations (x,y). The variable that needs to be interpolated can be considered as the height of the surface (z). A few interpolation methods can be applied within ArcGis software (ESRI ArcInfo 9.2): Inverse Distance Weighting (IDW), Spline and Kriging.

2.6. Interpolation methods

Inverse Distance Weighting, or Inverse Distance to a Power, is a weighted average interpolator. This means that weights are assigned to neighbouring measurements of the variable which is estimated, the sum of all the weights being equal to 1.0 (Yang *et al.*, 2004). The number of neighbouring measurements is chosen beforehand. A weighting power controls how the weight of neighbouring measurements decreases with the distance from the estimated location. The higher the weighting power, the less weight is assigned to relatively far measurements. As the weighting power increases, the estimation approaches the measured value at the nearest neighbour (Yang *et al.*, 2004). Also the weighting power is chosen before Inverse Distance to a Power is applied. IDW is simple and quick compared to other interpolation methods (Mueller *et al.*, 2004).

Kriging computes the best linear unbiased estimator based on a stochastic model of the spatial variation, whereas more traditional interpolation methods are based on mathematical models of spatial variation. As kriging is derived from regionalized variable theory, it is most useful if the measurement points are configured in a way that shows spatial structure. Kriging depends on expressing spatial variation of the property in terms of the variogram, therefore a structural analysis is needed before the interpolation to fit a covariance and a degree of trend (Dubrule, 1984). IDW and kriging both presume that linear combinations of available data should be used for the estimations. Both methods differ in how the weights for the data points are calculated (Schloeder *et al.*, 2001). Estimators from kriging are optimal and unbiased because the kriging equation obtains the weights in a way which ensures that the average error for the model is 0 and the model error variance is minimized (Dubrule, 1984; Schloeder *et al.*, 2001).

Spline interpolation uses specific families of mathematical functions, for example polynomial functions, to estimate unknown values in between measurement points. Because every segment in between measurement points is treated separately, this method results in interpolants that are easier to evaluate compared to methods which interpolate with only one function. Polynomial interpolation, for example, is able to fit one polynomial through all data points, but the polynomial will be of very high degree (N-1) when the number of data points is high. This makes polynomial interpolation complex and computationally expensive. Spline interpolation creates a smooth surface with minimum curvature which does not have to go exactly through the data points as it is not an exact interpolator (Yang *et al.*, 2004).

Spline interpolation is equivalent to kriging with fixed covariance and degree of polynomial trend. Covariance and degree of trend do not depend on the variable under study (Dubrule, 1984). This should result in a loss of accuracy of splines compared to kriging. Another disadvantage is that it is impossible to get an estimation of variance because the spatial structure of the variable is unknown (Dubrule, 1984). Compared to kriging it is faster to use spline interpolation as no preliminary structural analysis is needed, but the assumptions of fixed covariance and degree of trend are able to diminish accuracy. For quick and easy visualization there were no reasons found to prefer spline interpolation above IDW.

IDW and Kriging were compared in several studies concluding that Kriging can perform significantly better when the true variogram parameters are known beforehand (Kravchenko, 2003; Mueller *et al.*, 2004). Kriging is more complex and time consuming than IDW, but kriging provides the best linear unbiased estimator. (Mueller *et al.*, 2004). When the interpolation methods are tested on sufficiently large data sets their performance is similar in accuracy. IDW was found more accurate for small data sets or when data points were too far apart. If the variogram, needed for kriging, is unknown and has to be estimated, the number of data points has to be sufficiently large and the distance between the data points should be small enough, otherwise no reliable variogram can be obtained (Kravchenko, 2003).The number of data points in the Portuguese area under study (56) is small compared to the minimum number needed for kriging, which is 81 points for weakly spatially structured data (Kravchenko, 2003). Spatial correlation in maximum soil temperature data was weak, because a large fraction of variance in the temperature data was unexplainable. These reasons point to IDW as a favourable interpolation method for this study, because IDW is quick and easy and because kriging is not expected to perform better than IDW as the number of data points is small and spatial structure is weak.

2.7. Statistical analysis of explaining factors

Pre-fire collected data about soil properties, geographic differences and fuel characteristics was screened and analysed by descriptive statistics. Potentially explaining factors which were measured at the same points where soil temperatures were recorded are used for regression analysis. All statistical analysis: descriptive statistics such as minimum, maximum, mean and median; as well as inferential statistics are done using SPSS v. 17.0 (SPSS Inc., Chicago, IL).

Regression analysis is done in order to find out which of the potentially explaining factors play a role in soil heating, and which factors are most important. If results show significant correlation between soil heating variables and explaining factors, we will be able to point out which factors will be interesting for further research into soil heating by fire. Hopefully, after further investigations, we might be able to predict and model soil heating by fire.

2.8. Modelling soil temperatures

The first attempt to model soil temperatures beneath a fire (Scotter, 1970) was made without considering soil moisture changes. The next step in terms of modelling was taken by Aston and Gill (Aston and Gill, 1976). They modelled soil temperature and moisture content, as to be able to continue modelling above 100°C. Three equations were taken to represent vertical transfer of heat and moisture, one for heat, one for liquid water and one for water vapour. By coupling the three equations a model was made which is able to calculate soil temperatures in good agreement ($R^2 = 0.97$, d.f. = 33) with experimentally measured temperatures up to 420°C (Aston and Gill, 1976). However this model uses an input factor, the f factor, which needs to be optimized or replaced by experimental data for different soil types. Campbell and co-authors (Campbell *et al.*, 1995) reported difficulties with applying the model by Aston and Gill to different soils and with the use of excess heat above 100°C by the model. They improved the model by describing the temperature dependence of soil thermal conductivity, simultaneous rather than successive solution of the heat and water equations and an iterative numerical method to solve these nonlinear differential equations. The improved model appears to simulate heat and water flow correctly in soils heated to high temperatures (Campbell *et al.*, 1995).

To be able to accurately estimate thermal properties is of importance when soil temperatures are modelled and when consequences of elevated temperatures are predicted. Soil heating increases temperature, and high temperatures change thermal properties.

2.8.1. Soil thermal properties

The importance of soil thermal properties was recognized already in the 19th century (Forbes, 1849 cited in (Ochsner *et al.*, 2001)). Soil thermal properties determine the partitioning of energy at the ground surface and influence the transfer of heat and water through the soil (Ochsner *et al.*, 2001). The influence of volumetric fractions of solids, water and air on soil thermal properties was known early in the 20th century (Patten, 1909 cited in (Ochsner *et al.*, 2001)). More recent literature presents measurements of thermal diffusivity (k) and volumetric heat capacity (ρ*c*) with heat-pulse technology using needle probe instruments (Bristow *et al.*, 1993; Bristow *et al.*, 1995; Tarara and Ham, 1997). Thermal conductivity (λ) can be obtained from thermal diffusivity (k) and volumetric heat capacity (ρ*c*) by definition as in the following formula:
λ (W m^{-1} K^{-1}) = k (m^2 s^{-1}) · ρ*c* (J m^{-3} K^{-1}); (Bristow *et al.*, 2001).

In this definition soil density (ρ) is included as part of the volumetric heat capacity, so soil density directly affects thermal conductivity. Estimated thermal conductivity of solids range from 3.06 to 3.72 (W m^{-1} K^{-1}) respectively for silty clay loam and sandy loam (Ochsner *et al.*, 2001). Note that values are for solids only, not for soil with pores containing water and air. From the formula above it is clear that high soil density means high thermal conductivity, so densely packed soil heats and cools faster than loosely packed soil. Soil water content or the fraction of pores filled with water is a major factor in heat conductivity, because heat conductivity of water is over 20 times larger than the heat conductivity of air. While many studies focused on the effects of moisture content (θ) on thermal properties (Tarnawski *et al.*, 2001; Irtwange and Igbeka, 2003; Janssen *et al.*, 2004; Heinemann, 2008), correlation with the volume fraction of air in the soil (n_a) is stronger (Ochsner *et al.*, 2001). Thermal conductivity decreases when the fraction of soil pores filled with air increases, in medium textured soils this relation is linear (Ochsner *et al.*, 2001). Note that the air-filled porosity as volume fraction in the soil is defined by 1 – (volume fraction of solids + volume fraction of water).

Soil thermal conductivity means how fast heat moves through the soil, but it also changes as a consequence of heating. Thermal conductivity increases 3 to 5 times when soil is heated up to 90°C (Campbell *et al.*, 1994). Another study by Campbell et al. (Campbell *et al.*, 1995) focused on the effects of soil moisture on soil heating and concluded that heating slows down and stops between 90°C and 100°C, as long as the moisture content is above 2% by volume.

3. Results and Discussion

3.1. Maps

3.1.1. Maximum temperatures

The maximum temperature at soil surface ranges from 9.5°C to 842.0°C (Fig. 1). A maximum temperature level beneath fire at the soil-litter interface was suggested to be 850°C (DeBano, 2000).

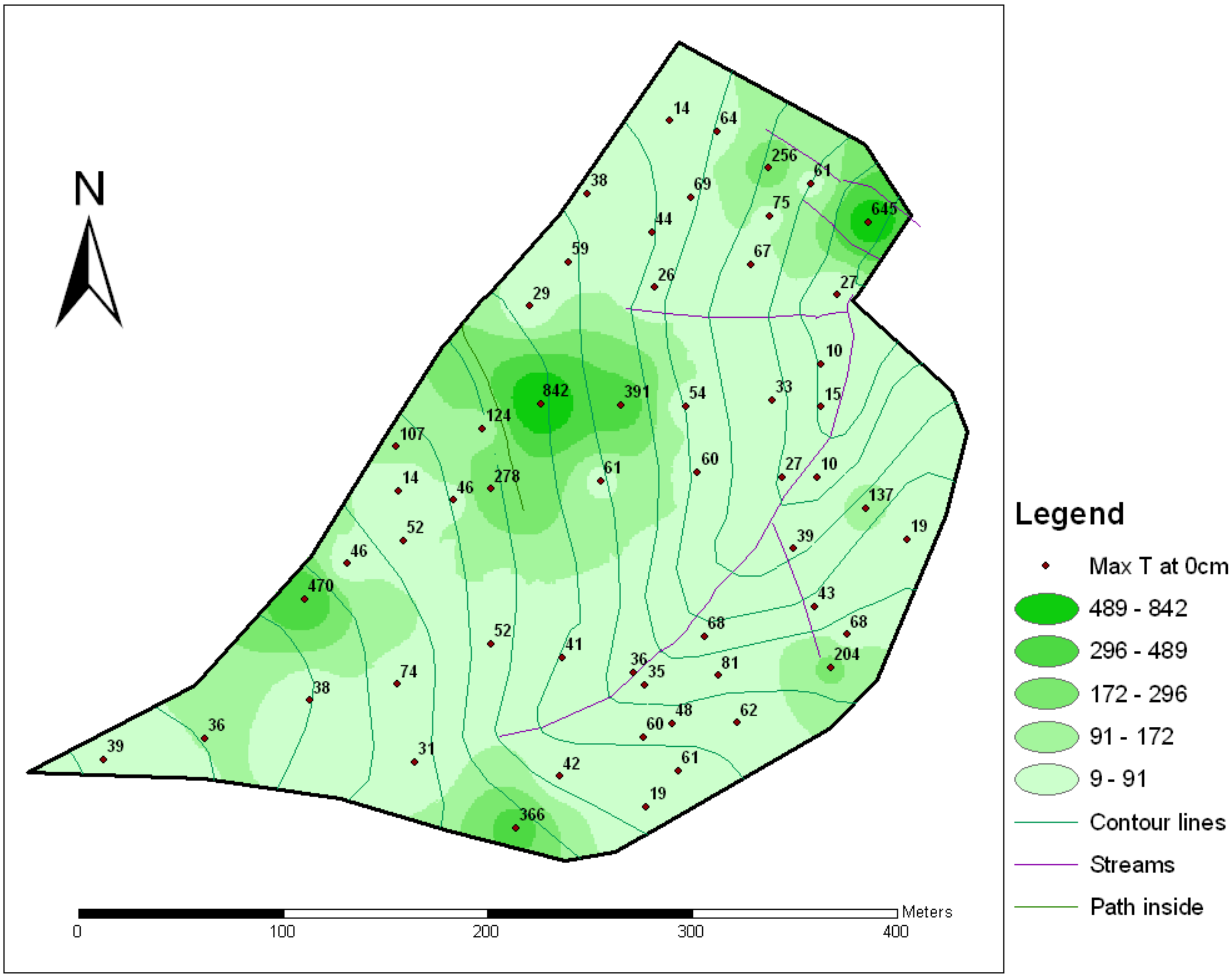

Figure 1– Maximum temperature (°C) at soil surface

Average maximum temperature of all measurements at the soil surface was 103.6°C. At most points the soil surface temperature was elevated by the fire, but at some points the surface temperature was not affected by the fire. Some measurement points did not have fuel on top or in close range, they were in bare soil and therefore they might have been unaffected. Few other measurement points were probably too much isolated from the fire by means of a litter layer which was too thick or too wet to be sufficiently burnt.

The boxplot of maximum temperature at soil surface (Fig. 2) shows a huge variability.

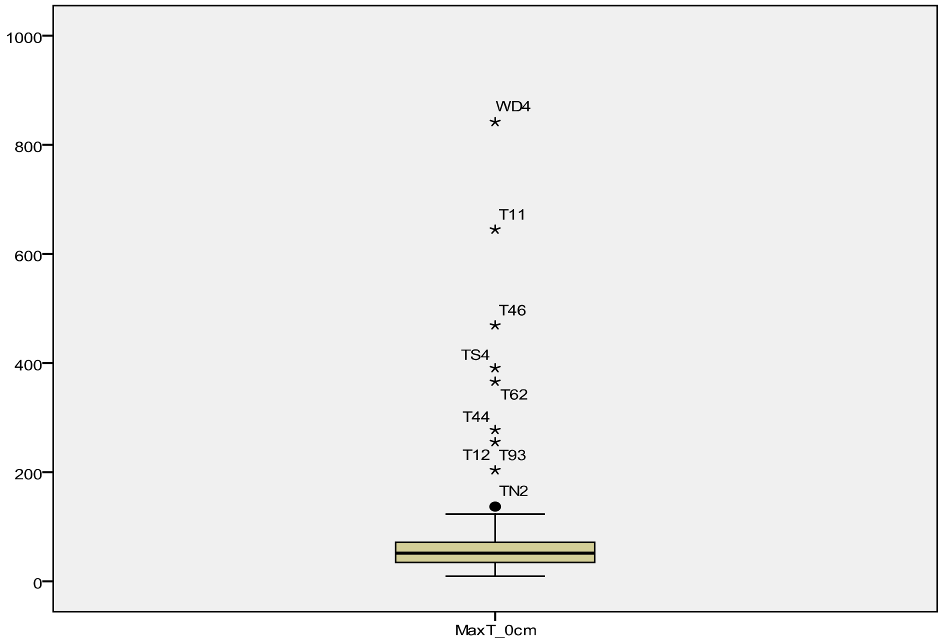

Figure 2 – Boxplot of maximum temperature (°C) at the soil surface

Average surface temperature is 104°C, while the median is only 52°C. Discrepancy between both measurements of central tendency is caused by (extreme) outliers. This plot gives nine outliers outside the box, in a sample size of 56. As the outliers are the measurements with high maximum temperatures, effect of the fire is obvious at these spots and therefore deleting the outliers is unwanted.

At 1cm depth in the soil maximum temperatures (Fig. 3) were lower than at the surface (Fig. 1), the range was from 6.5°C to 350.0°C and the average of 27.5°C was almost four times lower than at the surface. The maximum soil temperature at 1cm depth is comparable with earlier reported maxima 252°C (Howell *et al.*, 2006) and 370°C (Debano *et al.*, 1979) from the same depth.

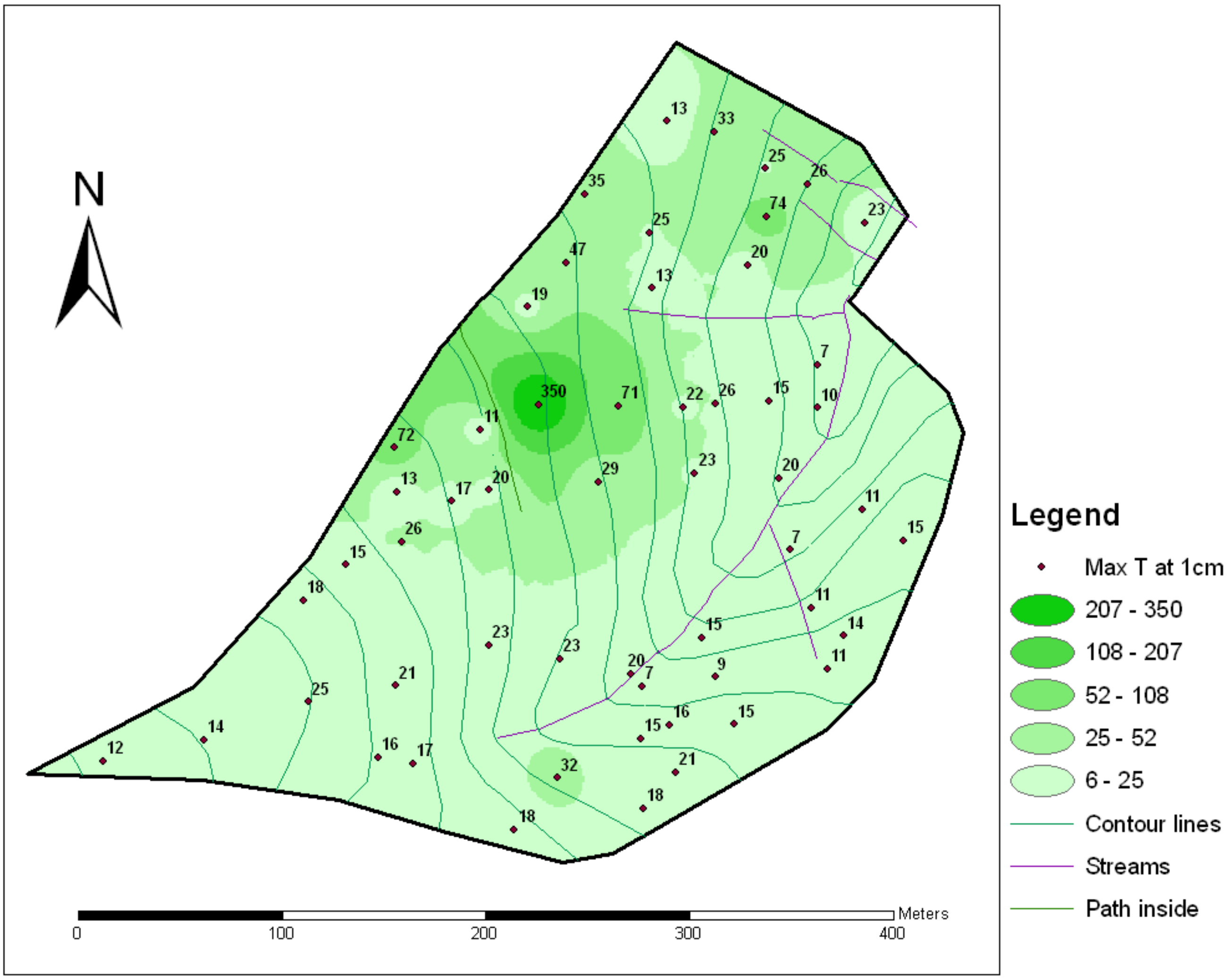

Figure 3 – Maximum temperature (°C) at 1cm depth

Where the maximum (350°C) was measured, also the maximum surface temperature (842°C) was measured. Generally, maximum temperatures measured at 1cm depth in the soil show less variability compared to maximum temperatures measured at the surface. This is to be expected because at 1cm depth the fire has less impact, compared to the soil surface.

High temperatures in the soil are expected only where surface temperature was high. Accordingly, the hotspots at 1cm depth were found under hotspot at the surface. But other hotspots in figure 1 do not come back in hotspots at 1cm depth (Fig. 3).

Figure 4 shows how the values of maximum temperature at 1cm depth were distributed over the range.

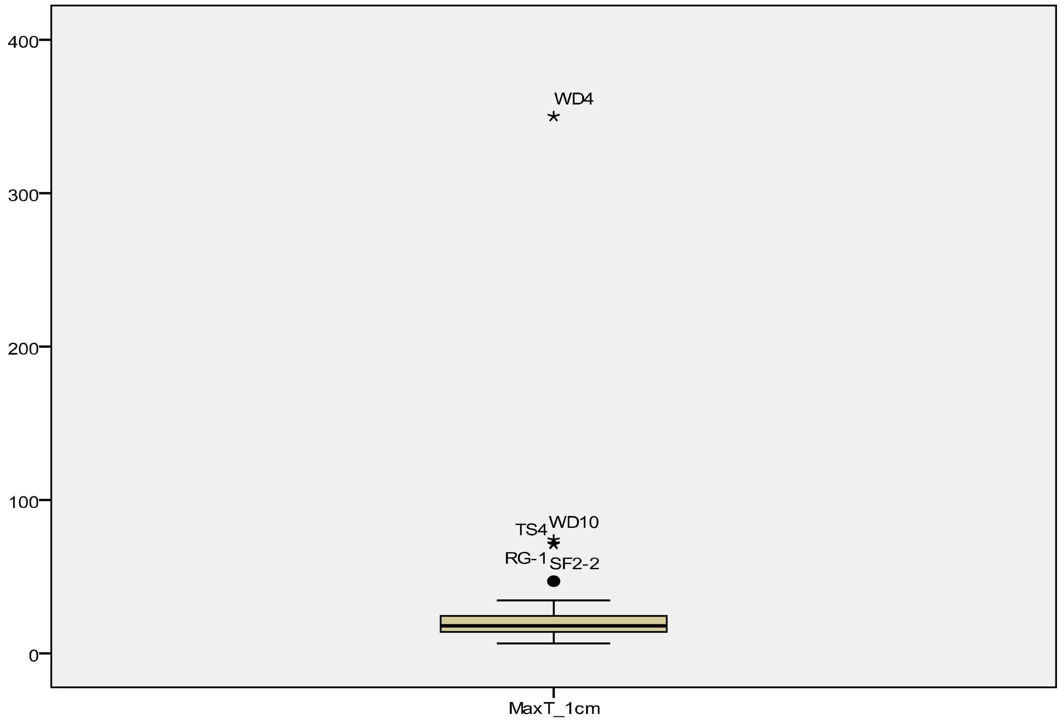

Figure 4 – Boxplot of maximum temperature (°C) at 1cm depth

At 1cm depth the number of outliers is lower, 5 out of a total of 55, but one outlier is very far away from the box. Therefore a considerable difference exists between the mean (27.5) and the median (18). Because soil temperature at this point was definitely influenced by the fire, deleting the outlier is unwanted.

Maximum temperatures at 3cm depth in the soil ranged from 6.5°C to 22.5°C (Fig. 5). Some other authors found negligibly elevated soil temperatures, for example 36°C as maximum at 2cm depth under a medium fuel forest fire (Massman *et al.*, 2003). But several authors found higher maxima at 3cm depth (Debano *et al.*, 1979; Howell *et al.*, 2006) or deeper down in the soil (Smith *et al.*, 2004)

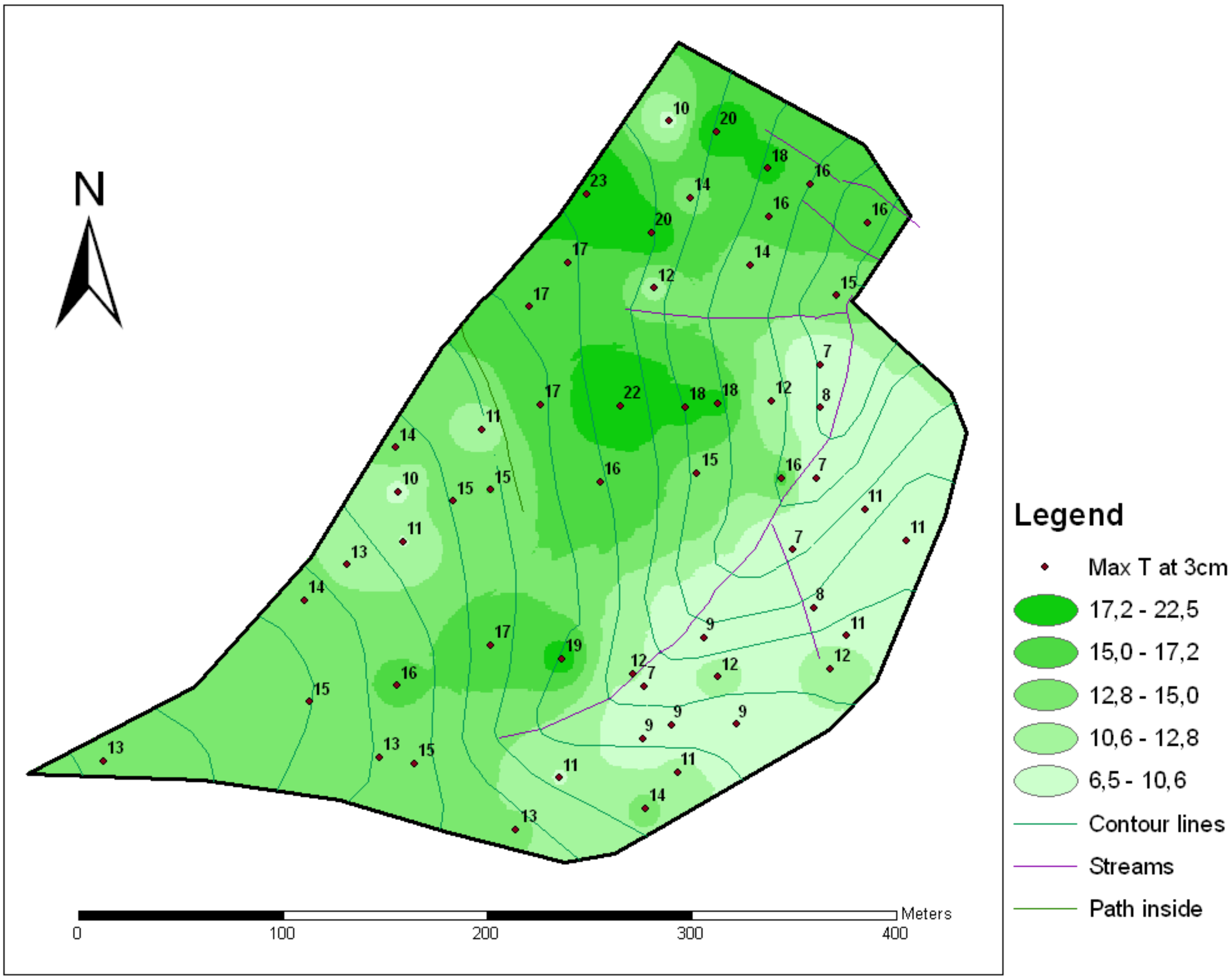

Figure 5 – Maximum temperature (°C) at 3cm depth

The average maximum temperature at 3cm depth was 13.3°C which is half of the average maximum at 1cm (Fig. 3). Less influence from the fire on soil temperatures is expected here in comparison with surface temperatures and with temperatures at 1cm depth.

