Effects of wildfire on a pine stand in the Bohemian Switzerland National Park

J. Trochta[1,2], K. Král[1], P. Šamonil[1]

[1]*Department of Forest Ecology, Silva Tarouca Research Institute for Landscape and Ornamental Gardening, Brno, Czech Republic*

[2]*Department of Geoinformation Technologies, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic*

ABSTRACT: The pine stand in the Havraní Skála locality in the Bohemian Switzerland National Park was affected by an extensive mixed-severity wildfire in summer 2006. The fire severity, fire type and fire extent were assessed by various fire severity measures collected in the field (mean bole char height on stems on sample plots, content of oxidizable C and total N at a soil depth of 0–5 cm), as well as by classification and filtering of green canopy cover from time series of aerial photographs acquired before the fire (2005), soon after the fire (2006) and one year after the fire (2007). The specific image analyses made it possible to uncover the spatial and temporal pattern of the stand defoliation. The central part of the site was mainly affected by the crown fire and thus defoliated substantially right during the fire. On the contrary, the peripheral part of the site was mostly affected by low-severity ground fire and therefore defoliated progressively one year later. All the fire severity measures used were well related.

Keywords: forest fire; aerial photographs; classification; defoliation; fire severity

An extensive wildfire occurred on 22 July 2006 near Jetřichovice in the Bohemian Switzerland National Park (BSNP). It was one of the biggest forest fires in modern history of the Czech Republic (Vonásek 2006). Extinguishing this fire was very difficult because of the inaccessible rocky terrain – the fire was extinguished after 8 days and the total burned area was ca 25 ha (Vonásek 2006). The area affected by the fire is rather small in comparison with Mediterranean and boreal wildfires; however, in the recent Central European context it is an outstanding disturbance event that deserves further attention. On the other hand, the latest anthracological research in the region (Novák et al. 2012) indicates that similar sites of pine forests in Northern Bohemia have been affected by forest fires through a substantial part of the Holocene. Recent human-induced accidental wildfire can therefore resemble natural fire disturbances that the local pine forests experienced in the past. The main objective of this study is to quantify the effect of fire on a forest stand – i.e. to evaluate the fire type (surface and/or crown) and fire severity. The spatial and temporal pattern of defoliation should be determined as well, so the assessment is provided for two consecutive years after the fire.

The study site is interesting also from the aspect of post-fire succession, as the original stand was invaded by the allochthonous white pine (*Pinus strobus* L.), which causes severe problems in the forests of the National Park. The forest fire substantially regulates the environmental variables of the site and the availability of ecological resources (e.g. light, soil nutrients). Fire severity is thus one of the key points of post-fire vegetation succession (Pausas et al. 2003; Lecomte et al. 2006; Otto et

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al. 2010). Obviously, it can play an important role in the natural re-establishment of the study site and the successful regeneration of invading white pine and indigenous tree species. This issue is a major focus of other ongoing researches (preliminary results e.g. in Jurek 2009; Marková et al. 2011).

A qualitative indicator of the effects of fire on an ecosystem is fire severity, which can measure fire effects on the forest floor, canopy and anything between them. Like fire intensity, fire severity reflects the amount of heat released by a fire, and therefore it is also dependent on fuels and fire behaviour. But fire severity also integrates fuel and soil conditions before a fire, energy released during and after flaming combustion, and visible effects after a fire. Unfortunately, there is no widely accepted or standardized quantitative measure of fire severity (Pausas et al. 2003); quantitative descriptions based on the degree of fuel consumption are common (e.g. Bradley et al. 1992; Turner et al. 1994; Pausas et al. 2003). Other researchers have used the degree of vegetation mortality as a measure of fire severity (e.g. Atkin, Hobbs 1995; Chappell, Agee 1996; Pausas et al. 2003). Since we collected data on several variables that can potentially be used for fire severity estimation, our study could also contribute to the debate on fire severity measures.

For the purpose of the study we combine data from remote sensing and from a field survey. Identification of the direct impact of fire on forest stands (e.g. detection of recent and past fire scars, burned area and burn severity mapping) is a common application of remote sensing data and techniques (e.g. Kokaly et al. 2007), mostly due to the general advantages of such techniques: synoptic overview and updateability (Kral et al. 2003). Regional studies usually make use of Landsat TM/ETM and MSS data (e.g. Salvador et al. 2000; Miller, Yool 2002); large-scale studies favour wide-span MODIS data (Roy et al. 2006; Urbanski et al. 2009). Our detailed study, however, required remotely sensed data of higher spatial resolution. Because of the best availability of data before and after the fire and because of the level of attainable detail, we used the time series of aerial photographs that were complemented by post-fire field reference data collected in the stand.

The paper addresses the following questions:

1. What were the extent, location and magnitude of immediate crown damage?
2. What were the extent, location and magnitude of the subsequent defoliation of trees?
3. What is the total extent and magnitude of defoliation due to the forest fire?
4. What is the relationship between different fire severity measures?

MATERIAL AND METHODS

Study Site

Defoliation after the fire was studied at the Havraní Skála ("Raven's Rock") site near Jetrichovice in the BSNP. The site is a sandstone ridge, with a central sandstone rock, after which the whole site is named, and the adjacent deep valley. The total burned area included the peak of Havraní Skála and the western slopes of the Mariana View mountain. Because of intensive tourist pressure around the Mariana View, only Havraní Skála (ca 13.6 ha) was fenced off and left to spontaneous development. As a result, we carried out further research only at this site. Elevation ranges between 245 and 393 m a.s.l., and the terrain is rugged with steep valleys bounded by rocks. Slope inclination ranges between 0 and 90°. The average inclination is 35°.

The central sandstone ridge lies in a NE–SW direction and is ca 350 m long. The side valleys, which vary in their depth and steepness, follow the line of the ridge. The eastern slopes are usually steeper but at the same time they have fewer side valleys than the western half of the site.

The original stand, up to 130 years old, was composed of eastern white pine (*Pinus strobus*) and Scots pine (*Pinus sylvestris*) with an admixture of European beech (*Fagus sylvatica*), Norway spruce (*Picea abies*), silver birch (*Betula pendula*) and sessile oak (*Quercus petraea*). As part of management efforts to reduce invasive species, ca 100 m^3 of white pine was cut and left at the site before the fire. Due to this factor, as well as to high temperatures and little rain in July 2006, the fire was able to start and spread with high intensity. The forest fire at Havraní Skála could be classified as a mixed severity fire (Jurek 2009). The intensive crown fire immediately damaged substantial parts of the original canopy. Major parts of the stand were affected only by surface fire, though successive defoliation and dieback of trees were observed in the next years.

Data collection

The directorate of the BSNP provided RS data (three orthophoto maps from 2005, 2006 and 2007) for the analysis. The data from 2005 (before the fire) was recorded in April as part of the Intereg IIIA project run by the Technical University in Dresden. The data are composed of a photo mosaic of RGB (red, green, blue) channels and NIR (near infrared channel); the spatial resolution is 1 m.

The RGB photo from 2006 shows the site after the fire with a spatial resolution of 0.2 m. However, these data are encumbered by low quality geometrics (poor mosaicing of the image, spatial deformation).

In 2007 the site was recorded in RGB once again. The original resolution of 0.1 m was transformed into 0.2 m for the purposes of this paper.

Ground-truth in a network of 135 permanent sample plots (PSP) established in a 30 m grid mainly for the study of post-fire vegetation succession was conducted in 2007. Mean scar height of stems was estimated on each PSP in a circle of 7 m in diameter. The presence of different types of surface was estimated within a square subplot of 2.25 m^2 in the centre of each PSP. We distinguished the following types of surfaces: uncovered upper mineral soil horizon, forest floor (L – litter and/or F – fermented and/or H – humification horizons, Klinka et al. 1997), stone, moss, wood and Graminoids (*Poaceae* + *Cyperaceae*). Close to the centre of 110 PSPs, shallow soil profiles were sampled at the depth of 0–5 cm (humification H- and upper mineral A-horizons, see Klinka et al. 1997; Zanella et al. 2011).