The boxplot of maximum temperature at 3cm depth (Fig. 6) shows no outliers.

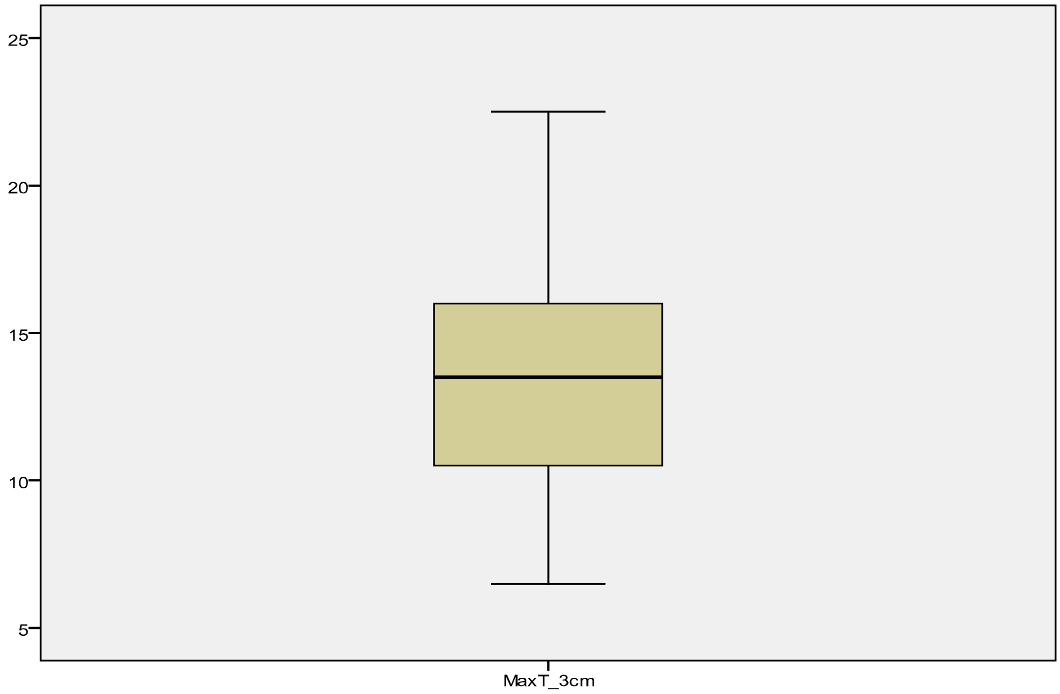

Figure 6 – Boxplot of maximum temperature (°C) at 3cm depth.

Logically the median of 13.5 is very close to the mean of 13.3 as no outliers pull them apart. Since there are no obvious outliers and variability in maximum temperatures is low at 3cm (Fig. 6), the distribution of measurement points at this depth looks more like a statistically normal distribution. Therefore high temperatures in figure 5 are more clustered into explainable sub areas, the slope exposed to the north shows low temperatures and the slope exposed to the south shows higher temperatures. North facing slopes receive less sunlight than south facing slopes, in the northern hemisphere. This might not directly explain lower temperatures at 3cm depth, but it could have an effect via the vegetation or the moisture content of vegetation, litter or soil. Because the vegetation at the north facing slope receives less sunlight, it dries slowly and was consequently wetter than vegetation at the south facing slope, when the experimental fire was conducted.

As the distribution of maximum temperature values at 3cm depth is similar to a statistically normal distribution, this variable will have more correlation with other factors than maximum temperatures at soil surface and at 1cm depth because their values were more irregularly distributed (Fig. 2 and 4).

3.1.2. Delay of maximum temperature in soil depth

Since delay of maximum temperature was defined as the time lag between when maximum temperature was recorded at the soil surface and at 1 or 3cm depth, this delay was zero by definition at the soil surface.

Delays to maximum temperatures at 1cm depth in the soil shown in figure 7 are easily understood, considering maximum temperatures at 1cm. At 1cm depth in the north facing slope no high maximum temperatures were found (Fig. 3), while 6 measurement points in the north facing slope had delays to maximum temperature of more than 24 minutes (Fig. 7).

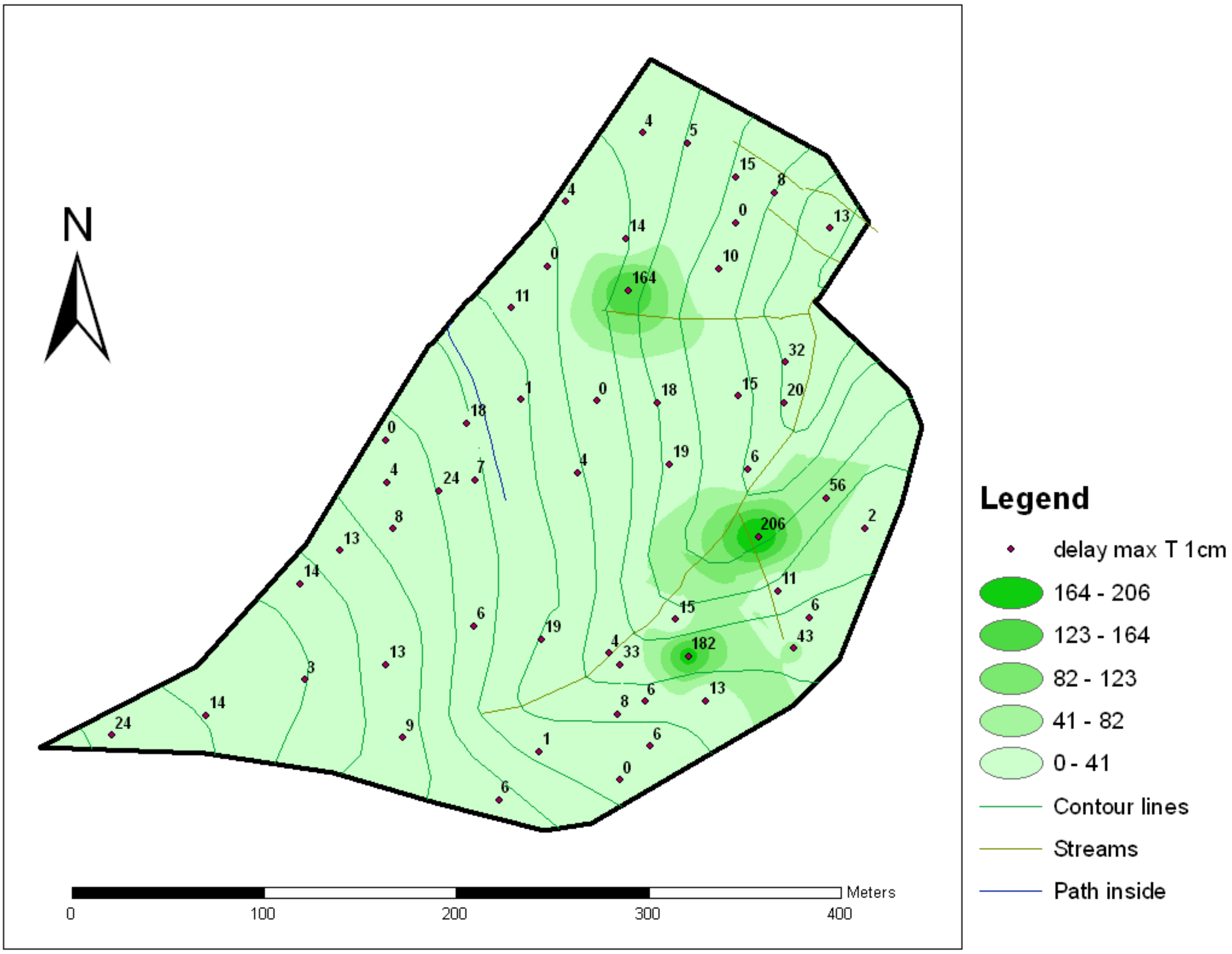

Figure 7 – Delay (minutes) before temperature reached maximum at 1cm depth

When maximum temperatures are relatively low (Fig. 3), a high delay to maximum temperature makes sense because maximum temperatures are not reached under influence of the fire. In the south facing slope only one measurement point had a delay to maximum temperature above 24 minutes and this maximum temperature was relatively low with 13°C (Fig. 3). Very high delays to maximum temperature were calculated from results of thermocouples which warmed up very slowly. Slow heating and only a few degrees of elevation indicate that recorded soil heating was not caused by the fire. Taking all measurement points into account the range of delays to maximum temperature is 0 – 206 minutes and the average is 23 minutes and 20 seconds.

Variance in delay before maximum soil temperature was recorded at 1cm depth, referred to when maximum soil temperature was recorded at the soil surface, is presented in figure 8.

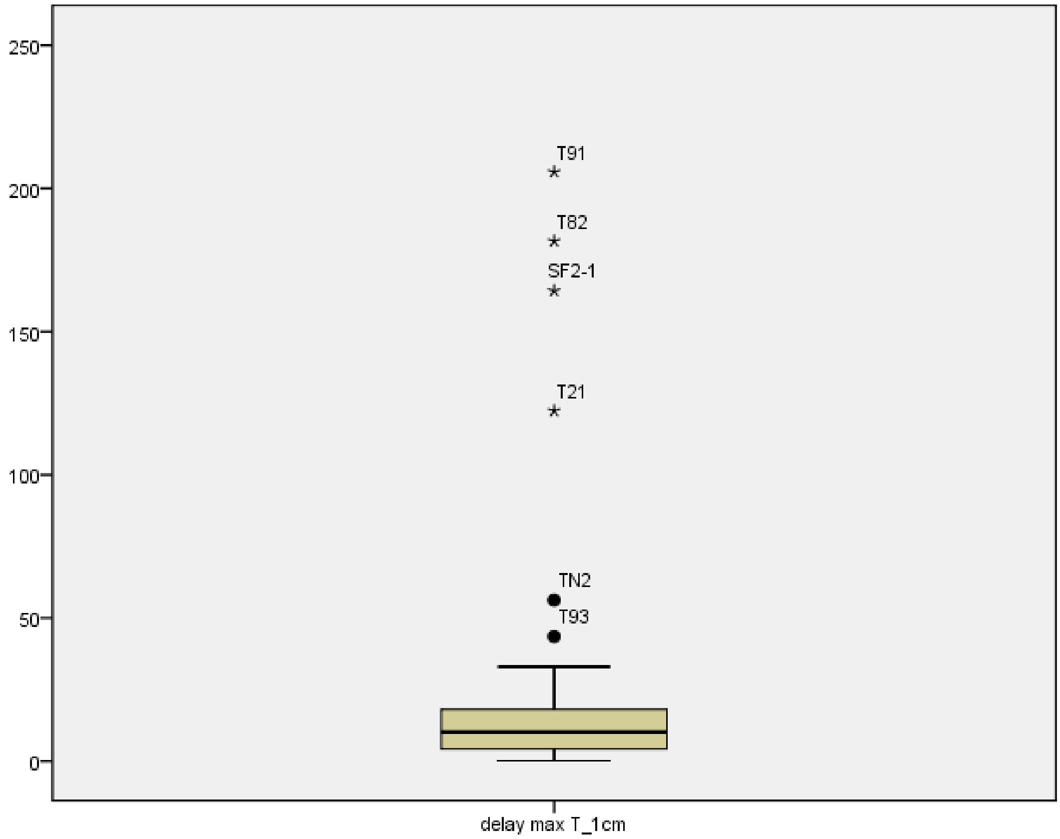

Figure 8 – Boxplot of delay (minutes) before temperature reached maximum at 1cm depth

As most measurement points recorded a short time between maximum temperature at the surface and at 1cm depth, the box is drawn at the low end of the range. A couple of outliers with high values pull the mean (23.3 minutes) above the median (10.1 minutes). Big delays together with low maximum temperatures indicate that the fire had no role in determining maximum temperature at these points.

Maximum temperatures at 3cm depth were delayed more (Fig. 9) than at 1cm depth, because both refer to the timing of maximum temperature at the surface. The dedlays are more evenly spread over the area when we compare figure 9 with figure 7.

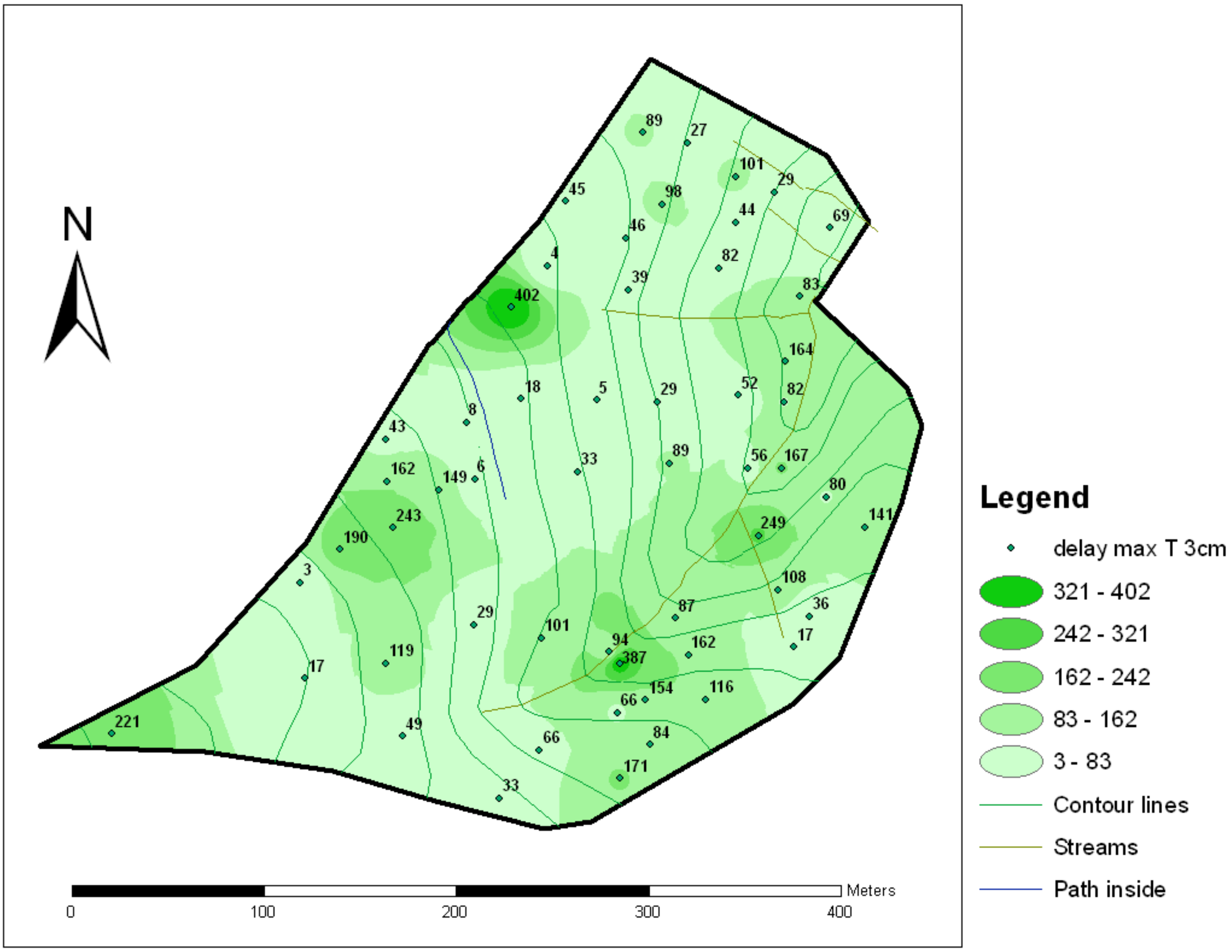

Figure 9 – Delay (minutes) before temperature reached maximum at 3cm depth

Although the map of maximum temperatures at 3cm (Fig. 5) looks very different from this map of the delays to maximum temperatures at 3cm (Fig. 9), both variables are related. Since the fire took place in the morning, the soil was warming up anyway, also at spots where it was not affected by the fire. So at these spots the delay to maximum temperature is expected to be high, as the process of warming up is very slow compared to spots where the maximum temperature is affected by the fire. Delays to maximum temperature at 3cm depth range from 3 to 402 minutes, with an average of 1hour 36 minutes and 20 seconds. This means delay to maximum temperature is about four times higher at 3cm compared to 1cm depth.

The variance in delay before maximum soil temperature was recorded at 3cm depth, referred to when maximum soil temperature was recorded at the soil surface, is presented in figure 10.

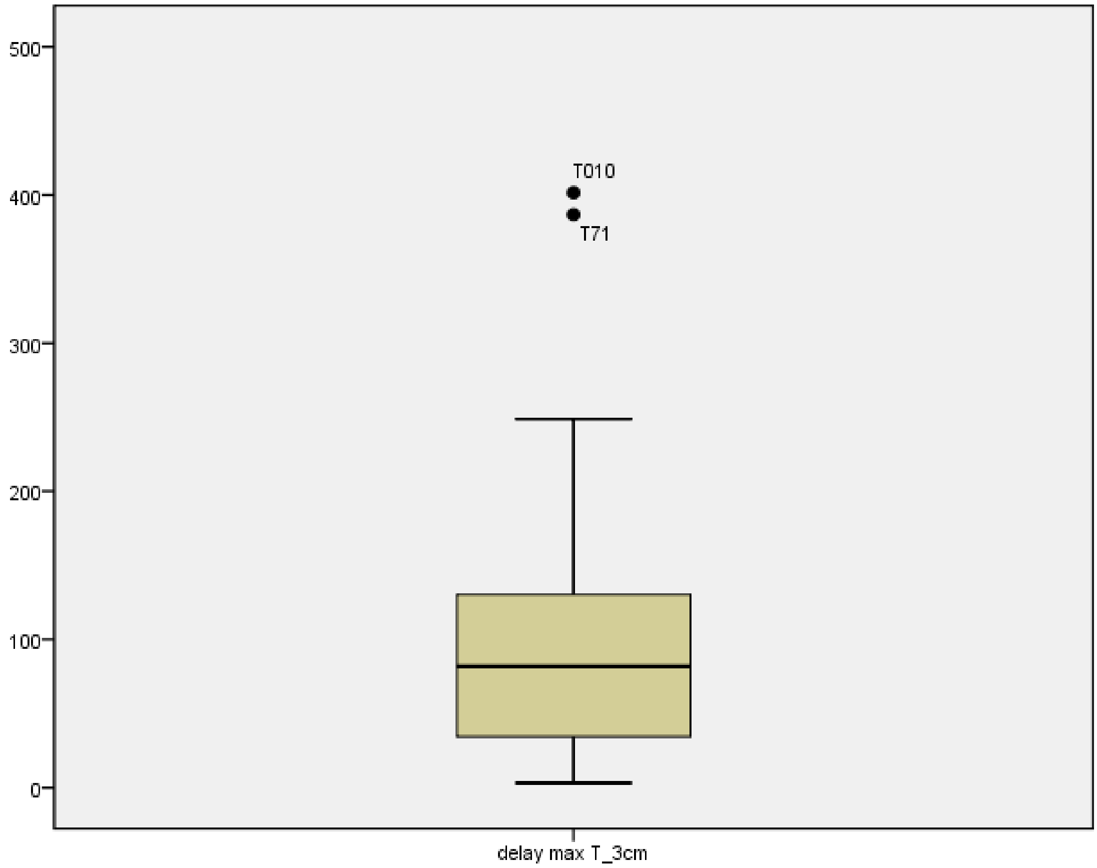

Figure 10 – Boxplot of delay (minutes) before temperature reached maximum at 3cm depth

High delays before soil temperature reached maximum values at 3cm depth indicate that the fire did not influence soil temperature at this depth. As the fire took place in daytime soil temperature was expected to rise anyway, as part of the daily cycle.

In figure 11 soil temperature recordings are presented from one measurement point in the north facing slope. It is clear that soil temperature at 1cm depth and at 3cm depth rose after maximum surface temperature (81°C) was reached. At both depths under the surface the soil temperature stayed below surface temperature before the fire reached this measurement point, during soil heating, and after the fire had passed. Soil temperature at both depths in the soil rose only a few degrees. Strangely temperature rose more and faster at 3cm depth than at 1cm depth.

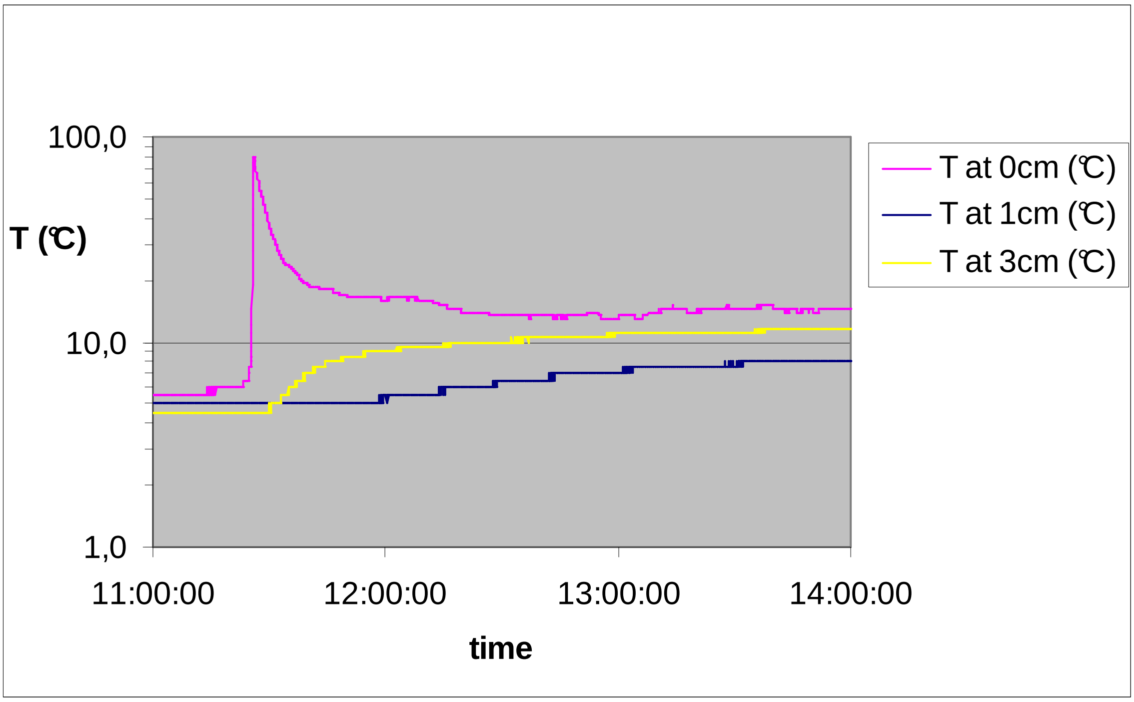

Figure 11 – Soil temperature (°C) at one point in the north facing slope

Figure 12 presents soil temperature at the three levels at one measurement point in the south facing slope. Here maximum temperature at the surface was 124(°C). Temperature at 1cm and 3cm depth started higher than in figure 11, rose only a few degrees and stayed below surface temperature all the time.