Supervised classification

Thematic categories representing surface cover were chosen for each RS dataset. The categories were selected with respect to vegetation classification, since the aim of the study is to evaluate the effects of fire on vegetation (Table 1). The names of the categories reflect as closely as possible the state captured by the RS sensors. **Green crowns** of trees are clearly distinguishable in orthophotos due to their green colour (in RGB composition) and their actual state, which shows functioning assimilation organs. **Dry crowns** of trees are visible because of their orange colour, which indicates burned assimilation organs and smaller branches that are still in the crown and not on the ground. **Broken crowns** are torsos of trunks and larger branches which have not yet fallen to the ground. The land cover categories mapped in the particular years are summarized in Table 1.

In order to achieve correct classification, two sets of independent reference data were created for each year. One set was used as training samples, on which spectral signatures of the individual signatures were defined. The other set served to verify the results of classification with the help of an error matrix and Kappa index. After counting the signatures of the categories, the classification of the whole image was carried out using the maximum likelihood classifier.

Because of their higher spatial resolution, data from 2006 and 2007 were filtered with a circular modal filter of 1 m in diameter. The resulting land cover maps are more comparable and reduce the noise created by per-pixel classification (the so-called "salt and pepper effect").

The categorized data were compared with the reference data in an error matrix. Overall accuracy of a map is calculated by dividing the correctly classified pixels by the total number of pixels checked (Congalton 1991). The Kappa coefficient is also a measure of overall agreement, but a chance agreement is removed from considerations (Nilsson 1998). Overall accuracy and Kappa index were calculated also for reclassified maps "green crowns/other categories", which are essential for green canopy cover calculation and consequently for the calculation of defoliation.

Analysis of green canopy cover and its defoliation

Changes in canopy cover were studied in a three-year period. For the purposes of this study, canopy

Table 1. Categories and their values for the calculation of canopy cover with the picture filter

Categories in 2005	Categories in 2006	Categories in 2007	Values of crown canopy (%)
Rock	rock	rock	0
Soil	soil	soil	0
Green crowns – coniferous Green crowns – broadleaf	green crowns	green crowns	100
	dry crowns	dry crowns	0
		broken crowns	0

cover is defined as the average percentage of green crowns in a particular plot (in this case a circle of 15 m around each pixel). For the actual calculation of canopy cover the method proposed by Král (2009) was used. First, land cover maps were reclassified into two categories: "green crowns/other categories". Green crowns received the value 100, other classes the value 0 (Table 1). This binary raster was filtered by a circular filter (diameter 15 m). The resulting value is the average value (%) of canopy cover in a predefined circle around each pixel.

Defoliation in this study was defined as the rate of change in canopy cover in the study period. It was calculated by subtraction of canopy cover raster layers from the particular years by means of Map Algebra (ArcGIS 9.3).

Laboratory analysis of soil samples

The soil samples were sieved after air drying (mesh size 2 mm). They were laboratory analysed according to methodological procedures described by Zbíral (2002) and Zbíral et al. (2004). All samples were subjected to the following analyses: exchange reaction of soil (pH KCl) – 0.2M KCl and active soil reaction (pH H_2O) at a ratio of 1:2.5 (v/w); oxidizable C (C_{ox}) – determined spectrophotometrically after oxidation with H_2SO_4 + $K_2Cr_2O_7$ according to Anonymous (1995) and total N content according to Kjeldahl (Bremner 1996).

Ordination analysis

To better understand the data structure, heterogeneity and mutual relations, we projected the dataset along two main non-canonical axes using Principal Component Analysis (PCA, Fig. 5) in the Canoco for Windows 4.5 (Ter Braak, Šmilauer 2002; Lepš, Šmilauer 2003). Given the high data homogeneity (exposed by the length of the first variability gradient), the gradient could be linearly interpreted. To better interpret the non-canonical axes, known environmental characteristics were introduced into the analysis as supplementary variables (altitude, exposure, slope, potential direct solar irradiation). By reason of limiting the spatial autocorrelation, sample plot geographical coordinates were used as covariables (e.g. Petřík, Wild 2006).

RESULTS AND DISCUSSION

Land cover and its changes

After the evaluation of classification with the help of overall accuracy and the Kappa index, the measurements of the categories were added together (Table 2).

Table 2 shows how the proportion of individual categories changed through the years as well as the accuracy with which orthophotos from the three years were classified. The lower overall classification accuracy from 2007 is a result of more categories; the categories "green crowns/others" were distinguished highly successfully in that year as well (see below and Table 2). Classifications from the years 2005 and 2006 both have over 90% accuracy.

From the changes in the proportion of categories it is evident how the fire affected the stand. Of the original 83% of green crowns there remained only 15% in 2007, and the rest was destroyed by the fire. The area of green crowns was reduced by

Table 2. The area and percentages of categories in the particular years; the precision of classification

	2005		2006		2007	
	(ha)	(%)	(ha)	(%)	(ha)	(%)
Rock	0.29	2	0.42	3	0.26	2
Soil	2.08	15	5.82	43	6.92	51
Green crowns	11.30	83	5.28	39	2.07	15
Dry crowns			2.14	16	1.13	8
Broken crowns					3.28	24
Total	13.66	100	13.66	100	13.66	100
Kappa		88		88		77
Overall accuracy		91		91		82
Overall accuracy – green/others		97		97		98

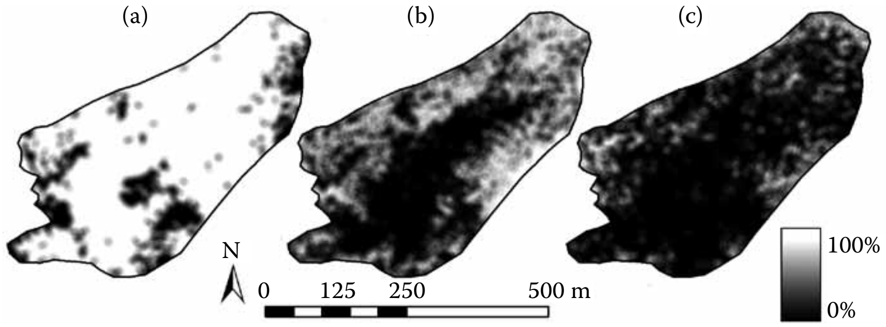

Fig. 1. (a) Green canopy cover before the fire in 2005, (b) after the fire in 2006, and (c) one year later in 2007

more than a half immediately after the fire. Most green crowns were completely burned (see the sharp increase in the category "soil" in 2006), and 16% were identified as dry. In 2007 green crowns made up only 15%, whereas dry and broken crowns accounted for 32%. Bare soil continued to occupy a significant area in 2007.

The accuracy of differentiation between green crowns and other categories was of crucial importance for the calculation of canopy cover. This is why Table 2 contains data on the precision of this simplified, binary classification. Because of the high values attained (97–98%), the data based on which the cover of green crowns is calculated can be considered adequate.

Magnitude and extent of forest decline

Canopy cover was calculated for each year (2005, 2006 and 2007) as the average value in a circle with radius 7.5 m around each pixel (Fig. 1).

Fig. 1a shows canopy cover before the fire in 2005. Darker spots (i.e. lower values or zero cover) are rocky patches or very steep slopes where soil creep occurs. From Fig. 1a and the histogram of the values (Fig. 2) it is evident that before fire the canopy cover was almost 100% on a major part of the area (ca 9 ha). Canopy cover over 70% was also significant. The above-mentioned rocky patches with low canopy cover (0–10%) are visible in the histogram as well.

From Fig. 1b, which was made on the basis of the orthophoto from 2006, we can identify the places where the fire had an immediate effect on green crowns. The most severely damaged location was the central and at the same time the highest part of the site, where crown fire also occurred. Further evidence of this can be found in the defoliation map, calculated on the basis of the difference in green canopy cover before and after the fire (Fig. 3a with the appropriate histogram in Fig. 4). More than 2 ha in this central area were completely defoliated. From the histograms in Figs. 2 and 4 it is also evident that a certain amount of opening up occurred at the entire site (canopy cover over 90% basically disappeared).