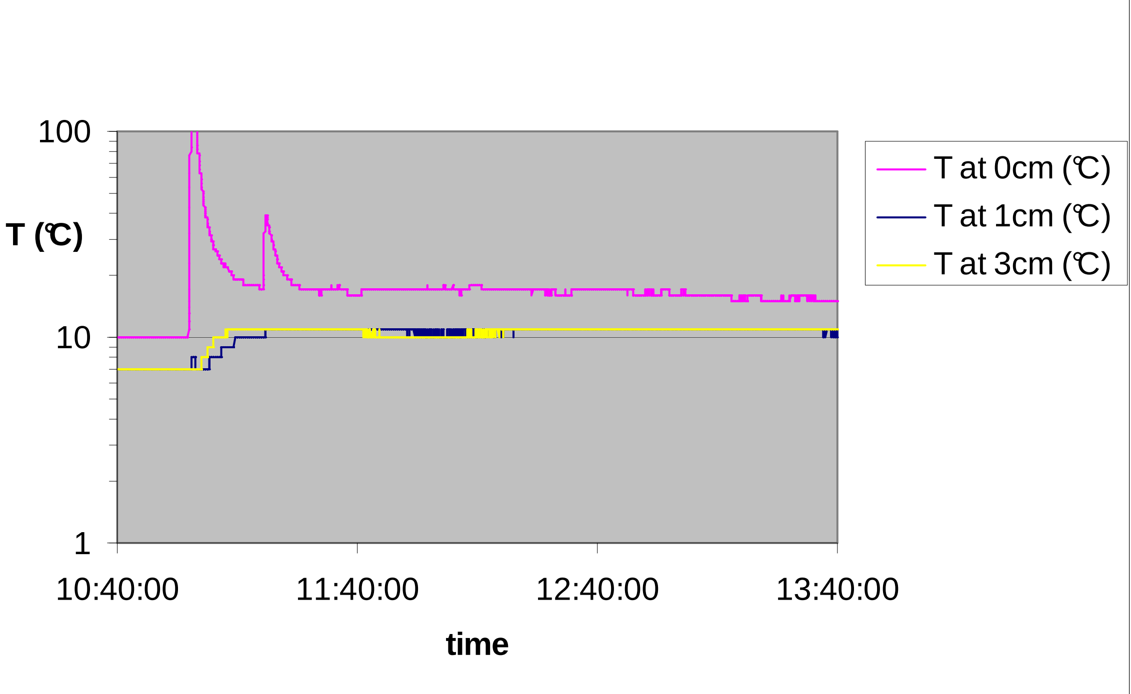

Figure 12 – Soil temperature (°C) at one point in the south facing slope

3.1.3. Residence time above threshold values

At the soil surface the time for which temperature threshold 40°C is exceeded gives a map (Fig. 13) similar to the map of maximum temperatures at the surface (Fig. 1).

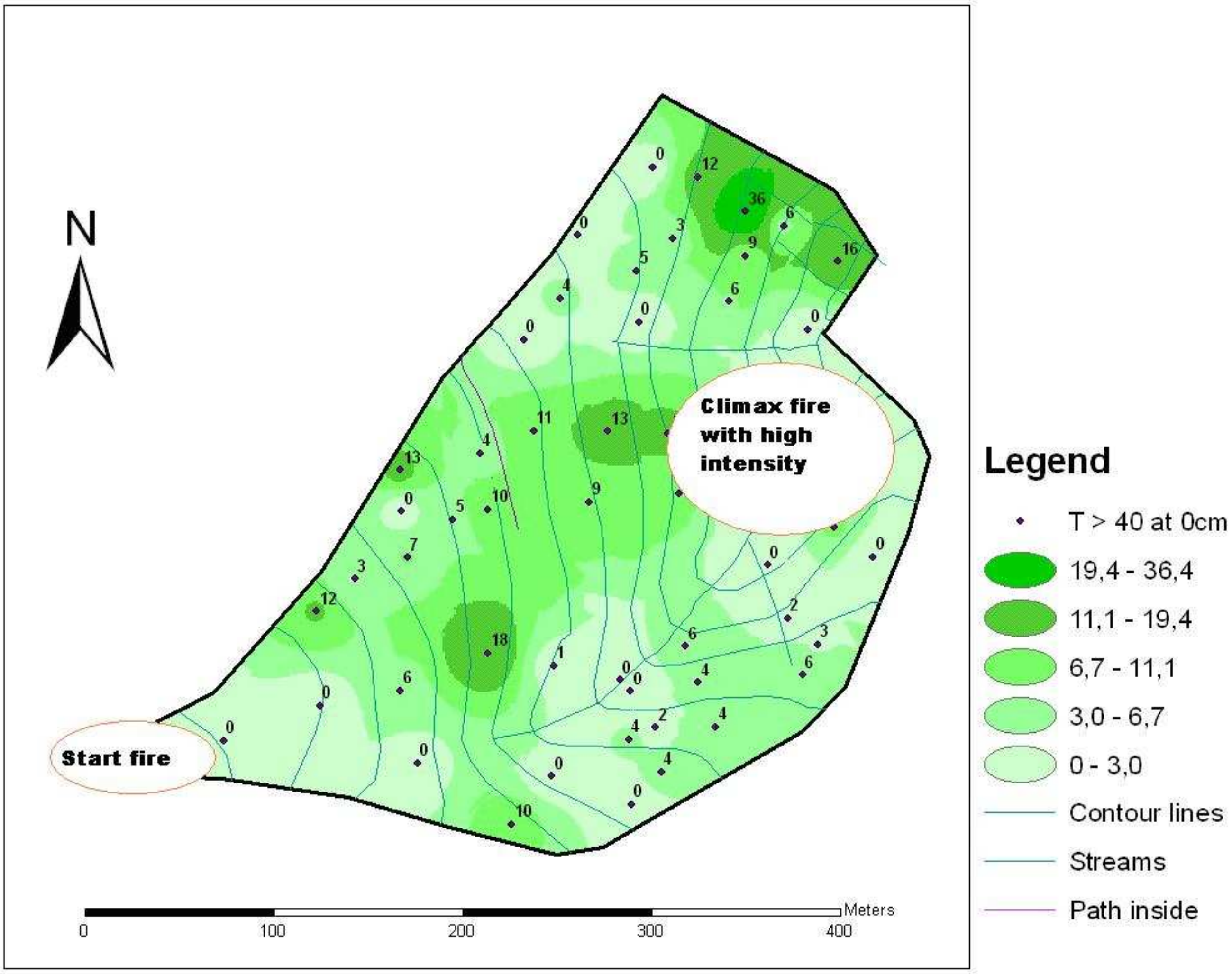

Figure 13 – Time for which temperature at soil surface exceeded 40°C (minutes)

Most hotspots are found on the south facing slope. The main hotspot is not in the middle of this slope like in figure 1, but at the lowest part of the catchment. The fire was started in the top of the catchment with low intensity like a prescribed fire, and the last part was made on purpose with high intensity. On average surface temperature exceeded 40°C for 5 minutes and 16 seconds.

At 1cm depth not many measurement points reached temperatures above the thresholds taken for analysis. Five points exceeded 40°C for some time (Fig. 14).

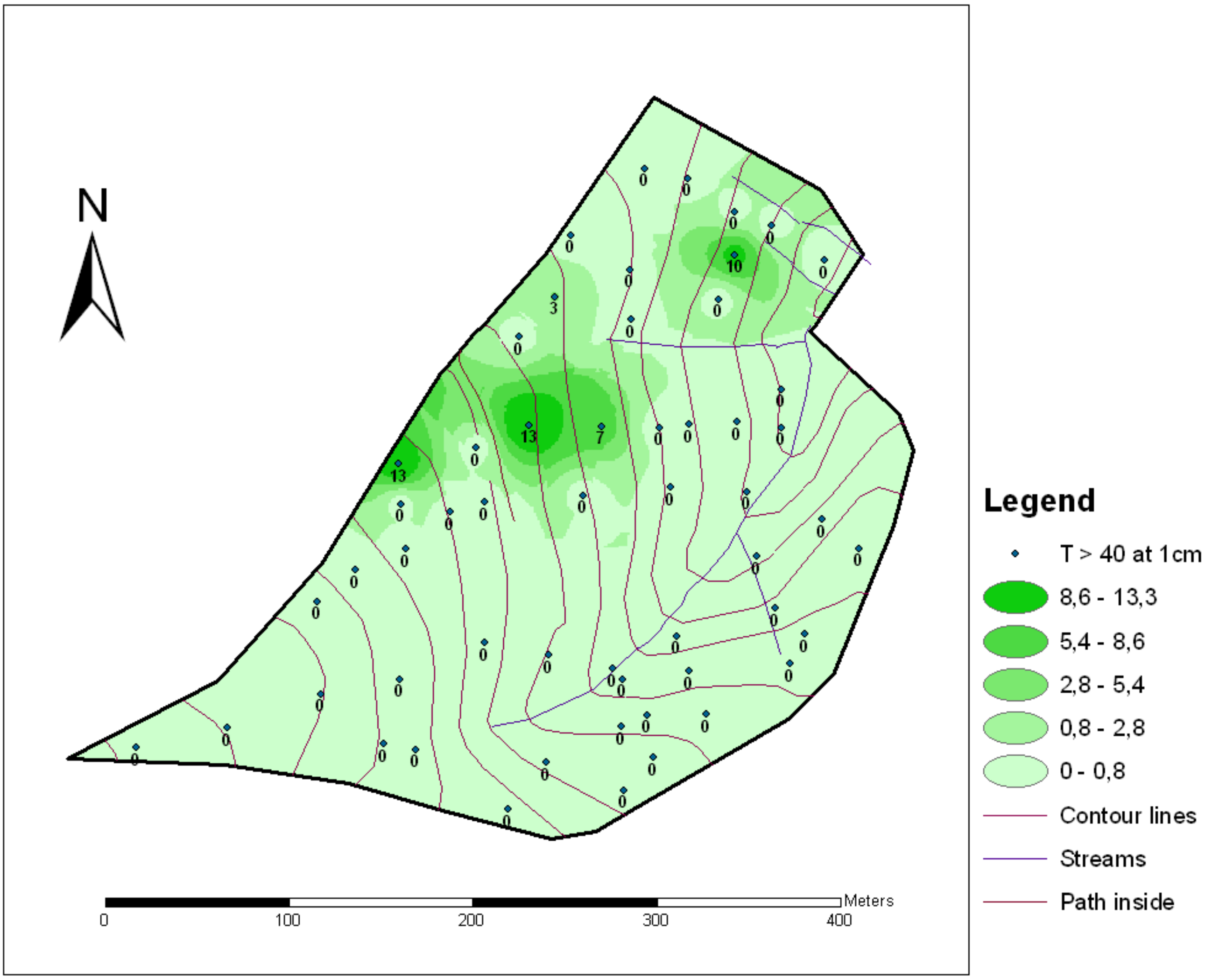

Figure 14 – Time for which soil temperature at 1cm depth exceeded 40°C (minutes)

The point which recorded the highest maximum temperature at 1cm depth also recorded the longest time above 40°C (Fig. 14). Average time above 40°C was 51 seconds, so over six times shorter than at the soil surface. The range of time above 40°C was almost three times shorter at 1cm depth compared to the surface (Fig. 13). Soil temperatures recorded at 1cm depth did not exceed 40°C anywhere at the slope facing north (Fig. 14).

At 3cm depth no temperatures above 40°C were measured at all.

Less measurement points show positive values when temperatures above 60°C are mapped (Fig. 15) compared to temperatures above 40°C (Fig. 13) because the threshold is higher.

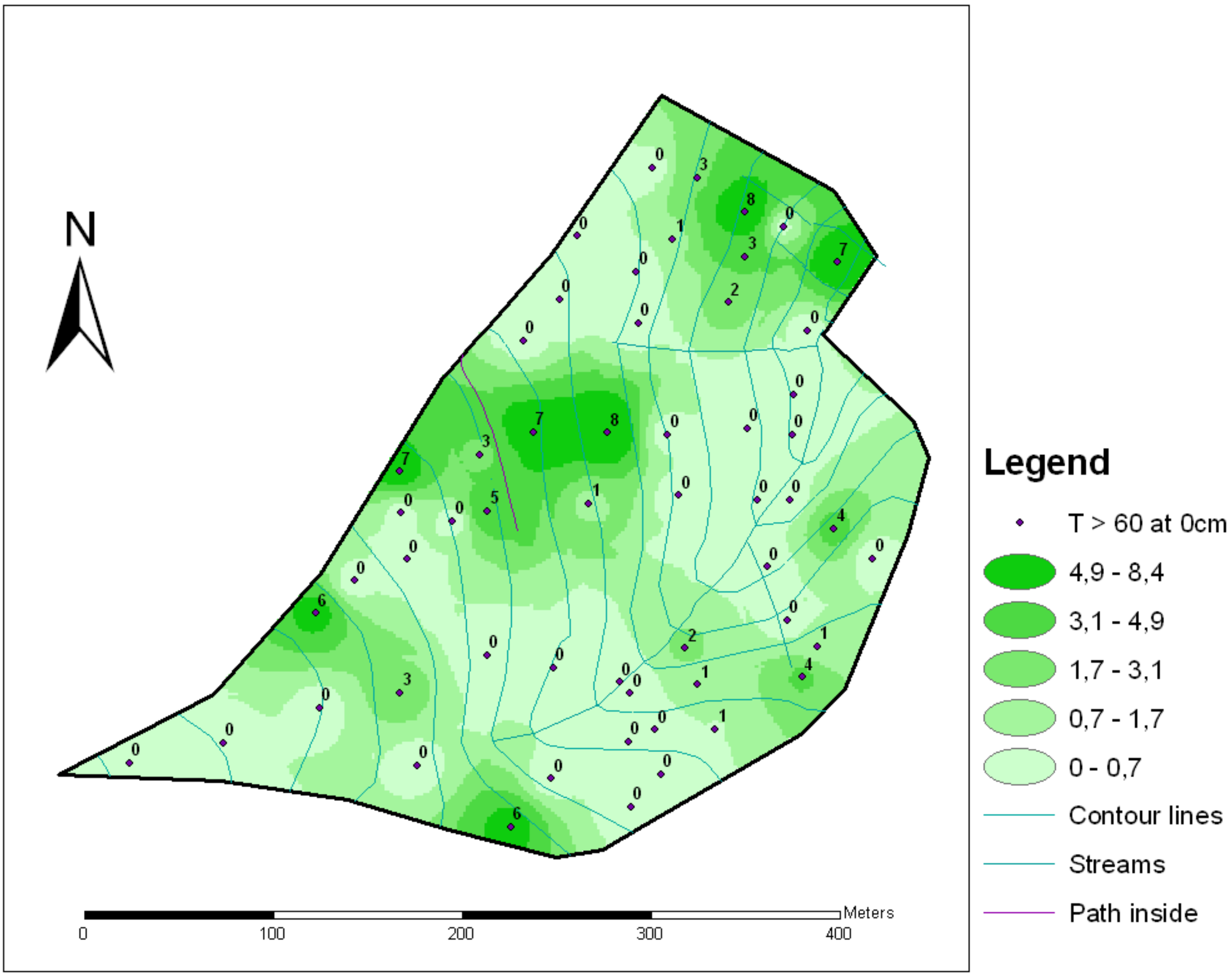

Figure 15 – Time for which temperature at soil surface exceeded 60°C (minutes)

Compared with figure 13, the range here is smaller (8 minutes and 24 seconds). Average time above 60°C at the soil surface was 1 minute and 33 seconds. In accordance with figure 13, most sites with surface temperature above 60°C were at the south facing slope. The fire was started at the highest point of the catchment (750m), but there no surface temperatures above 60°C or above 40°C (Fig. 13) were found.

At 1cm depth the time for which 60°C was exceeded ranged from 0 seconds to 8 minutes and 28 seconds (Fig. 16).

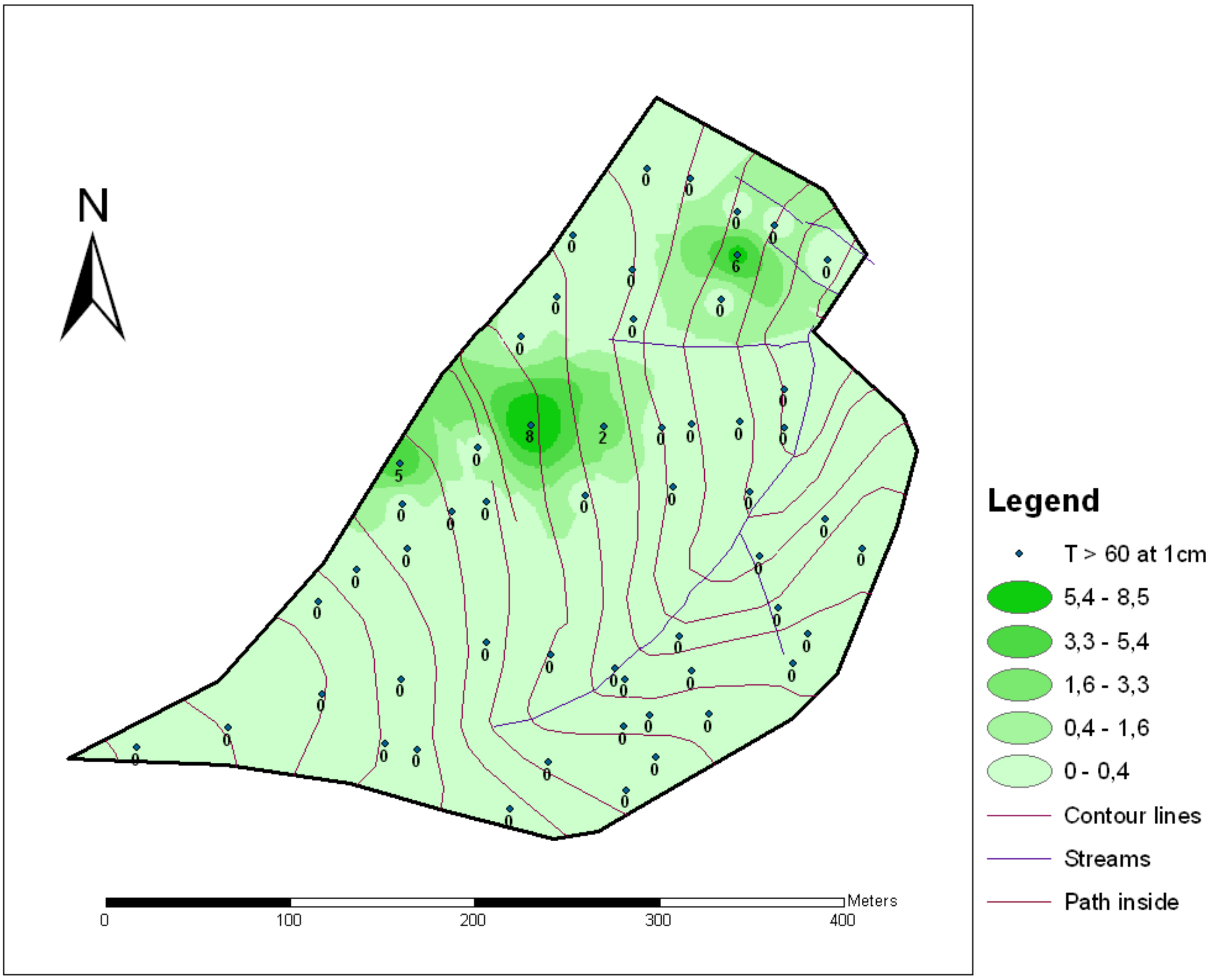

Figure 16 – Time for which soil temperature at 1cm depth exceeded 60°C (minutes)

Average time above 60°C at 1cm depth was 24 seconds, so almost four times shorter than at the soil surface. The range at 1cm depth (8 minutes and 28 seconds) was similar to the range at soil surface (8 minutes and 24 seconds). So slower heating at 1cm depth compared to the surface was compensated by slower cooling. Logically only sites which recorded temperatures above 40°C at 1cm depth (Fig. 14) could record temperatures above 60°C at 1cm depth (Fig. 16). Therefore no soil temperature above 60°C is expected in the north facing slope.

Time for which temperatures above 100°C were recorded at soil surface yields a map (Fig. 17) roughly similar to figure 15.

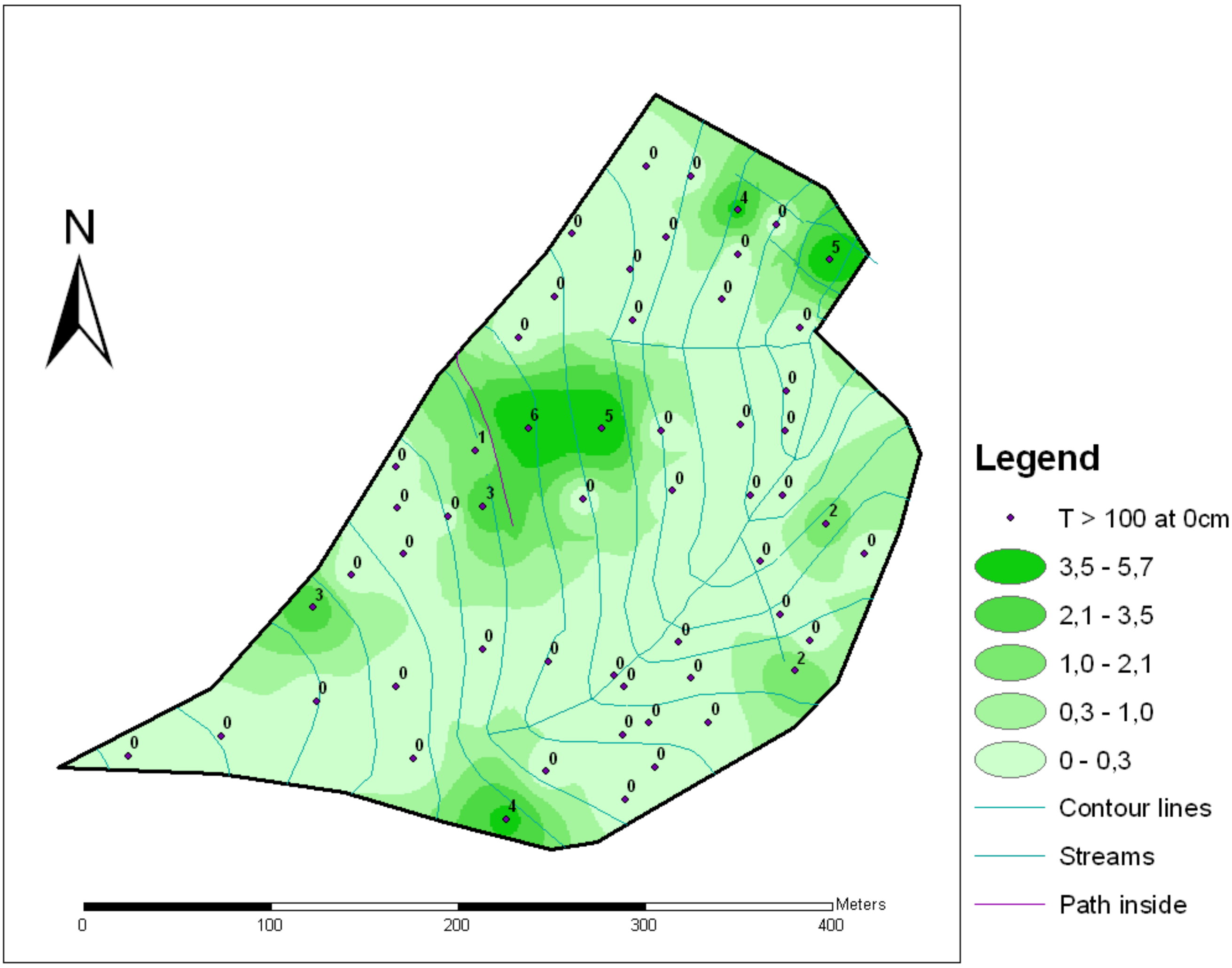

Figure 17 – Time for which temperature at soil surface exceeded 100°C (minutes)

The higher threshold means the number of measurements above 0 is lower, and the range is smaller. Longest period of time above 100°C (5 minutes and 44 seconds) was measured at the same spot where the highest maximum temperature was measured (Fig. 1). On average each measurement point at the surface exceeded 100°C for 39 seconds.

Only one measurement at 1cm depth exceeded 100°C (Fig. 18).