Figs. 1c and 2 show that one year later, in 2007, canopy cover at the entire site reached maximum values around 70% with dominating low values (right-skewed histogram). We conclude that even

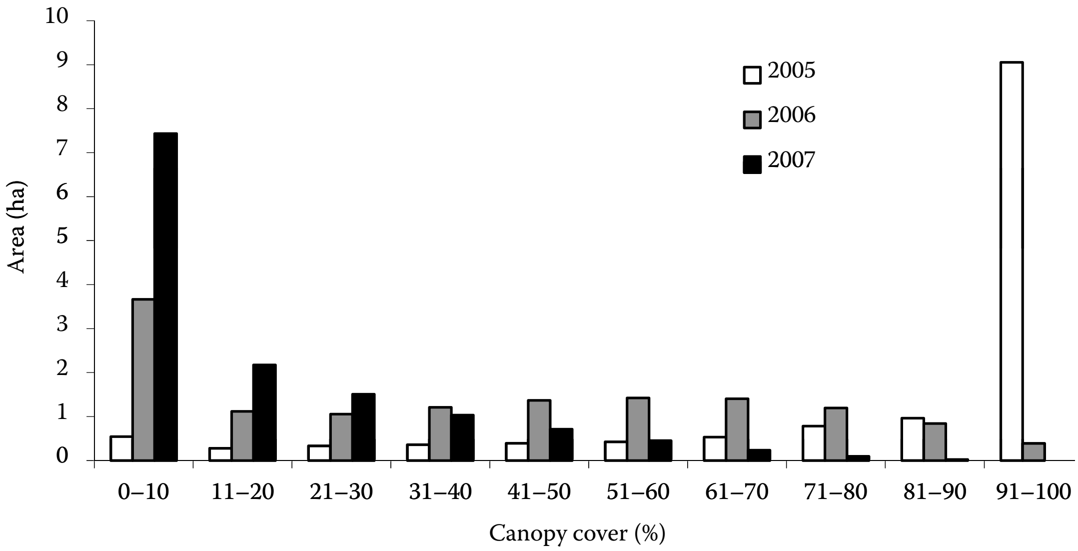

Fig. 2. Distribution of canopy cover values in corresponding maps from the years 2005, 2006 and 2007

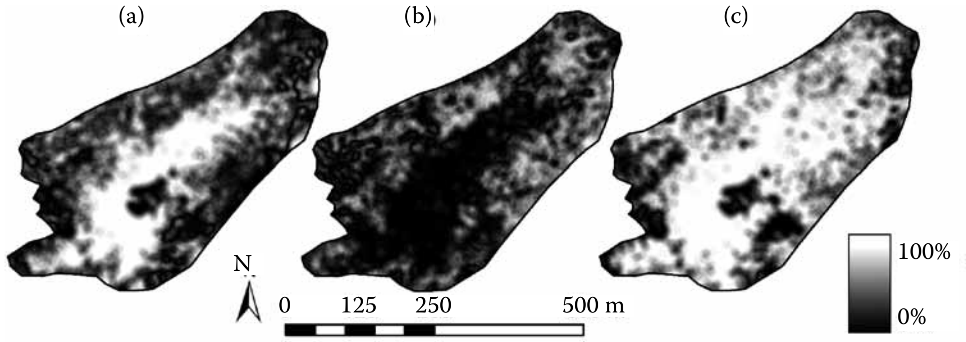

Fig. 3. (a) Defoliation after the fire – difference 2005–2006,(b) one year later – difference 2006–2007, and (c) total defoliation between 2005 and 2007

though crown fires did not occur in peripheral areas (see also the section on fire severity), ground fires damaged trees, which gradually became evident a year later. In 2007, defoliation mostly occurred in peripheral areas (the central area had been defoliated already in 2006 – Figs. 3a and 3b). The gradual process of defoliation is documented also in the histogram in Fig. 4.

Fig. 3 demonstrates the gradual progress of defoliation in the years 2005–2006 and 2006–2007. Crowns that did not directly burn in the fire died back gradually and with smaller intensity in the next year. In 2007, more than a half of the site had canopy cover up to 10% and ca 80% of the site had up to 30% (Figs. 1c and 2).

Fire severity

Fire severity (or burn severity) is ideally quantified as the amount of organic matter consumed (*sensu* Miyanishi, Johnson 2002; cf. Lecomte et al. 2006). However, as it is hard to know how much organic matter was present in the pre-fire stand, fire severity is usually quantified as the amount of organic matter not consumed by the fire (*sensu* Nguyen-Xuan et al. 2000; cf. Lecomte et al. 2006), i.e. the amount of residual organic matter. This is applied for assessing the fire effect both on the stand (trees and vegetation overstorey) and on the forest floor and/or mineral soil.