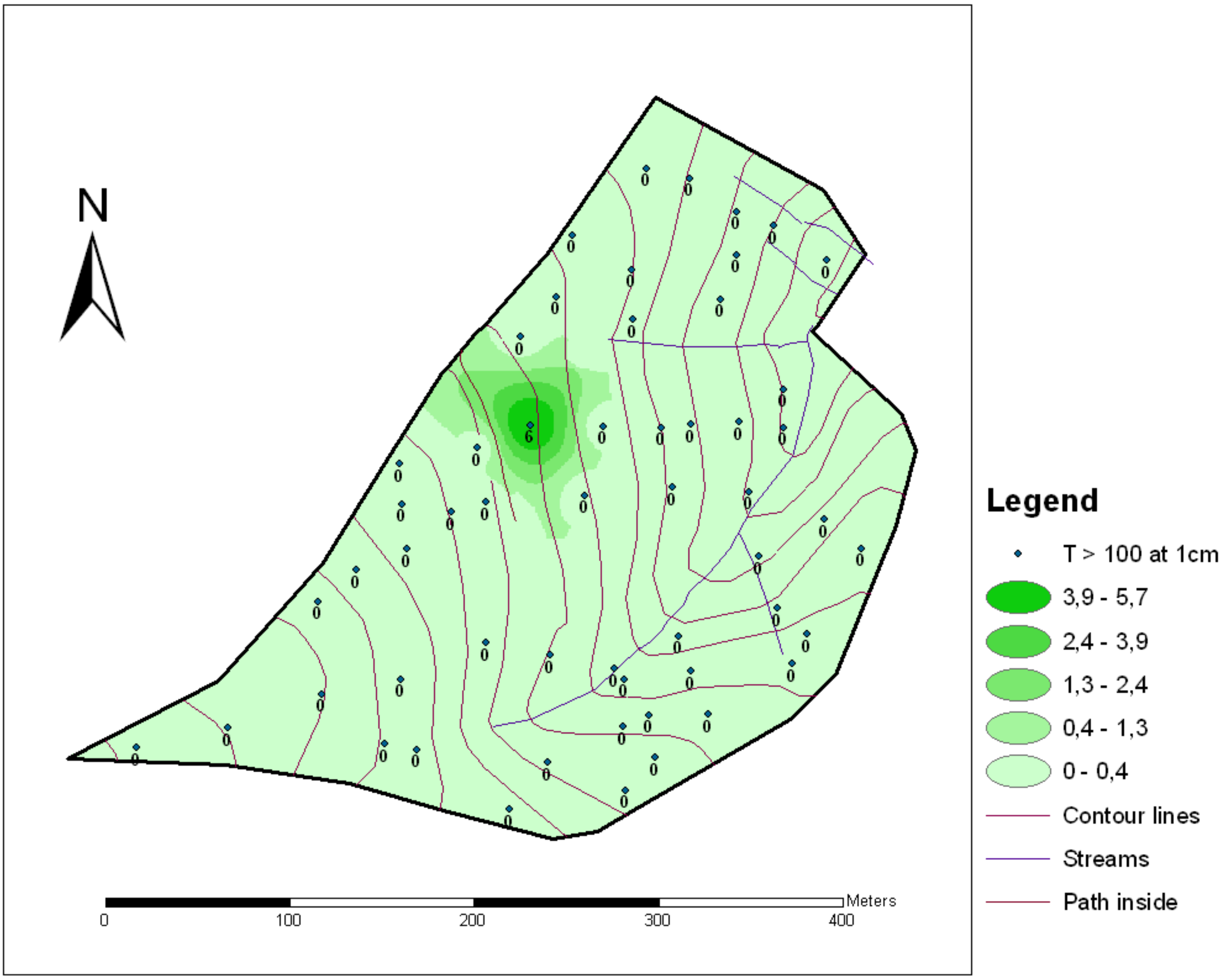

Figure 18 – Time for which soil temperature at 1cm depth exceeded 100°C (minutes)

This measurement point recorded the highest maximum temperature at the surface (842°C) and at 1cm depth (350°C). With only one value above zero the average time above 100°C of all measurement points was 6 seconds, over six times shorter than at the soil surface. The range at 1cm depth (5 minutes and 40 seconds) was very similar to the range at the surface (5 minutes and 44 seconds).

Increasing the threshold to 175°C again simplifies the map by lowering the range and reducing the number of points with positive values (Fig. 19), compared to the map of time for which temperature at soil surface exceeded 100°C (Fig. 17).

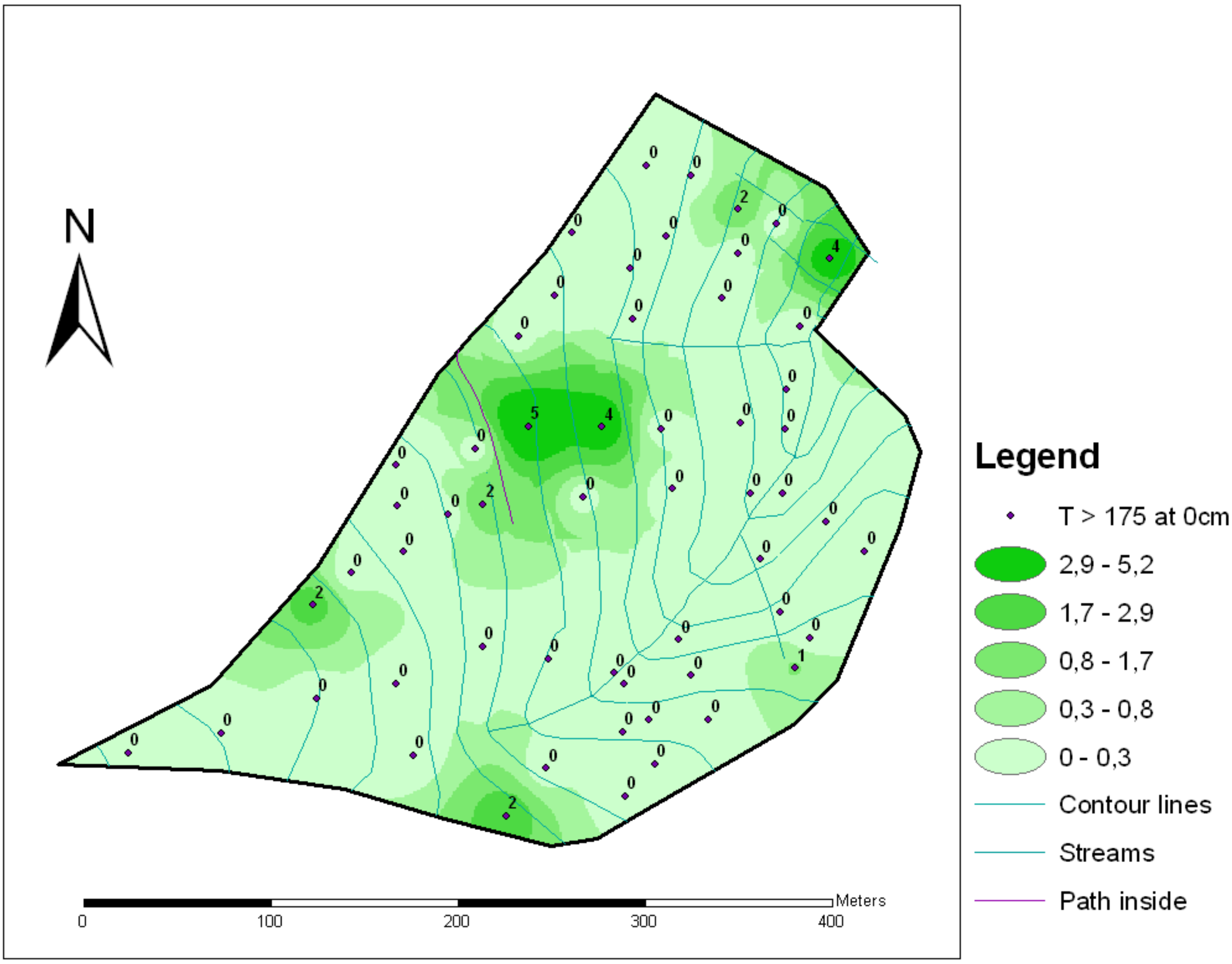

Figure 19 – Time for which temperature at soil surface exceeded 175°C (minutes)

Highest number of minutes above 175°C, 5 minutes and 10 seconds, was measured at the same spot where the highest maximum temperature of 842°C was measured (Fig. 1). Average time above 175°C was 24 seconds.

Figure 20 looks identical to figure 18, because the only point that reached a temperature above 175°C logically also exceeded 100°C at 1cm depth.

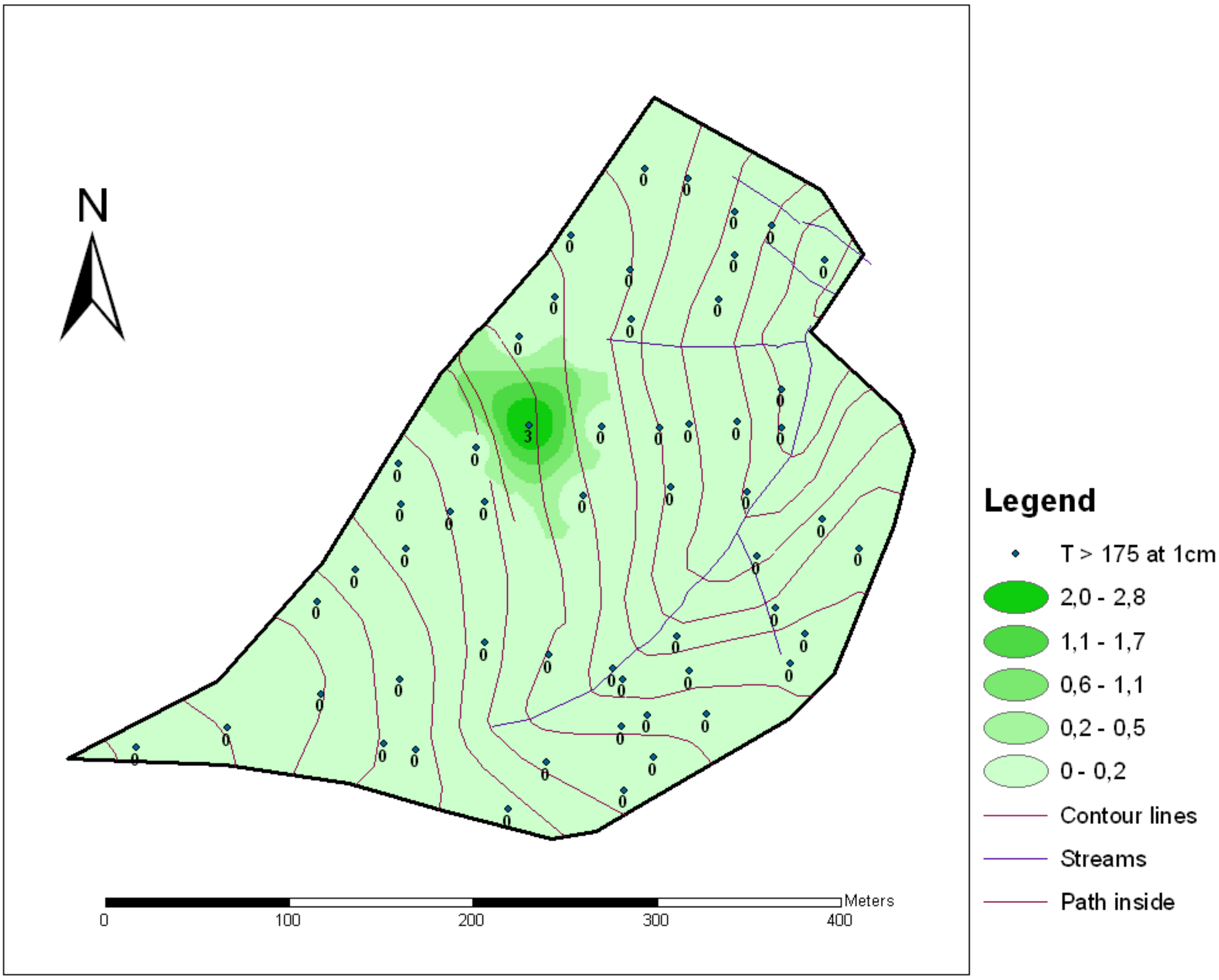

Figure 20 – Time for which soil temperature at 1cm depth exceeded 175°C (minutes)

At 1cm depth the range of time above 175°C was 2 minutes and 48 seconds, a little over half of the range at the surface. The average of time above 175°C per measurement point was 3 seconds, eight times shorter than at the surface.

3.1.4. Heat index above 30°C

This heat index was calculated as the integral of all temperature measurements above 30°C per thermocouple, measurements were taken every two seconds. In figure 21 the numbers represent cumulative temperatures above 30°C at the soil surface.

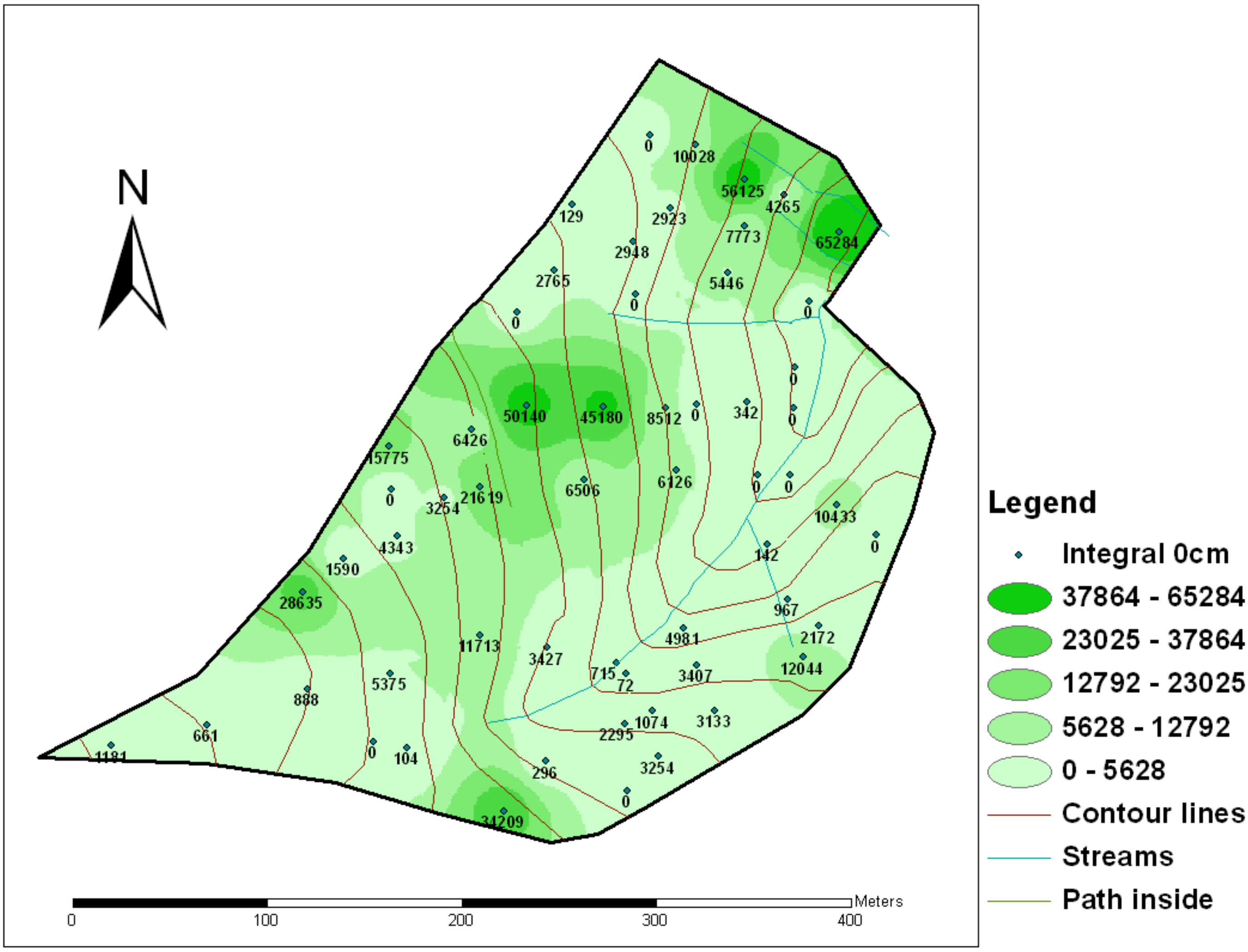

Figure 21 – Heat index (°C) above 30°C at soil surface

Values range from 0 to 65284°C with an average of 8190°C. As both the level of temperatures above 30°C and the time for which temperature was above 30°C are integrated, this map (Fig. 21) shows features of maximum temperatures and of the time for which temperature was elevated above 30°C. These numbers give a better idea of fire severity and potential consequences (§1.1.2.) than just maximum temperatures or just the time for which temperatures were elevated above threshold values. As suggested by other authors the main factor to determine fire consequences is for how long soil temperature is elevated (Neary *et al.*, 1999) above lethal levels (Schimmel and Granstrom, 1996; Hubbert *et al.*, 2006; Malmstrom, 2008), or to such extent that soil properties are changed (Giovannini and Lucchesi, 1997; Doerr *et al.*, 2004; Simkovic *et al.*, 2008). This heat index above 30°C was used before to characterize changes in soil temperature over time, induced by prescribed fire (Iverson *et al.*, 2004).

The hotspots here were also identified by maximum temperatures at the surface (Fig. 1) and the time for which surface temperatures exceeded 40°C (Fig. 13). To compare with other studies one should keep in mind that temperatures were logged every 2 seconds.

In this variable, all temperatures above 30°C cumulated per thermocouple, a wide distribution was found (Fig. 22). Outliers at the high end can be caused by extremely high temperatures or by many recordings of temperature above 30°C.

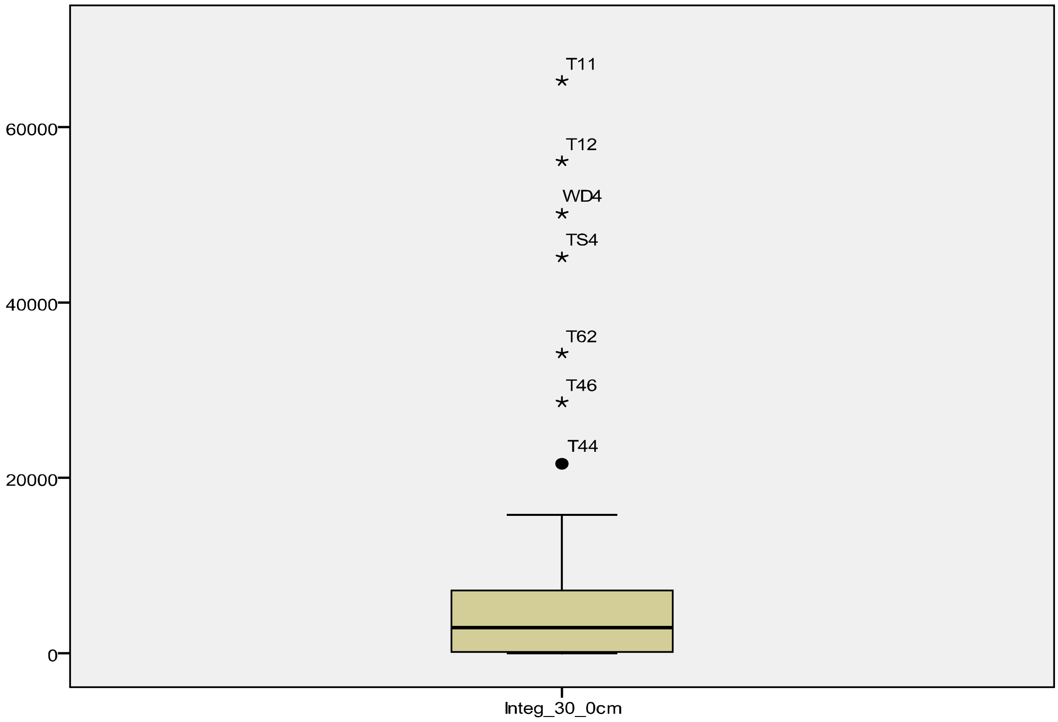

Figure 22 – Boxplot of heat index (°C) above 30°C at soil surface

The median was found at 2935, so half of the measurement points had lower values; a quarter did not reach above the threshold.

Only 8 measurement points reached temperatures above 30°C at 1cm depth (Fig. 23). All of them were located on the slope facing south.

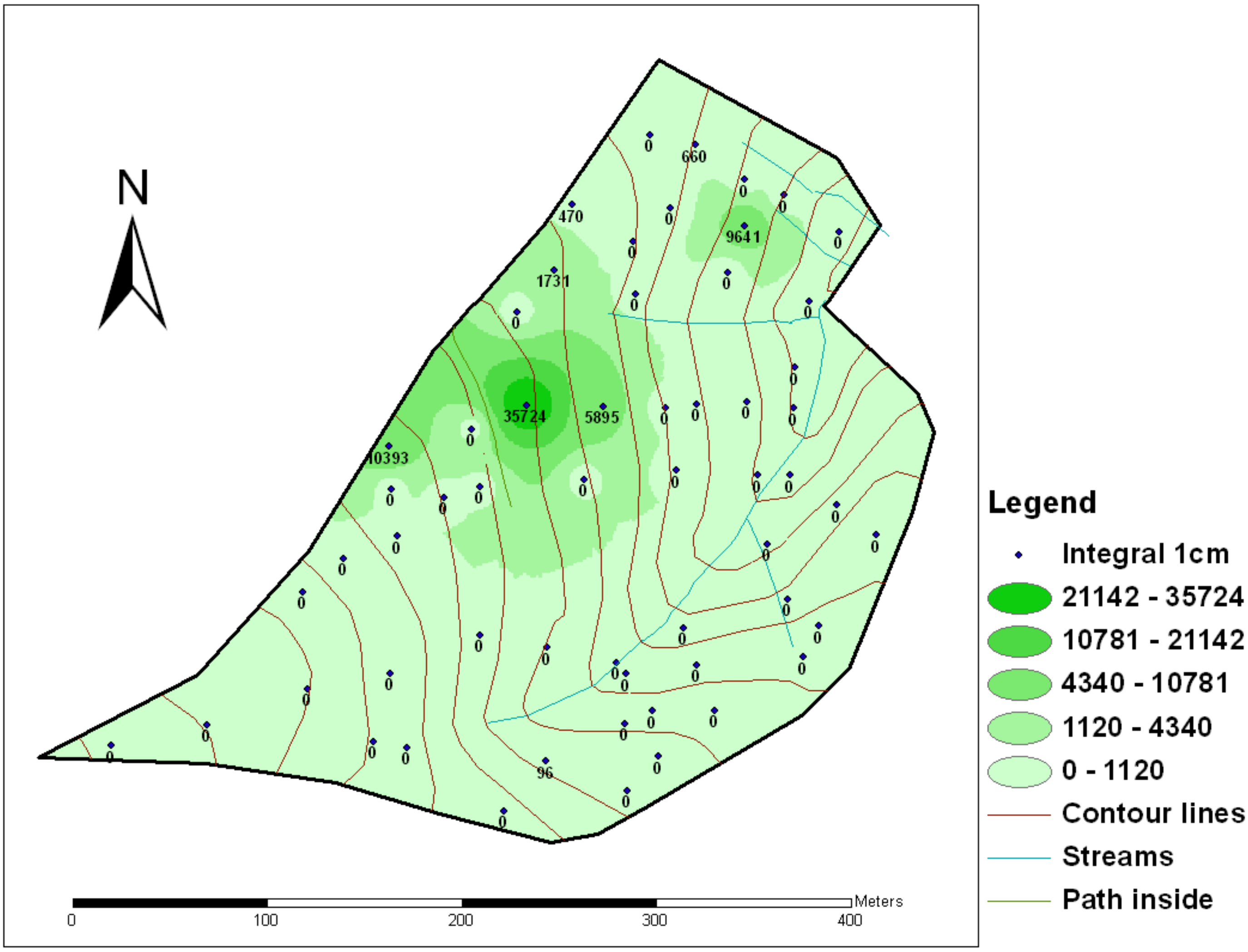

Figure 23 – Heat index (°C) above 30°C at 1cm depth

Values of all measurement points ranged between 0 and 35724°C with an average of 1175°C. This average is seven times smaller than at the surface, while the maximum is above half of the maximum at the surface (Fig. 21). The point at 1cm depth which recorded highest maximum temperature of 350°C (Fig. 3), is also highlighted here as a highest value.

At 1cm depth three quarters of all measurement points did not reach above the threshold of 30°C (Fig. 24).

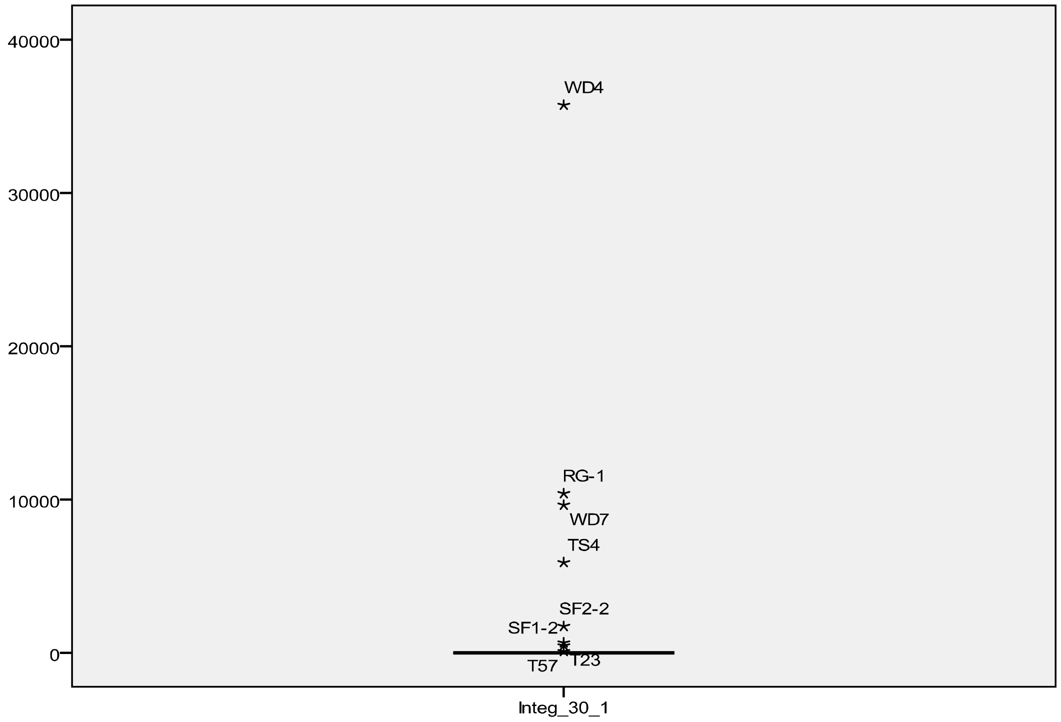

Figure 24 – Boxplot of heat index (°C) above 30°C at 1cm depth

One extreme outlier was found at the same measurement point where an extreme maximum temperature was recorded (Fig. 3).

At 3cm depth no temperatures above 30°C were recorded.

3.1.5. Heating velocity

Heating velocity was calculated as ΔT/Δt over the time span when thermocouples experienced rising temperature. In general high velocities at the surface (Fig. 25) were found at points where the maximum temperature was high (Fig. 1).

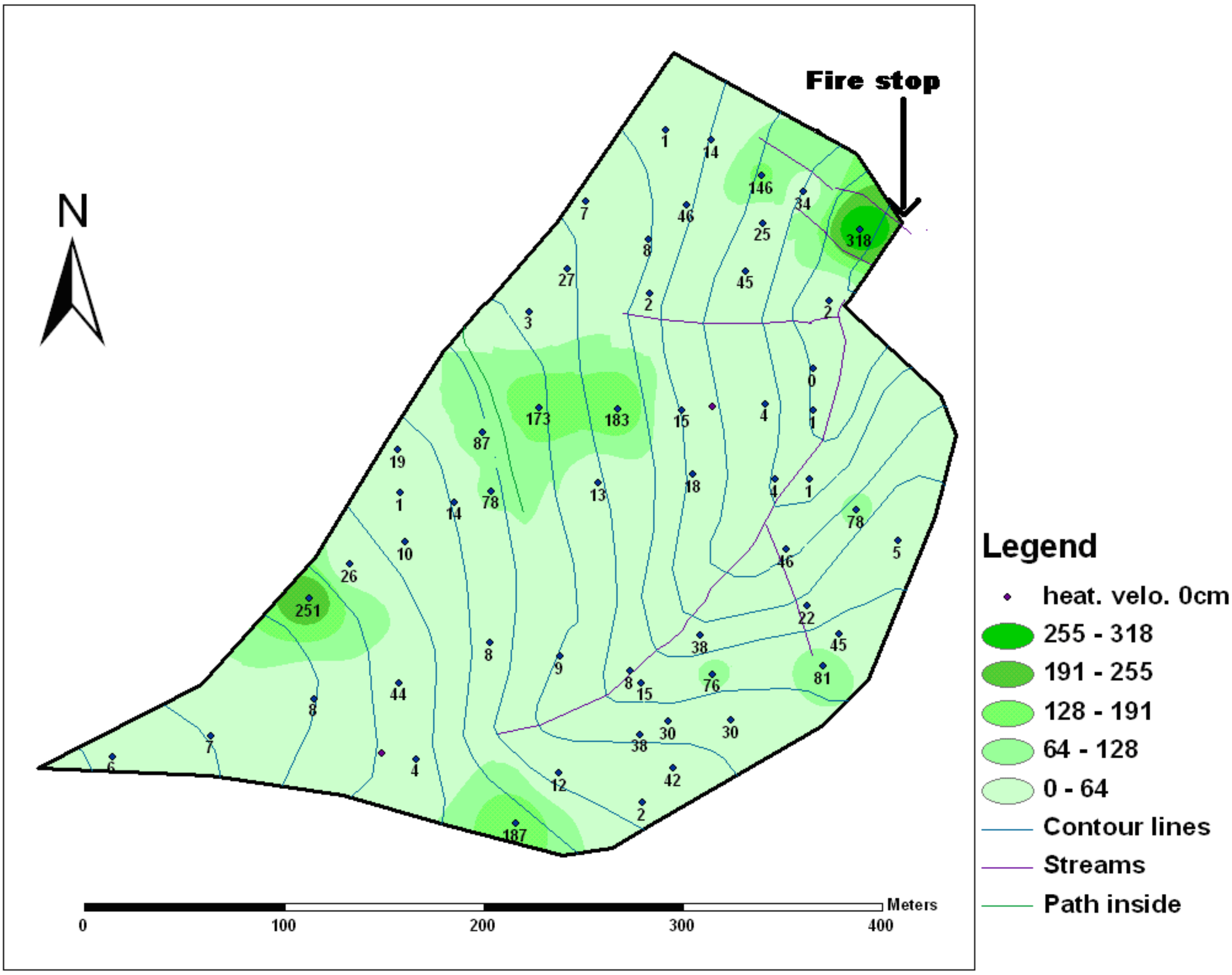

Figure 25 – Heating velocity at soil surface (°C / minute)

The highest heating velocity did not coincide with the highest maximum temperature, but with the highest heat index above 30°C (Fig. 21). Highest heating velocity, 318 degrees per minute, was reached where the experimental fire was stopped (see arrow Fig. 25); also the highest value for heat index above 30°C was found here (Fig. 21). Mean heating velocity of all measurement points was 43 degrees per minute. Missing values were caused by dysfunctional thermocouples.

The median in heating velocity at soil surface, 16 minutes and 36 seconds (Fig. 26), was lower than the mean as a consequence of outliers with high values.

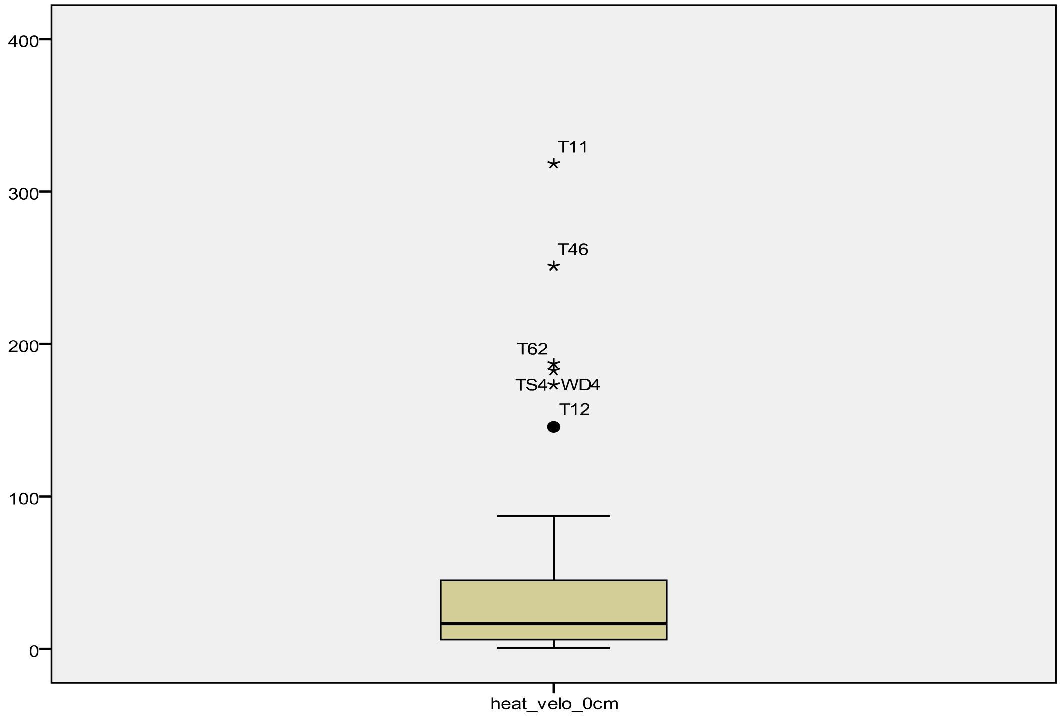

Figure 26 – Boxplot of heating velocity (°C / minute) at soil surface

The heating velocities were substantially lower at 1cm depth (Fig. 27), compared to soil surface (Fig. 25).

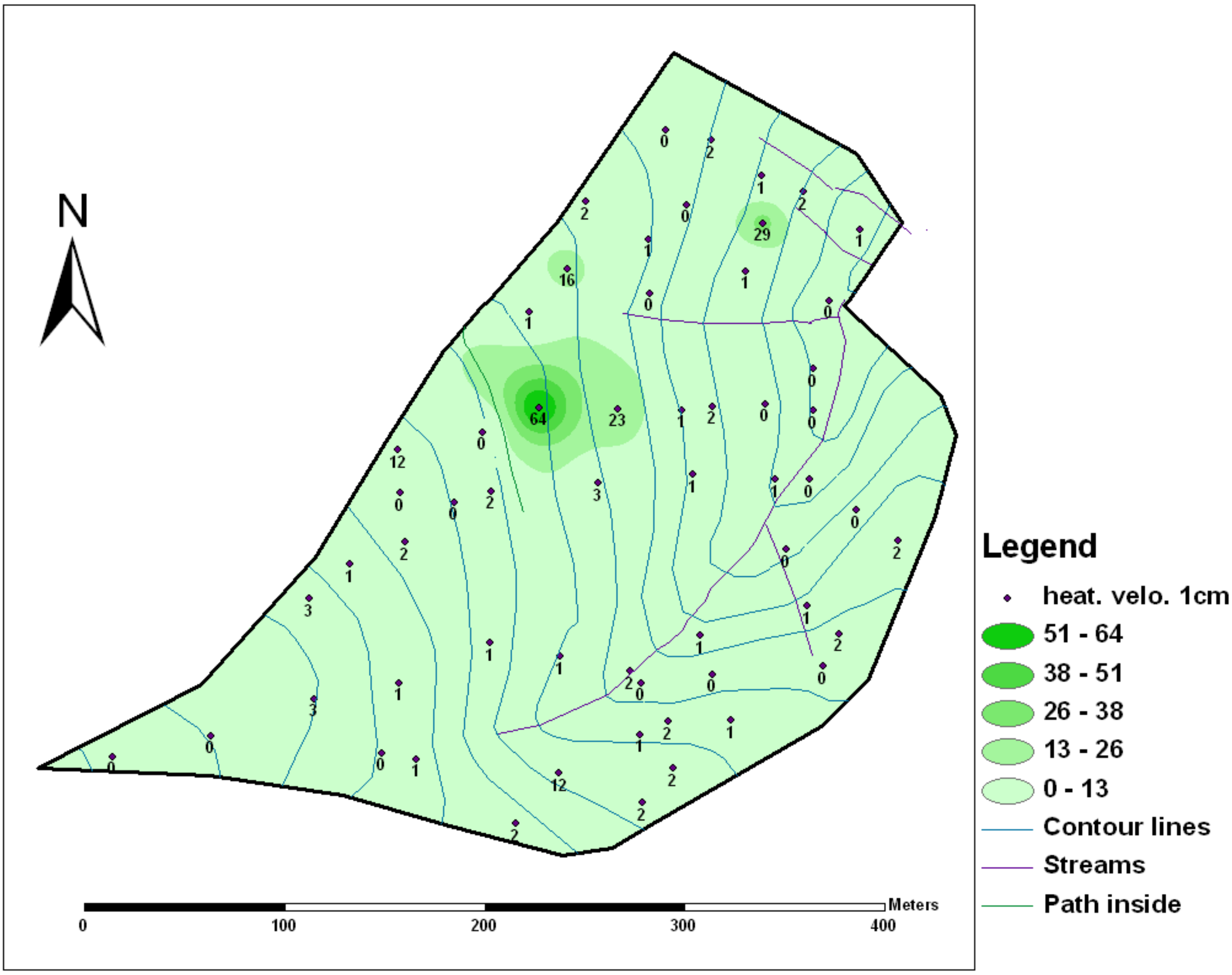

Figure 27 – Heating velocity at 1cm depth (°C / minute)

Average heating velocity at 1cm was 3.7 degrees per minute and that is almost twelve times lower than 43 degrees per minute at the surface. Maximum heating velocity of 63.8 degrees per minute was measured at the same point where highest maximum temperatures were found both at the surface (Fig. 1) and at 1cm depth (Fig. 3), but not at the point with maximum heating velocity at the surface (Fig. 25).

Also here in heating velocity at 1cm depth many measurement points had low values, half of them between 0 and 0.8 °C per minute (Fig. 28).

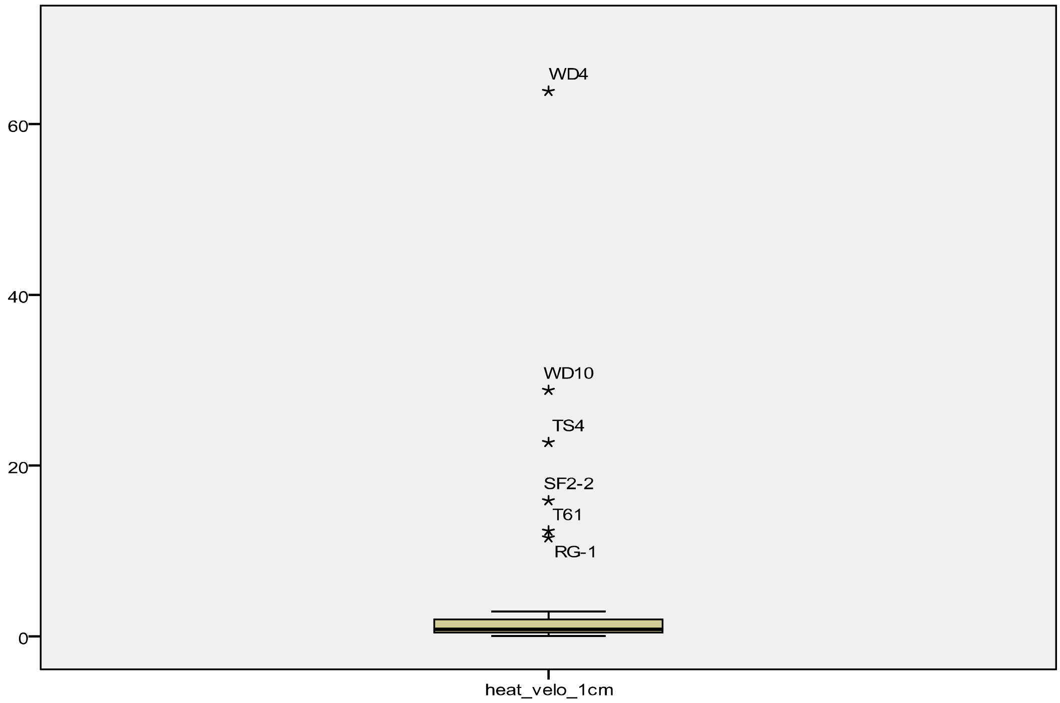

Figure 28 – Boxplot of heating velocity (°C \ minute) at 1cm depth

The measurement point with the highest value here also had the highest value in maximum temperature (Fig. 4), in heat index above 30°C (Fig. 24) and in time for which temperature exceeded threshold values.

At 3cm depth heating velocities were very low, on average 0.23 degrees per minute with a maximum of 2.3 degrees per minute. Highest heating velocity was not measured where the highest maximum temperature was found, compare figure 29 with figure 5.

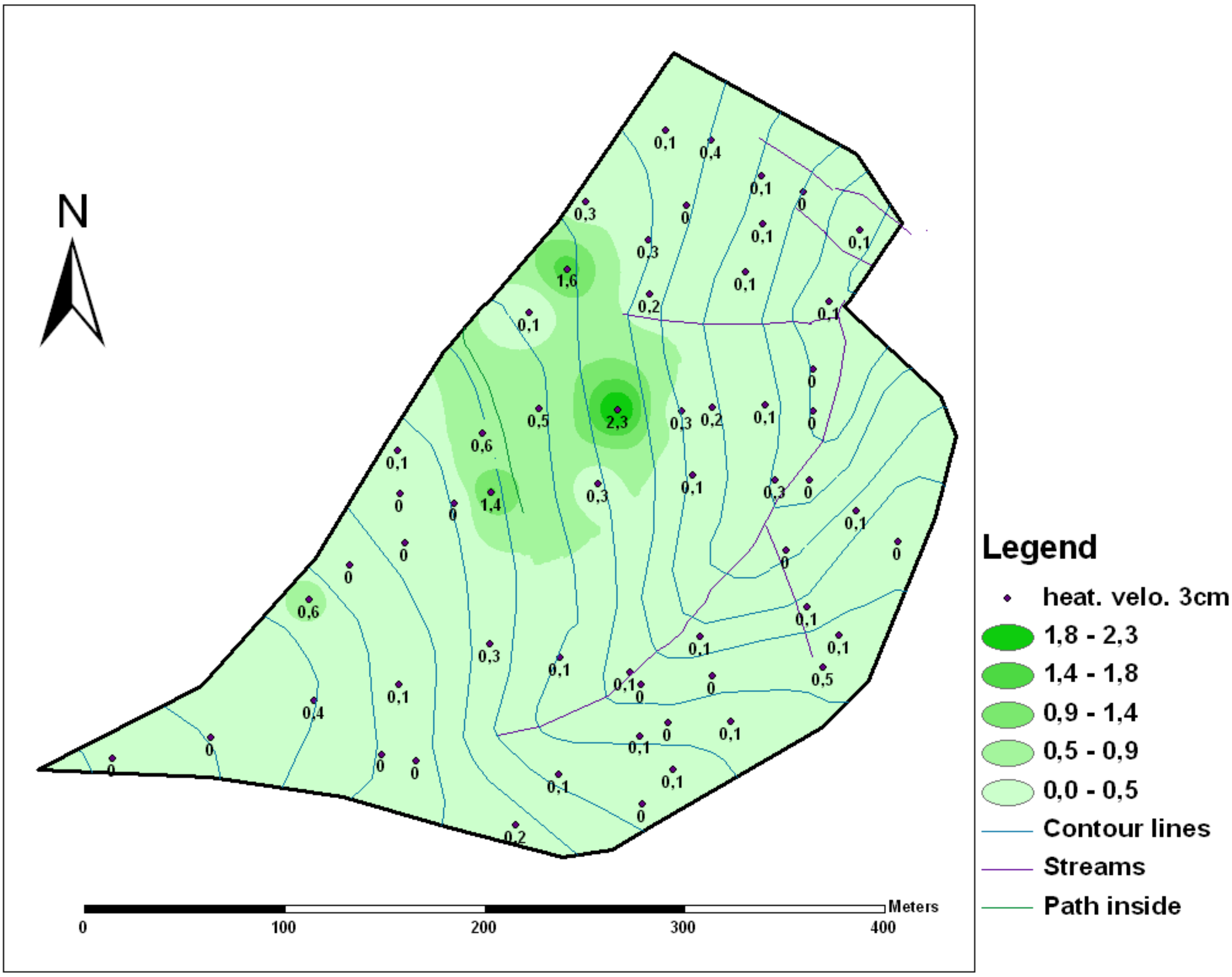

Figure 29 – Heating velocity at 3cm depth (°C / minute)

The range of heating velocity measurements at 3cm depth, with three outliers, is illustrated in figure 30.

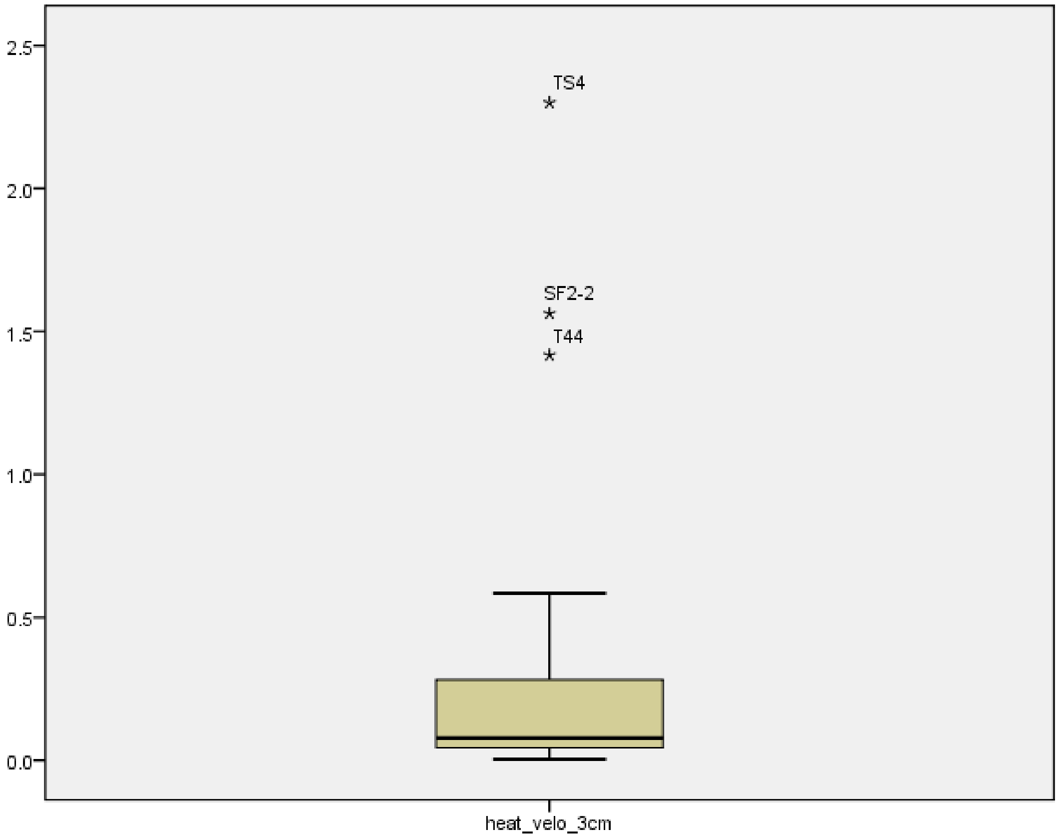

Figure 30 – Boxplot of heating velocity (°C / minute) at 3cm depth

Whether the mean or the median is considered, the value at 3cm depth is over ten times lower than the value at 1cm depth (Fig. 28).

3.1.6. Delay to heating propagation in soil depth

Since delay to heating propagation was defined as the time lag between heating started at the soil surface and at 1 or 3cm depth, this delay was zero by definition at the soil surface. Figure 31 presents the delay before heating started at 1cm depth.

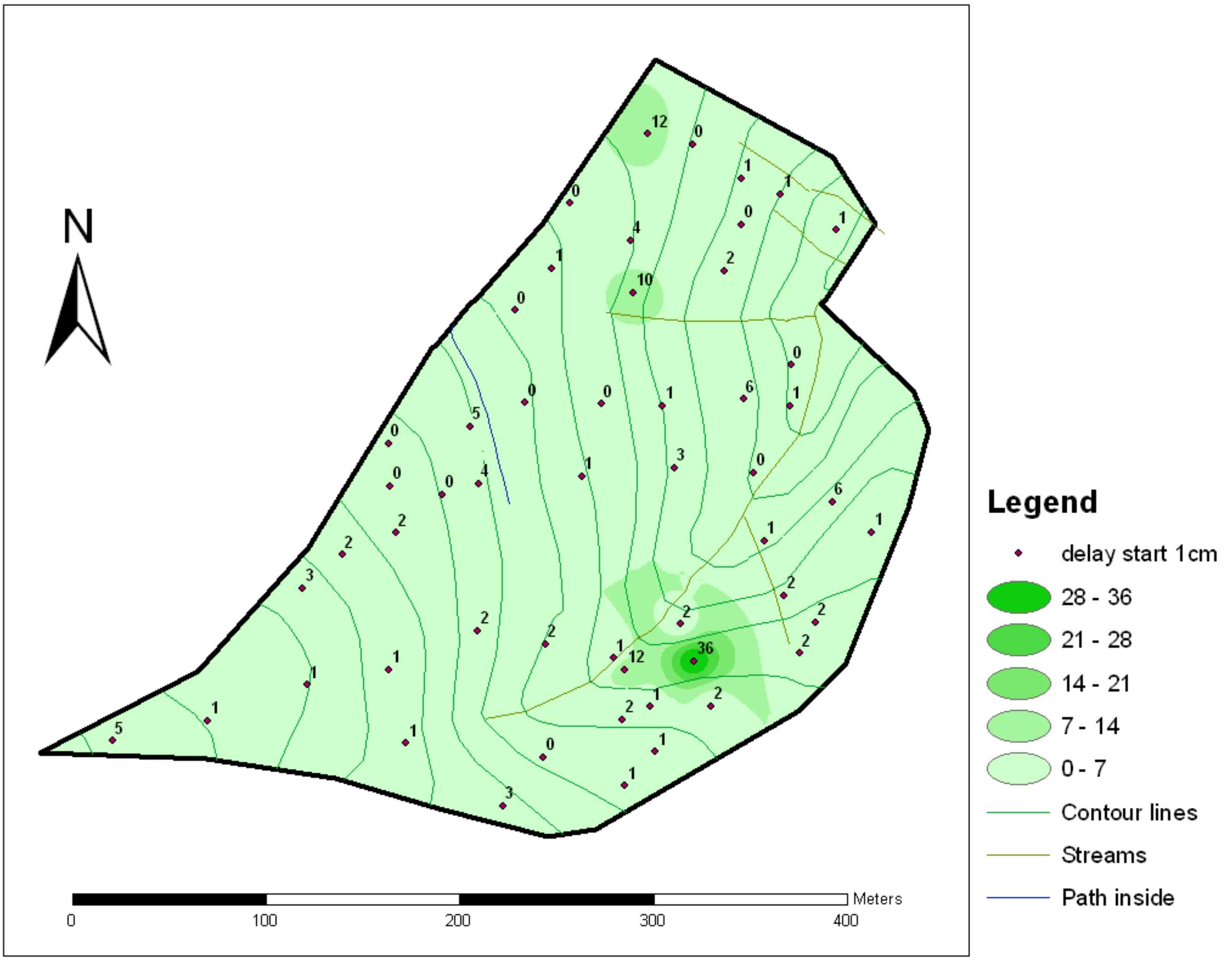

Figure 31 – Delay to heating propagation (minutes) at 1cm depth

Delay to heating propagation at 1cm depth ranged from 0 to 36 minutes, with on average 2 minutes and 51 seconds between the start of heating at the surface and at 1cm depth.