The residual organic matter in the forest floor can be estimated by a variety of approaches from simple ordinal classification of observed ground scars (Kokaly et al. 2007) to detailed laboratory analyses of organic horizons (Lecomte et al. 2006). In our study we used simple laboratory analyses of soil samples – amount of N_t and C_{ox} – as indicators of unburned soil organic matter in organic as well as in upper mineral soil horizons. Burning generally causes a significant change in nitrogen and carbon volume (final losses of C and N) as well as changes in soil reaction and C:N ratio in the uppermost soil horizons (e.g. Caldwell et al. 2002; Murphy et al. 2006).

Probably the most common indicator of stand fire severity (at a canopy level) is a visual estimation of the fraction of scorched and combusted tree canopies, expressed either in percentages (e.g. Otto et

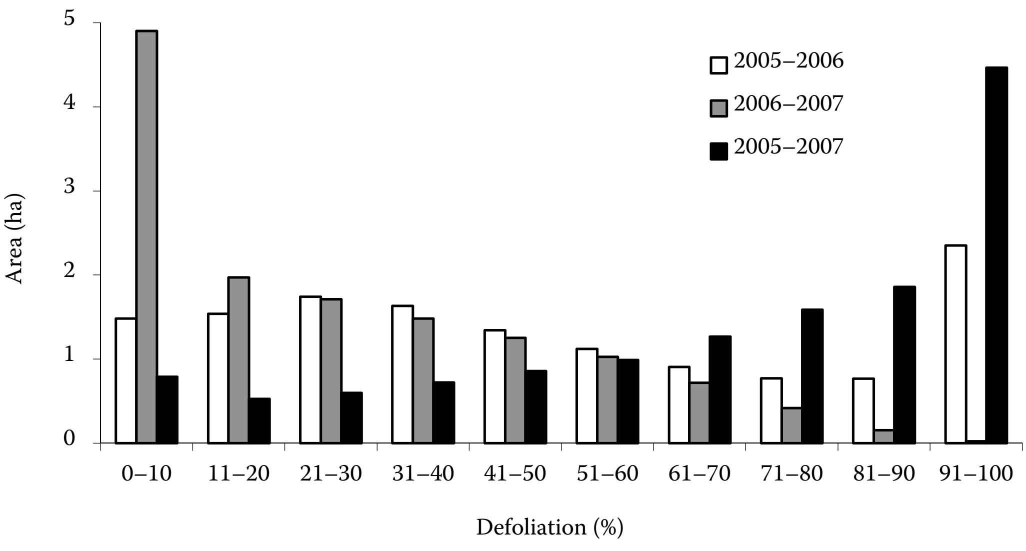

Fig. 4. Distribution of defoliation values in corresponding difference maps between the years 2005–2006, 2006–2007 and 2005 to 2007