Maximum temperature at 1cm depth was recorded shortly after maximum temperature was recorded at the soil surface for most measurement points (Fig. 32). Few extremely high values could indicate that the fire did not influence soil temperature at these points.

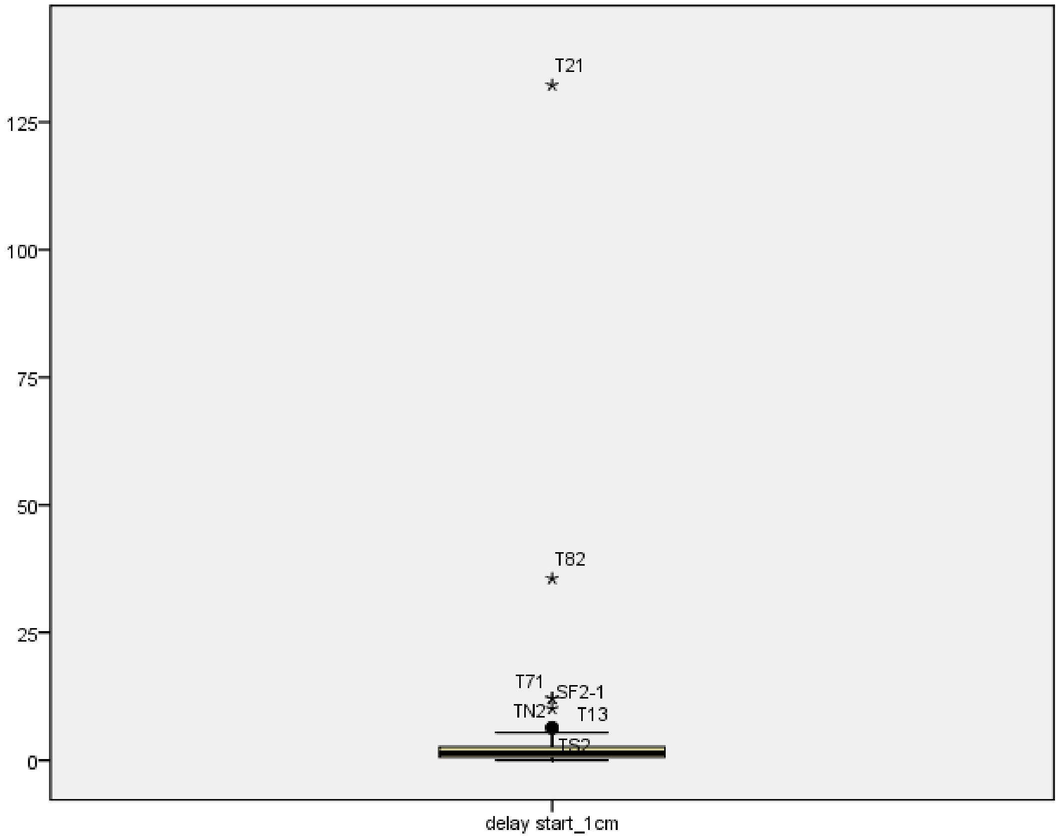

Figure 32 – Boxplot of delay to heating propagation (minutes) at 1cm depth

Figure 33 shows for all measurement points the delay before soil heating started at 3cm depth, referred to when soil heating started at the surface.

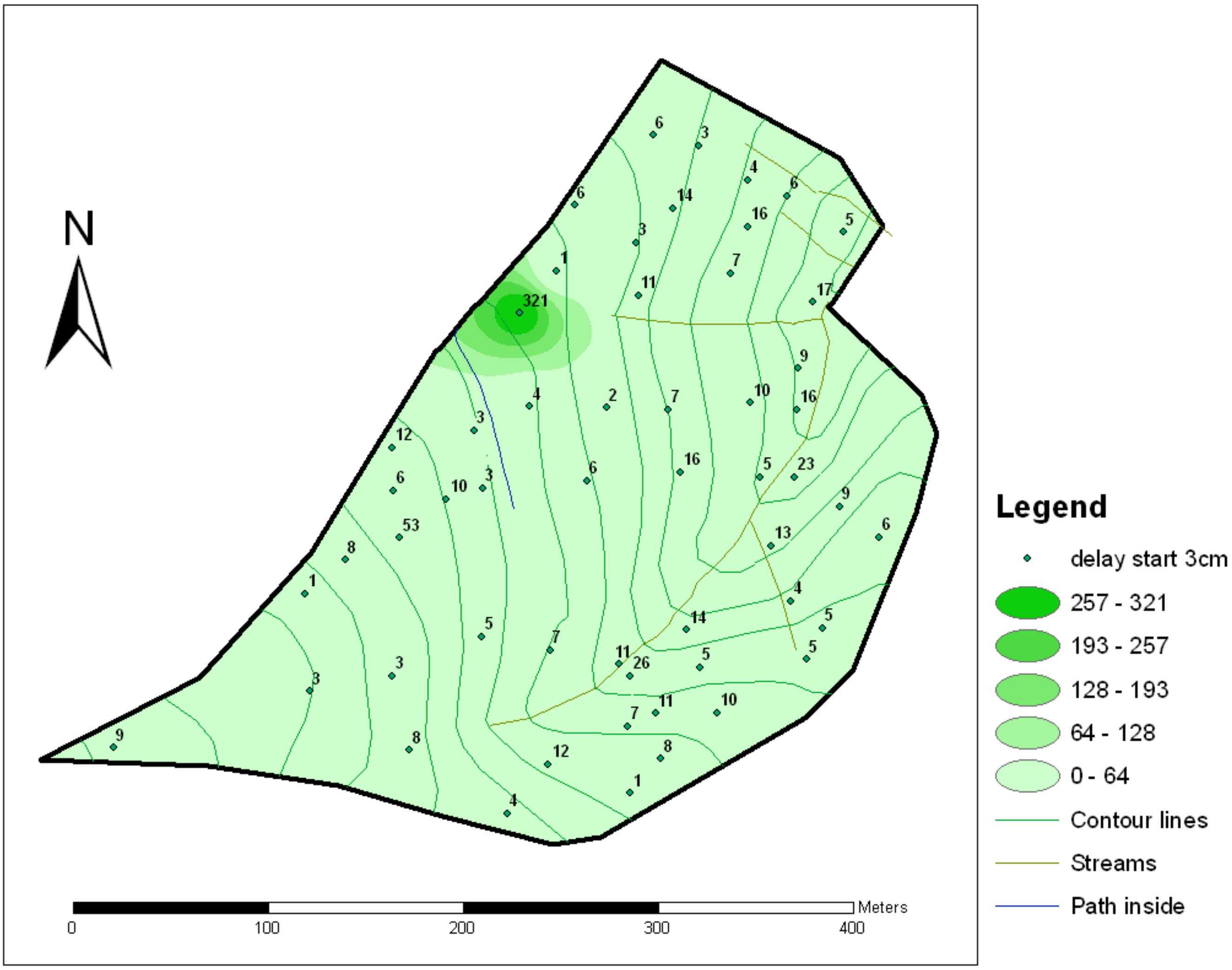

Figure 33 – Delay to heating propagation at 3cm depth (minutes)

At 3cm depth the delay to heating propagation ranged from 0 to 321 minutes with a mean of 14 minutes and 45 seconds. This average delay is over five times longer than at 1cm depth.

Variance in the delays before heating started at 3cm depth, referred to when heating started at the soil surface, is presented in figure 34.

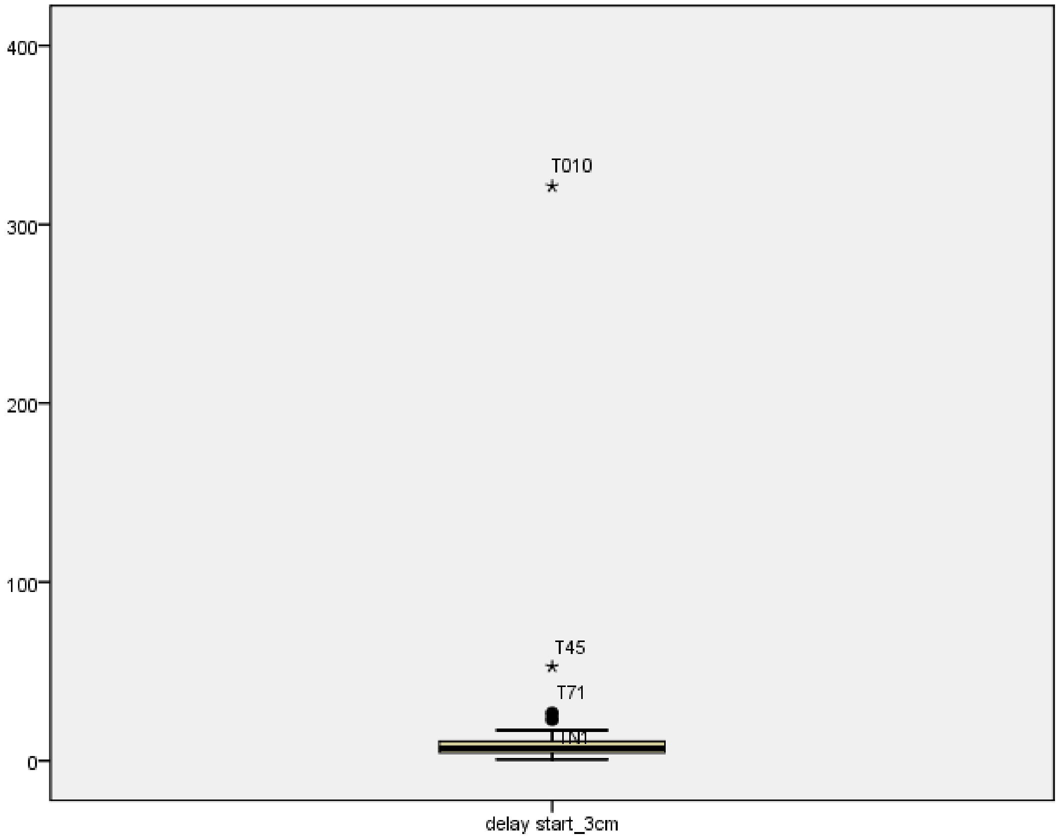

Figure 34 – Boxplot of delay to heating propagation (minutes) at 3cm depth

Both delays at 3cm (Fig. 10 and 34), referred to soil surface, show some extremely high values. On the other hand maximum temperature (Fig. 6) and heat index above 30°C do not show high values at 3cm depth, therefore temperatures at 3cm depth might not be influenced by the fire.

In figure 35 two values were artificially set to zero by deleting the two highest values from figure 33. Now the map (Fig. 35) is more in accordance with the results of other variables than figure 33. Largest delays are found in the lower part of the slope facing north, where maximum temperature was low (Fig. 5). High vegetation, at this north facing slope and in the main gully, might be the cause of large delays.

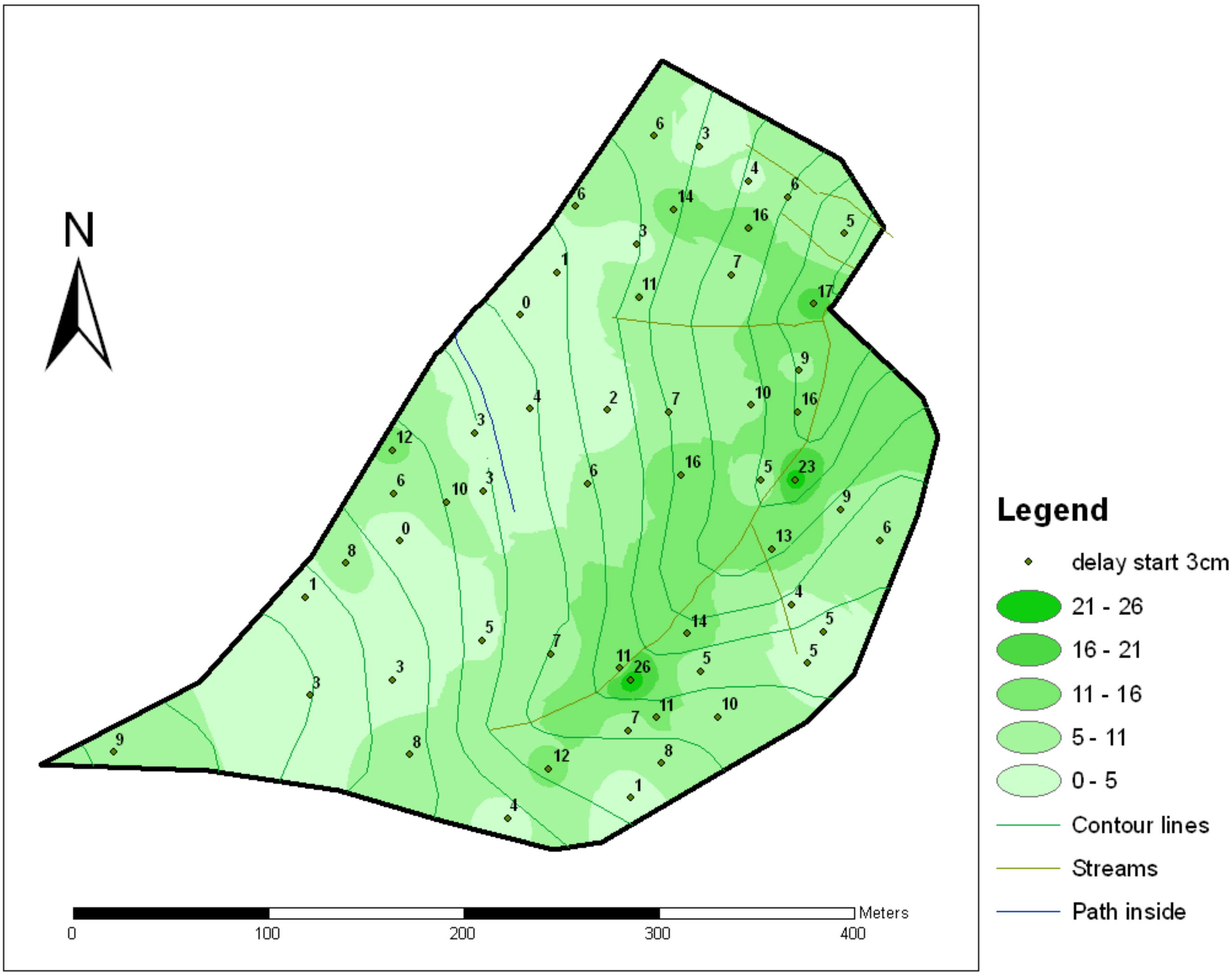

Figure 35 – Delay to heating propagation at 3cm depth (minutes); 2 highest values deleted

Large delays indicate that temperature measurements were not influenced by the fire, because the soil was warming up with the sunlight. Therefore deleting extremely high delays is permitted, unlike deleting high values of other data which were determined by heating from the fire. Comparing figure 35 with figure 33 shows that replacing the highest delay of 321 minutes by 0 definitely improved the map. As the 2nd highest delay was already a lot lower and therefore more in line with surrounding values, justification to replace this value (53 minutes) by 0 is less strong.

3.2. Potentially explaining factors

Three groups of different factors were identified that might influence the level to which soil temperatures are elevated when a fire is passing:

- Soil properties, which were measured in the topsoil (0-2.5cm)
    - Soil moisture
    - Organic matter
    - Bulk density
    - Stoniness
    - Rock cover at soil surface

- Vegetation / surface characteristics, factors in fuel load variability
    - Vegetation height
    - Soil depth
    - Surface cover by vegetation

- Topographical aspects
    - Altitude
    - Slope
    - Aspect of slope

3.2.1. Analysis of variance of potential explaining factors

In order to see how much variance in the temperature data measurements can be explained with the factors mentioned above, regression analysis was applied.

In this section the data distribution of all factors that were used as regressors are shown in a boxplot, additionally the range and mean value are given.

Soil properties

The values of soil moisture content ranged from 6.5% to 29.3% determined by volume (Fig. 36); with a mean of 13.4%.

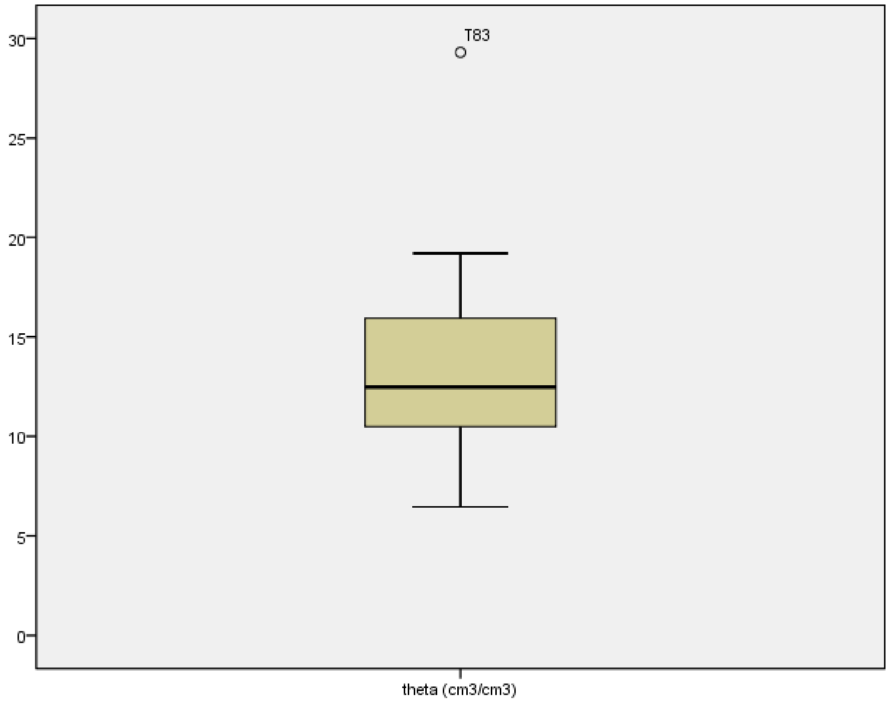

Figure 36 – Boxplot of soil moisture content (% by volume)

Soil organic matter ranged from 11.7 – 32.2% determined by weight (Fig. 38); with a mean of 20.0%

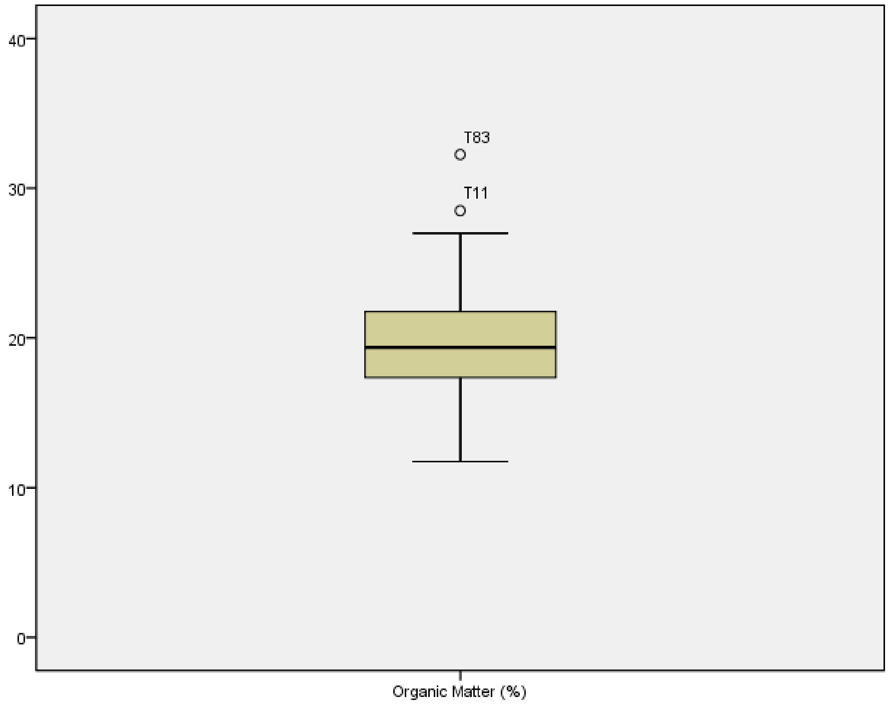

Figure 37 – Boxplot of soil organic matter content (% by mass)

Range of soil bulk density was 0.44 – 1.14 (g/cm^3) as presented in figure 38. Average bulk density was 0.80 (g/cm^3).

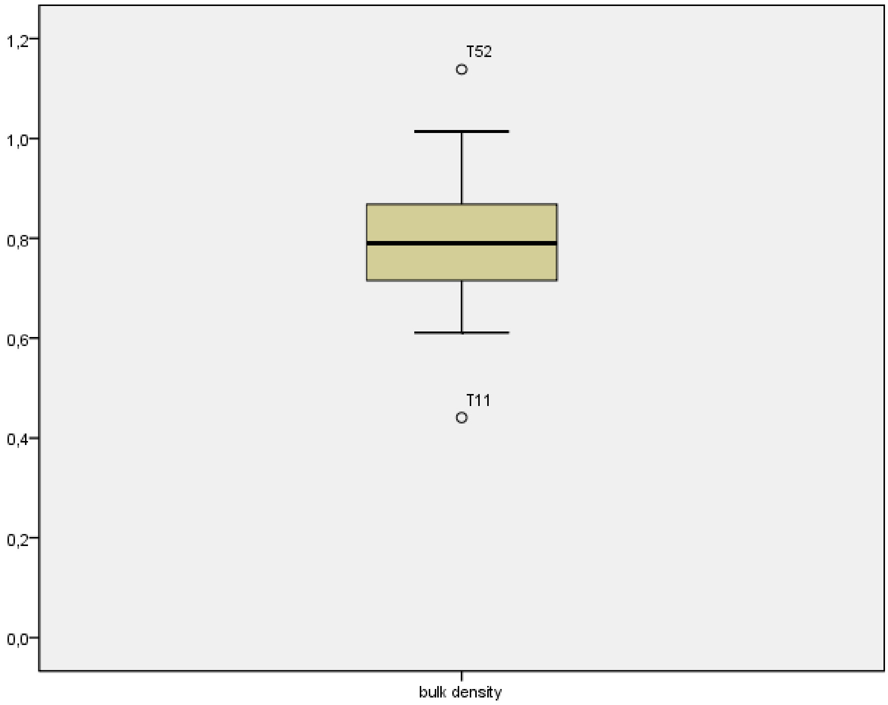

Figure 38 – Boxplot of bulk density of the soil (g/cm^3)

Range in stone volume as part of the soil volume was 4.2 – 31.7 % (Fig. 39), with a mean of 15.5%

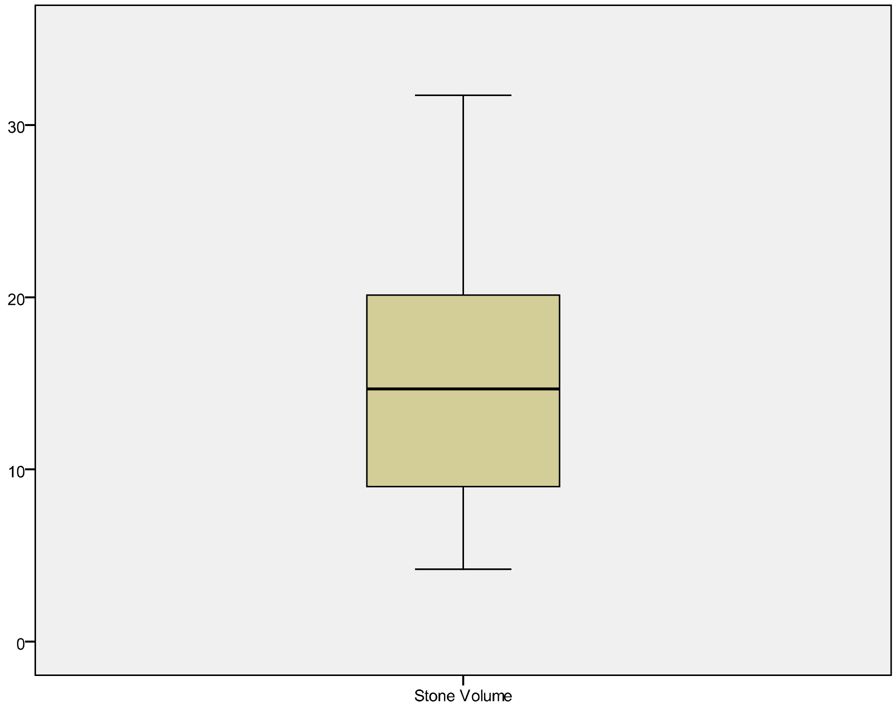

Figure 39 – Boxplot of stone volume in the soil (%)

Range in rock cover was 0 – 100 % (Fig. 40), with a mean of 31.2%.

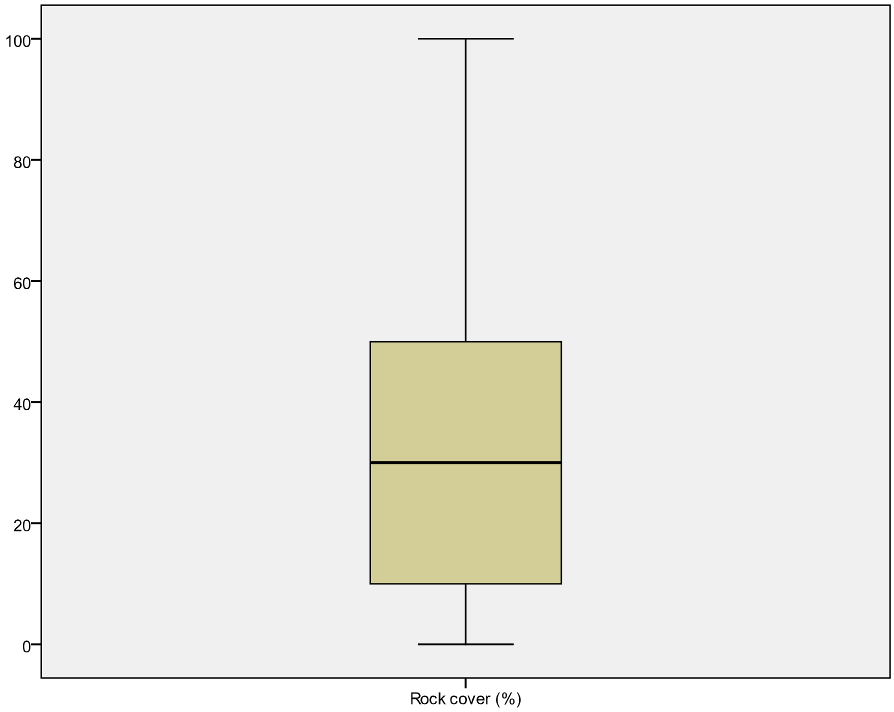

Figure 40 – Boxplot of soil surface covered by rock (%)

Vegetation characteristics

Range in vegetation height: 8–138cm (Fig. 41), with an average of 57.1cm.

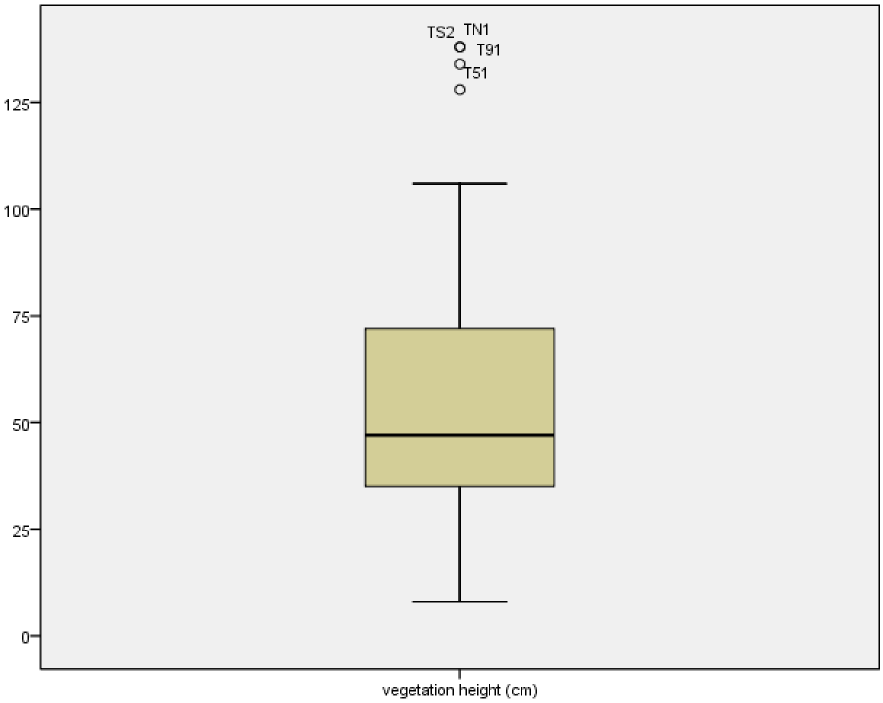

Figure 41 – Boxplot of vegetation height (cm)

Range in soil depth was 7 – 60cm (Fig. 42), with a mean of 25.0cm. Why the range stops at 60cm is artificial because measurements could not go deeper.

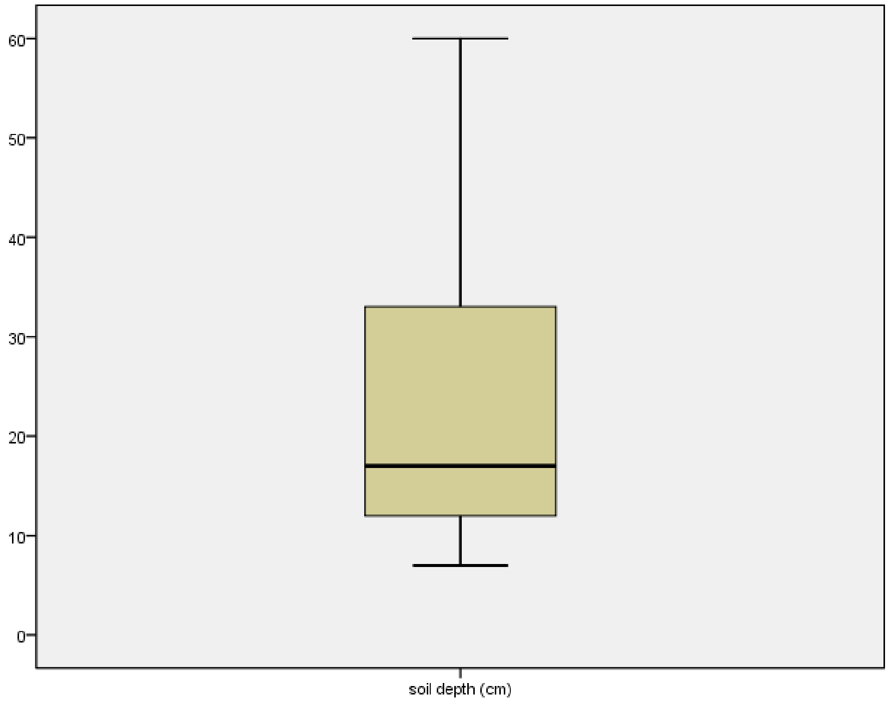

Figure 42 – Boxplot of soil depth (cm)

Range in surface cover by vegetation was 40 – 100 %. (Fig. 43). Mean value for the fraction of soil surface covered by vegetation was 82.6%.

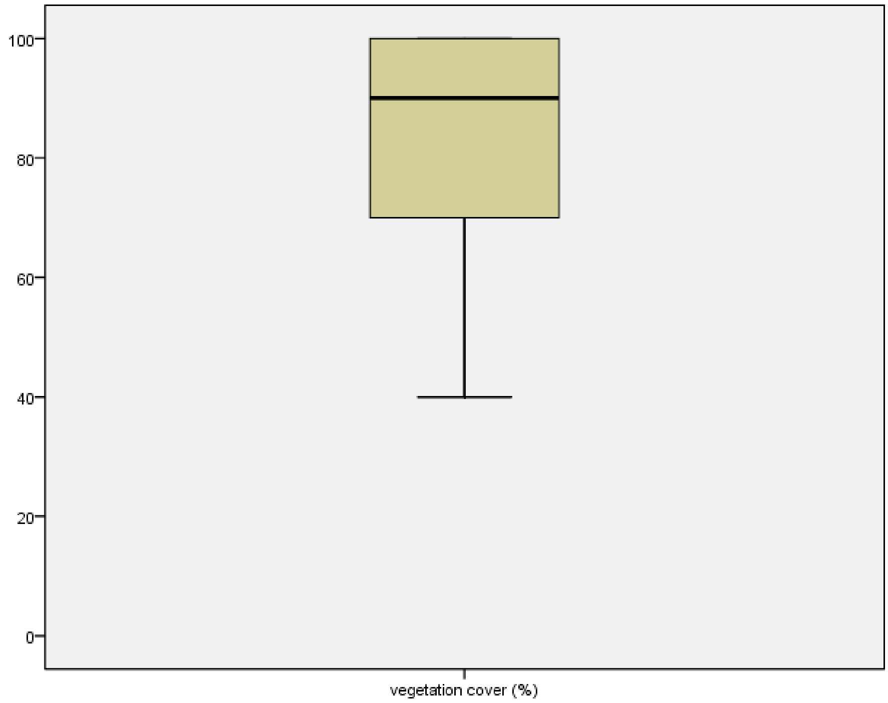

Figure 43– Boxplot of soil surface covered by vegetation (%)

Topographical aspects

Variance in slope (%) is presented in figure 44; the range is 15.0 – 57.4 % with an average of 37.7%

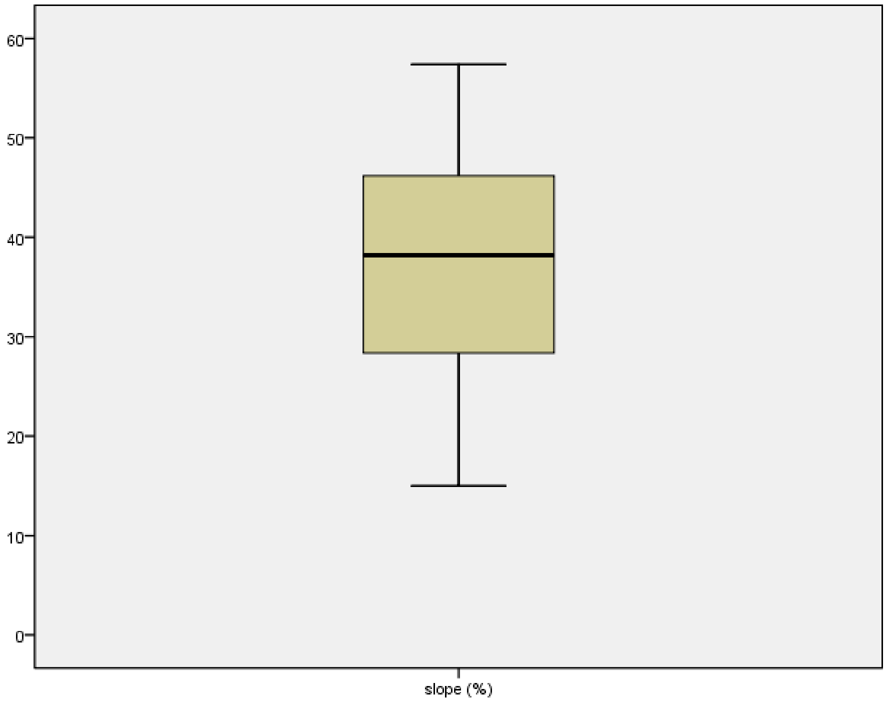

Figure 44 – Boxplot of slope (%)

Variance in altitude of the measurement points ranges from 613 – 747.9 metres (Fig. 45); the average is 670.1metre.

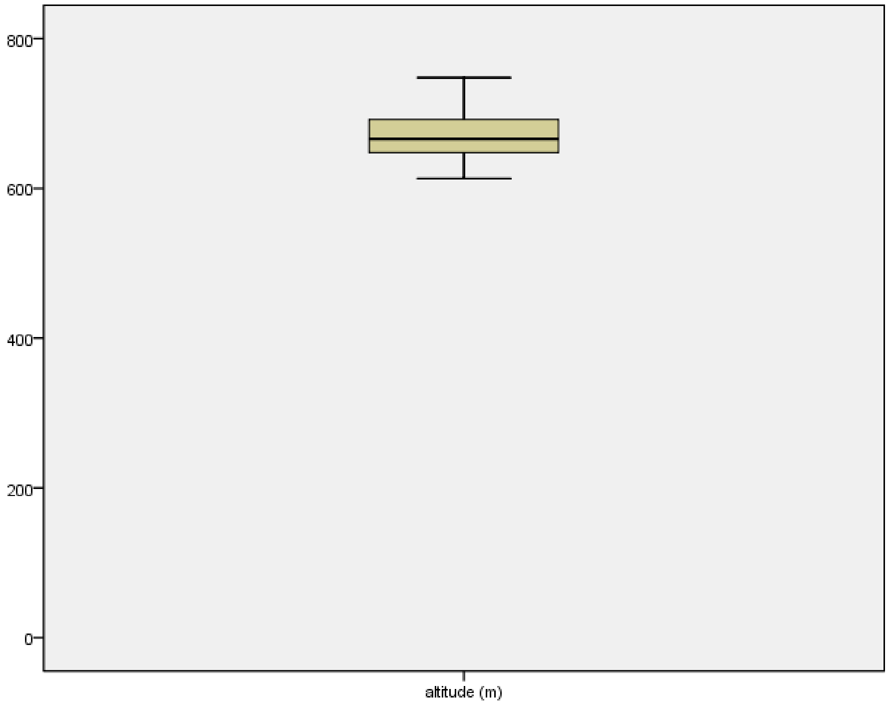

Figure 45 – Boxplot of altitude (m)

The variance in aspect of slope of the measurement points is presented in figure 46.

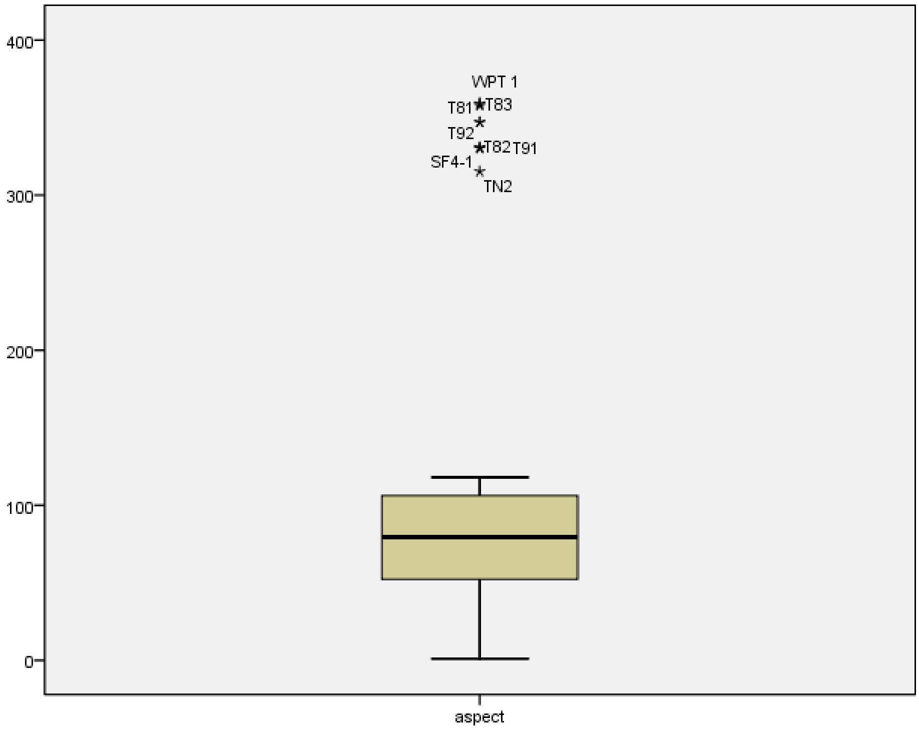

Figure 46 - Boxplot of aspect of slope (degrees)

Aspect of slope showed typical values because all measurement points were placed at two slopes. The range is 1.1 – 359°; mean is 111.6 and a high number of outliers (8) had high values.

3.3. Simple regression analysis

By simple linear regression analysis some correlations were found between the potentially explaining factors mentioned above and the soil temperature data which were measured at the surface, and at 1cm and 3cm soil depth.

3.3.1. Soil properties

Five variables were distilled out of the temperature measurements by thermocouples: maximum temperature, heating velocity, heat index above 30°C, if temperature thresholds (40°C, 60°C, 100°C, 175°C) were exceeded, delay before heating propagation and delay before maximum temperature. Variability in the data of these five variables is expected to be related with the soil properties mentioned before (§ 3.2). From testing temperature data at all measurement points at the surface, 1cm depth and 3cm depth against the five soil characteristics: moisture content, organic matter content, bulk density, stoniness and rock cover; a few significant ($p < 0.1$) relations were found. Organic matter content showed a relation with maximum temperatures at 3cm depth, with a P-value of 0.087 and an R^2 of 0.075 (Table 1). This means that 7.5% of the variance in maximum temperatures at 3cm depth could be explained by the variance in organic matter content. A relatively high P-value, close to 0.1, suggests that this correlation is not very strong.

Table 1 – Correlation with organic matter content

	Regressor	Sign C.C. (+/-)	P-value	R^2
Maximum temperature at 3cm depth (℃)	A	-	0,087	0 ,075

Soil organic material is a very vulnerable fraction of the soil related to fire, it is combusted at relatively low temperatures of 200-460°C (Giovannini, 1994; Neary *et al.*, 1999) while substantial loss of organic matter can start at lower temperatures (DeBano *et al.*, 1998 cited in (Neary *et al.*, 1999)). Therefore a relation between organic matter content and maximum temperature might be expected. However, maximum temperatures measured at 3cm depth (Fig. 5) were too low to be caused by combustion. Also the correlation coefficient (C.C. in Table 1) is negative , so predicted maximum temperatures go down when organic matter content increases (Fig. 47), while burning organic matter as part of the soil is expected to increase temperatures.

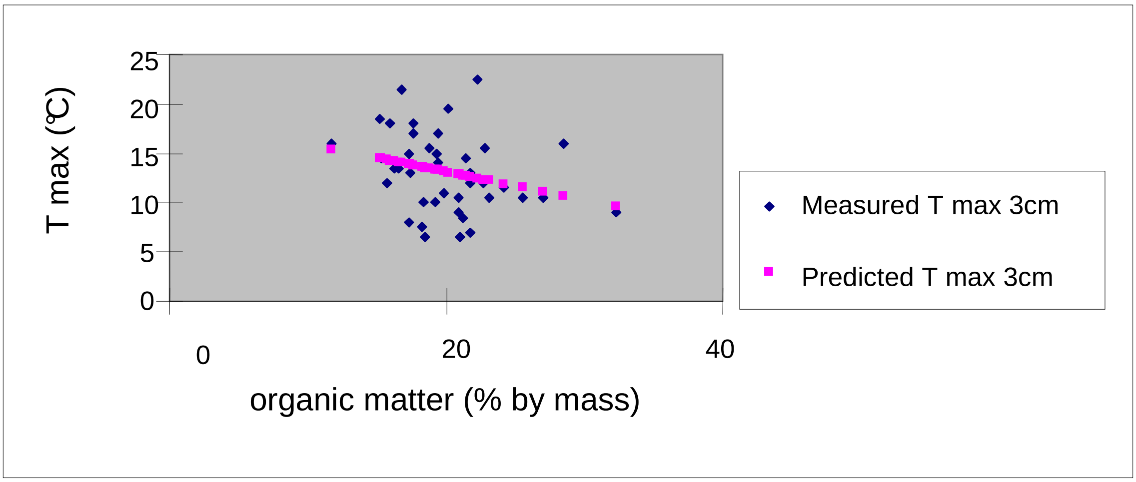

Figure 47 – plot of organic matter content *versus* maximum temperature at 3cm depth

With soil moisture content as dependent variable two regressors had correlations which could be considered significant (Table 2).

Table 2 – Correlation with moisture content

	Regressor	Sign C.C. (+/-)	P-value	R^2
Heat index > 30℃ at the surface (℃)	B	-	0,081	0,0 78
Maximum temperature at 1cm depth (℃)	C	-	0,076	0,0 69

Soil moisture content was correlated negatively with the heat index above 30°C at soil surface and with maximum temperature at 1cm depth (Table 2). As soil moisture reduces maximum temperature (Campbell *et al.*, 1995) by increasing heat capacity, negative correlations were expected. On the other hand soil moisture increases thermal conductivity (Aston and Gill, 1976; Janssen *et al.*, 2004; Heinemann, 2008), so soil heating was expected to go deeper in wet soil compared to dry soil. Probably the contradicting effects of soil moisture on heat capacity and thermal conductivity explain why no more significant correlations were found.

Rock cover, estimated before the fire, was also tested as regressor in the five variables related to soil heating. Results are presented in table 3.

Table 3 – Correlation with rock cover

	Regressor	Sign C.C. (+/-)	P-value	R^2
T > 40℃ at the surface (yes / no)	D	+	0,029	0,120
Delay maximum T at 1cm depth (minutes)	E	-	0,083	0,081
Maximum temperature at 3cm depth (℃)	F	+	0,012	0, 153

As time is not recognized in regression analysis the variables “time for which temperature thresholds were exceeded” were transformed into binary variables “if temperature thresholds were exceeded” (yes / no).

Rock cover had highly significant ($p < 0.05$ (Table 3)) correlation with “If surface temperature exceeded 40°C” and with maximum temperature at 3cm depth. The correlation coefficient with maximum temperature at 3cm depth was positive, so more soil covered by rocks would mean higher temperatures at 3cm depth. This indicates again that soil temperatures at 3cm depth were not determined by the fire, as rock cover decreases soil heating (Stoof *et al.*, in preparation). This highly significant correlation might have been caused by the fact that maximum temperature at 3cm depth was distributed statistically normal with a relatively small range (Fig. 6).

If more rock cover leads to more soil heating, as all three correlations above suggest (Table 3), it might be because less vegetation grows at sites with large part of the surface covered by rocks. Visual observations shortly before the fire said that the lower part of relatively high and dense vegetation, especially at the north facing slope, was wet when the fire was done. Therefore the sites with lower and less dense vegetation, and more rock cover at the surface, were more dry before the fire and consequently experienced more soil heating.

No other significant correlations ($p < 0.1$) were found between temperature data on one side and soil properties on the other side.

3.3.2. Vegetation characteristics

Fraction of surface cover by vegetation was estimated at the same spots where temperature was measured under the fire. Cover by vegetation was tested against maximum temperatures and derived measurements, three significant correlations ($0.05 < p < 0.1$) were found (Table 4).

Table 4 – Correlations with vegetation cover

	Regressor	Sign C.C.(+/-)	P-value	R^2

T > 175℃ at the surface (yes / no)	G	-	0,099	0,059
Heat index > 30℃ at the surface (℃)	H	-	0,076	0,0 68
Heating velocity at 3cm depth (℃ / minute)	I	-	0,0 79	0,055

Vegetation cover on the surface had weak negative correlations with three temperature variables (Table 4). Because not all cover is eliminated by the fire, a high fraction of the soil surface covered will restrict heating of the soil itself.

Soil depth was measured at five points in close range (maximum 2 meters) from the measurement points where soil temperature was measured beneath the fire. At all measurement sites the soil was deeper than 3cm; minimum soil depth was 7cm (Fig. 42). Average soil depth per measurement point was also used as regressor. Results show five correlations (Table 5) between soil depth and temperature related variables.

Table 5 – Correlations with soil depth

	Regressor	Sign C.C.(+/-)	P-value	R^2
T > 40 ℃ at the surface (yes / no)	J	-	0,013	0,124
T > 60 ℃ at the surface (yes / no)	K	-	0,024	0,104
T > 100 ℃ at the surface (yes / no)	L	-	0,087	0,06 1
Maximum temperature at 3cm depth (℃)	M	-	0,004	0, 161
Heating velocity at 3cm depth (℃ / minute)	N	-	0,0 75	0,066

As these five correlations had negative coefficients, they suggest that deeper soil decreases soil heating. This effect might come via vegetation height, which was very highly significant ($p < 0.000$), positively correlated with soil depth. Soil heating is lower when the vegetation, before the fire, was higher.