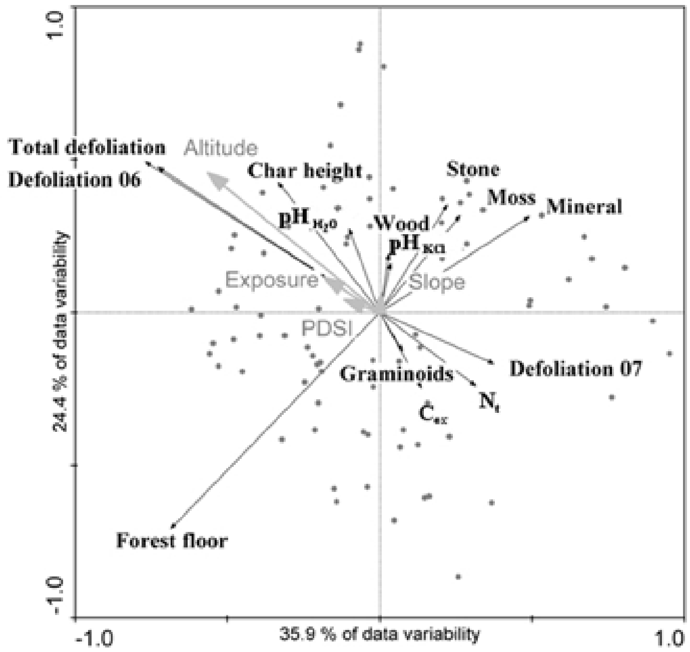

Fig. 5. Relations of potential fire severity indicators (defoliation, soil chemistry) and other environmental variables recorded on permanent sample plots – PCA analysis
grey characteristics – introduced into the analysis as supplementary variables, sample plots geographical coordinates – covariables, total defoliation (ha), defoliation 06, 07 (ha), bole char height (m), C_{ox} – oxidizable carbon content (%), N_t – total nitrogen content (%), pH H_2O – active soil reaction (/), pH KCl – exchange soil reaction (/), type of soil cover (%) – Forest floor, Uncovered upper mineral soil, Moss, Stone, Wood, Graminoids, Altitude (m a.s.l.), Exposure (°), Slope (°), PDSI – potential direct solar irradiation in the vegetation period 1st April–31st October (W × m^{-2}/vegetation period), grey points represent research plots of the network, for details see Section 2

al. 2010; Sah et al. 2010) or in discrete degrees of canopy damage (e.g. Pausas et al. 2003; Kokaly et al. 2007). An alternative approach employs char height measured on tree stems (Sah et al. 2010). This measure of fire severity, which is related to flame height, provides information on fire severity between the ground and canopy levels. To what extent fire severity at the canopy level is related to fire severity at the ground level remains unknown (Pausas et al. 2003). However, the fact that a certain amount of fuel on the ground may be necessary to produce long flames reaching the canopy suggests that fire severity on the ground and in the canopy may be well related.

Our use of a series of aerial photographs partly overcomes the knowledge gap on pre-fire conditions at the canopy level. Detailed aerial photos can provide reliable information on canopy cover before the fire. The difference between canopy cover before and (right) after the fire (Fig. 3a) is thus a good indicator of fire severity at the canopy level. It is a more precise measure of fire severity than simple canopy cover after the fire (Fig. 1b) where pre-fire canopy conditions are not included – notice the canopy gap in the centre of the study site before the fire (Fig.1a) where the massive bare rock is situated (i.e. no fuel for combustion). This gap is reflected in the difference image (Fig. 3a) but not in the simple post-fire canopy image (Fig. 1b).

PCA analysis (Fig. 5) shows that instant defoliation (in 2005–2006) and total defoliation (in 2005–2007) are very closely related and both are correlated to the bole char height of stems. These fire severity measures are closely negatively correlated with indicators of unburned soil organic matter – the amount of Nt and Cox in the upper soil layer. This confirms the original supposition that fire severity on the ground and in the canopy were closely correlated at our study site. However, the effects of burning on aboveground biomass can be variable compared to soils, particularly if mineral soil horizons are analysed (e.g. Rau et al. 2008, 2010). The effects of burning on forest soils may also depend on the depth of soil sampling, soil taxonomical unit or initial water content (Glass et al. 2008).

Delayed defoliation (2006–2007) is negatively correlated with previous fire severity measures (instant and total defoliation, char height) and therefore indicates only light surface fire (Fig. 5). Somewhat surprising is the indication that the soil-cover categories observed on PSP have a weak relation to fire severity gradient (perpendicular location of these characteristics between two main non-canonical axes; Fig. 5). This can be explained by different spatial scales of observation which are not entirely compatible. While categories of soil cover were estimated in square sample plots of 2.25 m^2 used for a natural regeneration census, canopy defoliation and mean stem char height were calculated in circles of ca 176.7 m^2.

CONCLUSIONS

The specific analysis of time series of aerial photographs made it possible to quantify the spatial and temporal pattern of defoliation of the pine stand after the wildfire. The highest – central – part of the site was largely affected by the crown fire and thus defoliated radically and immediately. On the contrary, the peripheral part of the site was affected predominantly by low-severity ground fire and therefore defoliated gradually one year later. The total (final) defoliation that adds up the two complementary defoliation phases was, however, substantial in the entire study site, although the parts affected by the crown fire exhibit higher total defoliation.

The fire severity measures used by different authors proved to be well related. In addition, the fire severity on the ground and in the canopy showed a close correlation.

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Corresponding author:
Ing. Jan Trochta, Mendel University in Brno, Faculty of Forestry and Wood Technology
Department of Geoinformation Technologies, Zemědělská 3, 613 00 Brno, Czech Republic
e-mail: j.trochta@gmail.com