Vegetation height was also measured at five points in close range (maximum 2 meters) from the measurement points and averaged. Results of regression analysis show significant correlations between vegetation height and the soil temperatures related data (Table 6).

Table 6 – Correlations with vegetation height

	Regressor	Sign C.C.(+/-)	P-value	R^2
Maximum temperature at the surface (℃)	O	-	0,054	0,082
Heat index > 30℃ at the surface (℃)	P	-	0,028	0,0 97
T > 40℃ at the surface (yes / no)	Q	-	0,054	0,082
T > 60℃ at the surface (yes / no)	R	-	0,058	0,079
T > 100℃ at the surface (yes / no)	S	-	0,041	0,092
T > 175℃ at the surface (yes / no)	T	-	0,036	0,090
Delay maximum T at 1cm depth (minutes)	U	+	0,009	0,146
Maximum temperature at 3cm depth (℃)	V	-	0,000	0, 309
Heating velocity at 3cm depth (℃ / minute)	W	-	0,0 63	0,072

Vegetation height was most useful as regressor, as it showed significant correlation with nine temperature data variables (Table 6). From these nine correlations eight had a negative coefficient, only the delay before maximum temperature at 1cm depth was positively correlated. The negative correlations are in accordance with the five correlations found with soil depth (Table 5) and with the correlations found with vegetation cover (Table 4). As mentioned above (§3.3.1) the lower part of high and dense vegetation was wet when the fire was conducted, and therefore mitigated fire effects on soil heating. High vegetation comes with deep soil, and restricts soil heating because it was partly wet.

Strongest relation was found between vegetation height and maximum temperature at 3cm depth. This relation might have been strong because maximum temperature at 3cm depth was distributed in a statistically normal way (Fig. 6).

3.3.3. Topographical characteristics

Altitude, slope and aspect of slope at the measurement points were also available and tested for their value in explaining maximum temperatures and the temperature related data. Four significant correlations were found, two with slope as independent variable (Table 7),

Table 7 – Correlations with slope

	regressor	Sign. C.C.(+/-)	P-value	R^2
T > 40℃ at the surface (yes / no)	X	+	0,012	0,163
Delay maximum T at 1cm depth (minutes)	Y	+	0,045	0,107

and two with aspect of slope as independent variable (Table 8).

Table 8 – Correlations with aspect of slope

	regressor	Sign. C.C.(+/-)	P-value	R^2
Maximum temperature at 3cm depth (℃)	Z	-	0,004	0,153
Delay maximum T at 1cm depth (minutes)	Ç	+	0,002	0,170

Slope (Table 7) and aspect of slope (Table 8) both were significantly correlated with two temperature data variables. Slope correlated positively with delay before maximum temperature was reached at 1cm depth, and also positively with if surface temperature exceeded 40°C. This is strange because high surface temperature is not expected to slow down heating at 1cm depth. Probably the binary variable (yes / no) if surface temperature exceeded 40°C does not have enough meaning to distinguish differences in slope. A steep slope means the fire travels slowly because it is applied downhill, while fire naturally tends to travel uphill. In this way it is logical that heating in the soil is delayed, referred to heating at the surface. Aspect of slope probably had some explaining power as it seems to split off a group of eight measurement points facing north-north-west which supported rather high vegetation. Support for this explanation is found by correlation between aspect of slope and vegetation height ($p < 0.01$).

Altitude as independent variable did not give any significant correlations; apparently soil heating was not related to the altitude of the measurement sites. Because the higher parts of the catchment were burned with lower intensity than the lower parts, we expected to find a difference related to altitude. As the difference in fire intensity did not show in the spatial pattern of soil temperatures, it is to be understood that no correlation was found with altitude.

3.4. Multiple Regressions

After exploring relations between temperature data as dependent variables and land characteristics as regressors by simple linear regression, characteristics which had significant explaining value in the same type of temperature data were tested by multiple regressions in order to see if their combination had a higher correlation with the same type of temperature data. A combination of regressors which individually correlated with the dependent variable needs to be tested to know if the regressors were sufficiently independent. If regressors are not sufficiently independent, their explaining powers in the dependent variable overlap and the combination will not be significant.

With maximum temperatures at 3cm depth as dependent variable, several regressors were tested significant, and four combinations could be considered significant. Soil depth and organic matter content, regressors M and A (Tables 1 and 5), yielded an R^2 of 0.238 ($p < 0.008$, $p < 0.044$ respectively). Highest explaining power (an R^2 of 0.412) in maximum temperatures at 3cm depth was found by a combination of the regressors vegetation height (V, Table 6) and organic matter content (A, Table 1), with $p < 0.000$ and $p < 0.056$ respectively.

In heating velocity at 3cm depth three individual regressors with P-values between 0.05 and 0.1 were identified, regressors: vegetation cover (I), soil depth (N) and vegetation height (W) (Tables 4, 5 and 6), but no combination of these regressors was tested to be significant. Highest explaining power in heating velocity at 3cm depth was an R^2 of 0.072 with vegetation height (W) as regressor (Table 6).

Dependent variable “if surface temperature exceeded 40°C” had four significant individual regressors: rock cover (D), soil depth (J), vegetation height (Q) and slope (X). The combination of regressors J and X yielded the highest R^2 of 0.246, with $p < 0.001$ and $p < 0.010$ respectively.

Four significant individual regressors were identified also with “delay before maximum temperature at 1cm depth” as dependent variable: rock cover (E), vegetation height (S), slope (Y) and aspect of slope (Ç). Highest R^2 of 0.229 was found by combining slope (Y) and aspect of slope (Ç), with $p < 0.005$ and $p < 0.057$ respectively.

Another four different dependent variables were correlated with two regressors each. Heat index above 30°C at the soil surface was correlated with regressors H (surface cover by vegetation, see Table 4) and P (vegetation height, see Table 6). If surface temperatures exceeded 60°C was correlated with regressors K (soil depth, see Table 5) and R (vegetation height, see Table 6). If surface temperatures exceeded 100°C was correlated with regressors L (soil depth, see Table 5) and S (vegetation height, see Table 6). If surface temperatures exceeded 175°C was correlated with regressors G (surface cover by vegetation, see Table 4) and T (vegetation height, see Table 6). None of these four combinations was tested significant.

3.5. Correlate maximum temperature in depth

As expected it is easier to explain temperatures in the soil, at 1cm or 3cm depth, when temperature data at the soil surface are used as regressors. Variability in surface temperature data was very large, which makes it difficult to find any factors with strong correlation to explain the temperature measurements at the surface. Nevertheless this data can still be used to explain part of the variance in temperature data below the surface.

When maximum temperature at 1cm depth was tested against temperature variables at the surface strong correlations were found (Table 9).

Table 9 – Correlations with maximum temperature at 1cm depth

	regressor	Sign. C.C.(+/-)	P-value	R^2
Maximum temperature at the surface (℃)	α	+	0,000	0,421
Heat index > 30℃ at the surface (℃)	β	+	0,001	0,207
Heating velocity at the surface (℃ / minute)	γ	-	0,036	0,083
T > 175℃ at the surface (yes/no)	δ	-	0,010	0,123
T > 100℃ at the surface (yes/no)	ε	+	0,037	0,082
T > 60℃ at the surface (yes/no)	ω	+	0,087	0,056

With multiple regressions a combination of several independent regressors are tested for their explaining value in one dependent factor. Combining regressors α, γ, δ and ω (Table 9) in multiple regression resulted in an R^2 of 0.90, so almost all variance (90%) in maximum temperatures at 1cm depth could be explained with surface temperature data. Highest P-value in this combination was 0.053 with regressor ω. Considering the coefficients the results are odd, as coefficients with α and ω (Table 9) are positive, while γ and δ were negatively correlated with maximum temperatures at 1cm depth. Regressors β and ε were not significant in combination with the other regressors, because they do not have additional explaining power. From the original regressors (Tables 1 to 8) only soil moisture content had some explaining power in maximum temperatures at 1cm depth (Table 2). But soil moisture content limited the possibilities in multiple regressions, because it was not measured at all measurement points. Moisture content as additional regressor in the combination mentioned above did not result in significant multiple regression with maximum temperature at 1cm depth.

Maximum temperatures at 3cm depth also showed variance which could be partially explained, by maximum temperatures and derived parameters at the surface. But R^2 does not get anywhere near as high as 0.90 as was found in maximum temperature at 1cm depth as dependent variable. All significant individual regressors in maximum temperature at 3cm depth are listed in table 10.

Table 10 – Correlations with maximum temperature at 3cm depth

	Regressor	Sign C.C.(+/-)	P-value	R^2
Maximum temperature at the surface (℃)	a	+	0,079	0,059

Heat index > 30℃ at the surface (℃)	b	+	0,007	0,1 34
T > 175℃ at the surface (yes / no)	c	+	0,079	0,059
Maximum temperature at 1cm depth (℃)	d	+	0,034	0, 085
Heating velocity at the surface (℃ / minute)	e	+	0 ,037	0,082
T > 40℃ at 1cm depth (yes / no)	f	+	0,026	0,094
T > 60℃ at 1cm depth (yes / no)	g	+	0,044	0,077
Delay maximum T at 1cm depth (minute)	h	-	0,032	0,087

Testing combinations of these regressors revealed that only the delay before maximum temperature was reached at 1cm could be combined with another regressor; all other combinations were not significant. Highest explaining power in the dependent variable maximum temperature at 3cm depth (an R^2 of 0.196) was found by combining regressors h and b (Table 10) in multiple regressions.

Integral of temperatures above 30°C at soil surface is positively correlated with maximum temperature at 3cm depth, because high temperatures at the surface mean increasing temperatures in the soil. Delay before maximum temperature is reached at 1cm depth, is negatively correlated with maximum temperature at 3cm depth. If this delay is big it means the impact from the fire is small at 1cm depth, and a low maximum temperature at 3cm depth is logical. It is not surprising that (maximum) temperature at this depth of 3cm is more difficult to explain than at 1cm depth, because attenuation of temperature comes with depth and the heating source fire is further away. With a combination of regressors A, S and b (Tables 1, 8 and 10) in maximum temperature at 3cm depth, an R^2 value of 0.489 was found.

3.6. Correlate heating velocity in depth

When heating velocity at 1cm depth was taken as dependent variable, a lot of explaining power was found in surface temperature data. Maximum R^2 of 0.702 resulted from a combination of the regressors maximum surface temperature, heating velocity at soil surface and if surface temperatures exceeded 175°C. So 70% of variance in heating velocity at 1cm depth is explained by those three regressors ($p < 0.000$, $p < 0.000$ and $p < 0.052$ respectively).

Heating velocity at 3cm depth is significantly correlated with several regressors in temperature data, at the surface and at 1cm depth. A combination of the regressors if temperatures at 1cm depth exceeded 40°C and 60°C and if surface temperature exceeded 100°C yielded the highest R^2 of 0.378 ($p < 0.000$, $p < 0.016$ and $p < 0.055$ respectively). But the largest correlation coefficient (if T>40°C at 1cm depth) was positive, the second coefficient (if T>60°C at 1cm) was negative and the third and smallest coefficient was positive (if surface T>100°C). Logically it is not possible that these regressors have opposite signs in their relation with maximum temperature at 3cm depth.

3.7. Paint sticks versus thermocouples

Temperature indications from the paint sticks were tested for correlation with the maximum temperatures measured by thermocouples at the same site. Only maximum temperatures at 3cm depth were significantly correlated ($p < 0.05$) with the indications from the paint sticks. However, the R^2 of this correlation was only 0.081 which means that the relation between these two variables is not very strong.

Table 11 – Correlations with maximum surface temperature indication by paint sticks

	Regressor	Sign C.C. (+/-)	P-value	R^2
Maximum temperature at 3cm depth (℃)	0	+	0,045	0 ,081

As the paint sticks indicate maximum temperature at soil surface, correlation with maximum surface temperature measured by thermocouples was expected. Lack of correlation was probably caused by the wide range of maximum temperature measurements at soil surface (Fig. 2). At 3cm depth the range of maximum temperatures is much smaller and the distribution does not show outliers (Fig. 6), therefore a weak relation is easier to find with maximum temperature at 3cm depth than with maximum temperatures at the surface.

3.8. Correlation with litter layer after fire

Although litter depth before the fire was not sampled, litter depth was sampled after the fire. Simple regression analysis resulted in correlations between temperature data from beneath the fire and this litter depth (Table 11).

Table 12 – Correlations with litter depth after the fire

	Regressor	Sign C.C.(+/-)	P-value	R^2
Maximum temperature at the surface (℃)	1	-	0.111	0 .053
Heat index > 30℃ at the surface (℃)	2	-	0.045	0.0 80
T > 40℃ at the surface (yes / no)	3	-	0.002	0.187
T > 60℃ at the surface (yes / no)	4	-	0.032	0.095
T > 40℃ at 1cm depth (yes / no)	5	-	0.099	0.059
T > 60℃ at 1cm depth (yes / no)	6	-	0.099	0.059
Maximum temperature at 3cm depth (℃)	7	-	0.000	0.2 96
Delay maximum T at 3cm depth (minute)	8	+	0.024	0.103

When the regressors with individual explaining power in the variance of litter depth after the fire (Table 11) are combined in multiple regressions, the maximum value for R^2 of 0.369 is found with regressors 3 and 7. Regressor 1 till 6 got a negative correlation coefficient, as these regressors increase with fire impact it is logical that litter depth after the fire decreases. Regressor 8 correlated positively with litter depth after the fire and regressor 7 negatively. These correlations are plausible if the fire raised soil temperature at this depth of 3cm. High temperatures and small delays be consequences of fire impacts, which would cause the retaining litter layer to be thin. However, this can not be concluded from these correlations as the retaining litter layer could not be compared with the litter layer before the fire.

Measurements of the thickness of retaining vegetation stumps after the fire were also available, but did not correlate significantly with any of the temperature data.

4. Conclusions

Soil temperature at the surface during the fire was highly variable, maximum recordings per measurement site ranged from 9.5°C to 842°C with the average at 104°C. The flames were 735°C on average. At most measurement sites the surface was heated by the fire; this is concluded from temperature data values and from clear spikes in surface temperature (Fig. 11 and 12). Spatial patterns in maximum surface temperature (Fig. 1) show that at the south facing slope was heated more than the north facing slope. The catchment as a whole gives a heterogeneous pattern because large variation in maximum surface temperatures is found at short distances. Other heating variables like heating velocity and if temperature thresholds were exceeded gave similar patterns: more heating at the south facing slope than at the north facing slope, and a heterogeneous pattern over the whole catchment.

Although average maximum temperature at 1cm depth was only 27.5°C, the range was from 6.5°C to 350°C. An average maximum temperature of 27.5°C is low, compared to 40°C measured on average at 2cm depth beneath prescribed fire (Penman and Towerton, 2008), and is not expected to increase mortality in roots, seeds or soil fauna. At 1cm depth the spatial pattern in maximum temperature shows more heating at the south facing slope compared to the north facing slope, and heterogeneity over the whole catchment. Delays before heating started at 1cm depth and before maximum temperature was reached at 1cm depth showed a lot of variation with more high values at the north facing slope, indicating less heating than at the south facing slope. The fire had an impact on soil temperature at 1cm depth (Fig. 3), but obviously less than at the surface, compare figures 4 and 2.

At 3cm depth no clear proof of impact from the fire on soil heating was found, the maximum temperatures were low and had a small range from 6.5°C to 22.5°C (Fig. 6). This small range could mean that the fire had little effect on soil heating at 3cm depth. In accordance, another study in experimental fire showed that soil temperature increased negligibly at 2.5cm depth (Giovannini and Lucchesi, 1997). Nevertheless some recordings showed an increase in temperature at this depth following the spike in surface temperature (Fig. 11 and 12), which indicates fire effects. In order to be able to distinguish soil heating as fire effect from warming by the daily air temperature cycle, more data on daily soil temperature fluctuations are needed.

Explanations for the variance in soil heating were limited, although some factors showed significant explaining power. Regressors significantly correlated with soil heating, from strong to weak correlations were: vegetation height, soil depth, rock cover, aspect of slope, inclination of slope, vegetation cover, soil moisture content and organic matter content. As some explaining factors (regressors) depended on each other, many combinations did not correlate significantly with soil heating. The large spatial variability in soil heating was an important cause for the lack of significant correlations and for the weakness of most significant correlations. As the variability in soil heating was much lower at 3cm depth than at 1cm depth or at the surface, relatively strong correlations were found with the heating variables: maximum temperature and heating velocity at 3cm depth. But over all correlations with soil heating were weak. Stronger correlations were found between soil surface heating and heating of soil below the surface.

The two different stages in the experimental fire, low and high intensity, did not cause differences in soil heating. The soil was not more heated by the climax fire with high intensity than by the fire with low intensity. One explanation is that the high intensity fire was made where the vegetation was high, dense, and wet at the lower half, and therefore did not have much effect on the soil. This is why vegetation height and vegetation cover correlated negatively with soil heating, and rock cover and soil depth positively. Another possible explanation why high intensity fire did not affect soil heating more than low intensity fire could be the very short duration of high intensity fire compared to low intensity fire.

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Appendix 1 - Protocols

Bulk density, dry bulk density and soil moisture content

Soil samples are collected in metal rings. By placing the rings into the soil and closing the top and bottom of the ring, no change in volume/weight ratio occurs. By weighing the soil sample, combined with the volume of the metal ring, the bulk density can be calculated.

$$\varphi_b = \frac{M_s + M_l}{V}$$

Drying the sample for 24 hours at a temperature of 105°C will remove all moisture from the sample. By reweighing the soil sample the dry bulk density and the volumetric soil moisture content can be calculated.

$$\varphi_b^d = \frac{M_s}{V}$$

$$\theta = \frac{V_l}{V}$$

Mass based moisture content

Samples originally taken for water repellency analyses, were also used to determine the moisture content based on weighing the sample, drying it for 24 hours at 105°C and reweighing (Mass %).

$$Moisture(\%) = \frac{M_{moisture}}{M_{sample}} * 100\%$$

These samples were taken with no specific volume and after this analysis they were used again for analysing organic matter content.

Organic matter content

A small soil sample of about 2 grams will be weighed and placed in a muffle furnace which will heat up the sample to 550°C. The soil is heated for three hours at 550 degrees. After heating, the sample will be re-weighed to measure the loss in weight. Using the change in weight of the sample the organic matter content can be calculated:

$$OM = \frac{M_{om}}{M_{sample}} * 100\%$$

Appendix 2 - Soil properties

Soil moisture content

Soil heating is generally faster with high moisture content because water conducts heat better than air. But the water forms a barrier when the soil approaches 100°C and the water is vaporized (Campbell *et al.*, 1995). According to Giovannini (Giovannini), all soils react to heating with the same thermal reactions, starting with dehydration up to 170°C and dehydration of the gel forms at 170°C-220°C. (Hubbert *et al.*, 2006) found a decrease in soil moisture content after a prescribed fire. Soil moisture content can be highly spatially variable (Dekker *et al.*, 1999); and it is one of the factors determining fire severity (Neary *et al.*, 1999).

Bulk density

Porosity is a determining factor in thermal conductivity, in combination with moisture content. In a clayey textured soil porosity increases when the soil is heated up to 460°C, while in a sandy textured soil porosity decreases with rising temperatures (Giovannini, 1994). Some authors concluded that bulk density does not increase significantly with an increase in soil temperature caused by fire (Fernandez *et al.*, 2008). Another study found that median soil bulk density increased by 26% in the upper 5 cm of the soil, as porosity decreased (Hubbert *et al.,* 2006). When organic matter is lost or soil aggregates destructed, bulk density increases (Giovannini *et al.,* 1988). High bulk density is associated with a decrease in porosity (Boyer and Miller, 1994; Kennard and Gholz, 2001). A lower porosity will reduce the infiltration capacity of a soil and thus increase the chance of surface runoff.

Organic matter content

Organic matter influences soil properties such as the porosity and the coherence of the soil (Gimeno-García *et al.,* 2000). As mentioned before, it is suggested that products of the combustion or the vaporization of organic matter can increase the water repellency of the soil (DeBano, 2000). However, the quantity as well as the type of organic matter is related to the severity of water repellency (Debano, 1981; Doerr *et al.*, 1998). By stimulation of macro aggregates formation, organic matter increases the rate and capacity of water infiltration into the soil (Cerda, 1998).

Where soil temperatures stay below 170°C, no effect on the organic matter content is expected. Until 220°C it decreases a little and at 460°C combustion is completed and all organic matter is eliminated (Giovannini, 1994; Neary *et al.*, 1999), if soil is heated for sufficient time.

Stoniness

In the literature no direct relations between stoniness and (elevated) soil temperatures was found. But recent experiments (Stoof *et al.*, in preparation) found that stones in and on the soil affect heat penetration and heating duration. Stones on the surface insulate the soil, decrease maximum temperatures and increase heating and cooling durations. Stones will affect soil heating because they have different properties than the soil matrix in terms of thermal conductivity and thermal resistivity.

Additionally, stones are expected to have indirect effects on soil heating, because if the soil surface contains many stones water will infiltrate faster and deeper into the soil

(Poesen *et al.*, 1990). Stones in the soil can affect soil temperatures via infiltration and differences in water content, so they could have an impact on soil heating.

Rock cover

Experiments in a laboratory setting have shown that rocks covering the soil surface reduces soil temperature under fire and increase the time for which temperature thresholds are exceeded under the rock cover (Stoof *et al.*, in preparation).

Appendix 3 - Pictures

Figure 48 – Start of experimental fire with low intensity

Figure 49 – Climax of experimental fire with high intensity

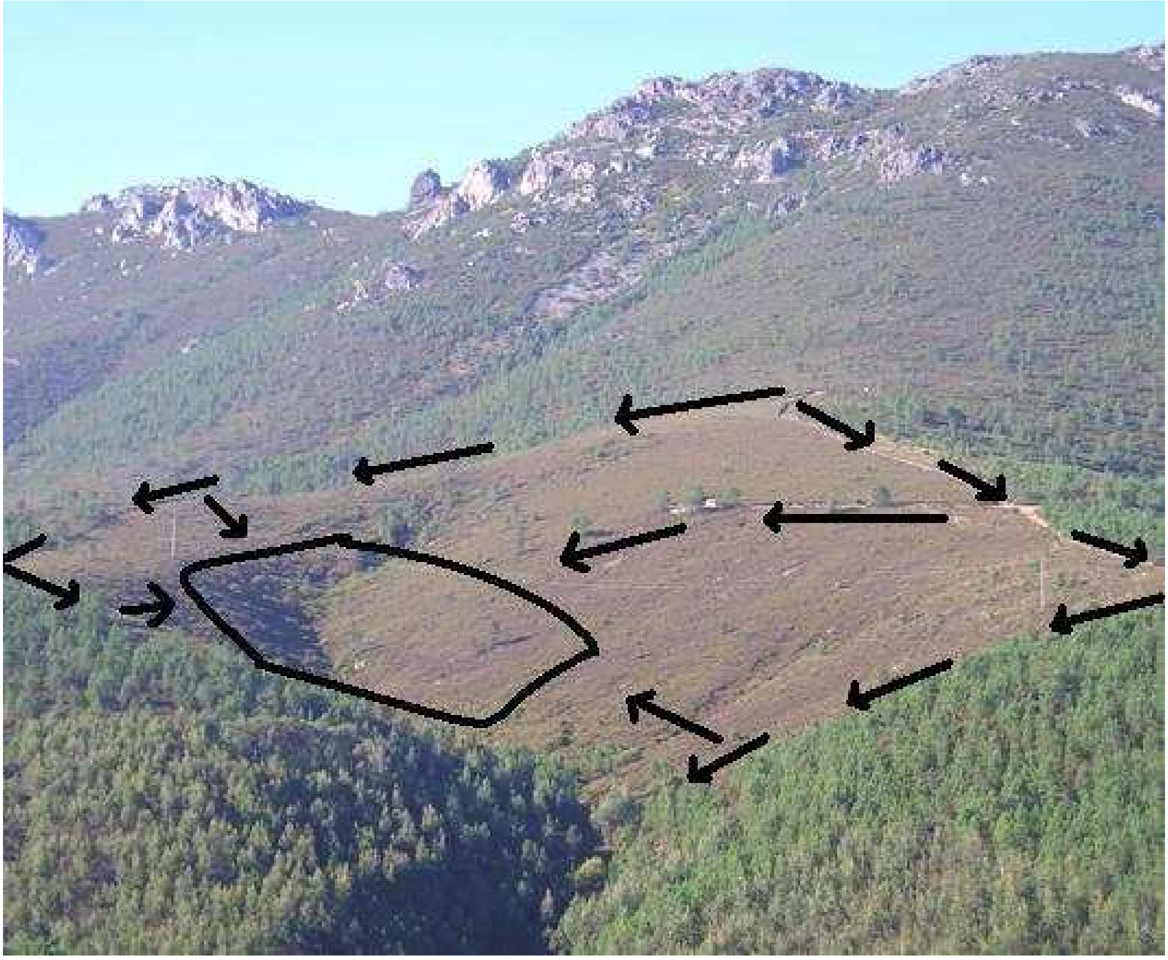

Figure 50 – Ignition pattern with climax fire zone