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The effect of forest disturbance on landscape temperature

Petra Hesslerová[a,*], Hanna Huryna[a], Jan Pokorný[a], Jan Procházka[b]

[a] ENKI, o.p.s. Dukelská 145, Třeboň 379 01, Czech Republic
[b] Faculty of Agriculture, University of South Bohemia in České Budějovice, Studentská 1668, 370 05 České Budějovice, Czech Republic

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ABSTRACT

Since the 1990s, the territory of the Šumava National Park (Czech Republic) has faced significant changes in land cover, especially deforestation, in conjunction with several bark beetle disturbances and hurricane Kyrill in 2007. The aim of the study is to review the hydrological and climatic function of the forest and deforestation impacts on the landscape temperature. As a case study, surface temperature changes of the selected area of Šumava National Park from the satellite Landsat thermal data is presented from 1991 to 2016. At the sites with decayed forest, the surface temperature increased by 2–4 °C. Images from ground temperature measurements illustrate extreme temperature differences (~35 °C) at locations where dead wood has not been removed; in the live forest, they are around 5 °C. Further, we show the increase in air temperature is associated with the decay of forest stands, including snow melting. The duration of the permanent snow cover on the mountaintops with the growing forest in the last four years is, on average, 11 days longer than the areas with decayed forest. The results show that the increase in surface temperature in the large area causes changes in the local climate and hydrological regime. These changes may have a negative impact on the surrounding ecosystems, including the Šumava wetlands and peat bogs belonging to the Ramsar sites.

1. Introduction

1.1. Opinions on the role of forests in water balance/hydrology and climate

The debate on the role of forests in the hydrological cycle can be traced back in history – Antiquity, Middle Age and up to the present. Man tried to understand the impact of forests on the water cycle and was aware of the serious consequences deforestation had on hydrology, soil, climate, precipitation, and temperature. The role of forest stands and the consequences of their damage were based on long-term observations and personal experience; scientific measurements and the effort to describe the whole system in scientific terms appear in the 19th century. Adult forests dampen the extremes of climate; this is the experience of both historical civilizations and generations of landscape managers, which was reflected in the Forest Law from the 18th century in the Austrian Monarchy. Over a long period of time a series of scientific papers and books were published on damping of temperature extremes (Geiger, 1957; Geiger et al., 2003, 2009). Forest practitioners wrote comprehensive books based on long- term experiences explaining the irreplaceable hydrological role of forests (Marsh, 1864; Úlehla, 1947).

Andréassian (2004) gives a historical evolution of ideas on the role of forests in hydrology and shows results of 137 paired watershed studies: deforestation was always immediately followed by a period of water yield increase and the subsequent period of recovery (forest regrowth) may or may not be characterized by a decrease in water yield.

WeForest (2015) and Ellison et al. (2017), in a thorough review, state the following five forest processes as more important than previously thought. Management to support them can result in short and long-term benefits for water availability and climate:

1. Forests promote precipitation.
2. Trees and forests are natural cooling systems.
3. Forests generate air and moisture flows.
4. Trees and forests can improve groundwater recharge.
5. Forests can moderate flooding.

The authors bring evidence both from ecophysiological studies and from evaluation of how large forest complexes function. They emphasize the direct role of forests in the distribution of solar energy, cooling, water cycle, and local climate.

The IPCC (Intergovernmental Panel on Climate Change) and mainstream science focus on the role of forests and wetlands in global climate change in terms of the greenhouse effect: forests affect climate by serving as a sink/source for carbon dioxide and other greenhouse gases (GHGs). Forests affect the climate positively through carbon dioxide

* Corresponding author.
E-mail addresses: hesslerova@enki.cz (P. Hesslerová), huryna@nh.cas.cz (H. Huryna), pokorny@enki.cz (J. Pokorný), prochaz@zf.jcu.cz (J. Procházka).

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sequestration. On the other hand, a forest is dark (low albedo) and absorbs solar radiation, which contributes to planet warming. According to Bala et al. (2007), burning of boreal forest would contribute to planet cooling because the warming caused by the release of carbon dioxide is lower than the cooling effect of increased albedo (the reflection of solar radiation) of burned forest. This thesis considers the forest as a passive subject of global warming driven by an increasing concentration of GHGs. According to the IPCC, the radiative forcing has increased since 1750 by 1–3 $W{\cdot}m^{-2}$ and resulted in higher evapotranspiration and water losses from the landscape by evaporation. The IPCC (2013, p. 666) claims that land cover does not affect the amount of water in the atmosphere; it is global warming which accelerates evaporation. Therefore, the only way to mitigate global warming and climate change is to reduce GHG production. Adaptation is based on the cultivation of species that tolerate lack of water and higher temperatures.

1.2. Forests attract water from oceans several thousand km deep in continents

Evapotranspiration from forests plays an extensive role in the transport of moisture from oceans to continents. It is evident that annual precipitation is high in continents with large and continuous tracts of forest that extend from the coast to the continental interior (West Africa, Amazonia). The biotic pump theory (Makarieva and Gorshkov, 2007, Makarieva et al., 2009) suggests the atmospheric circulation that brings rainfall to continental interiors is driven and maintained by large, continuous areas of forest beginning from coasts. The theory explains that through transpiration and condensation, forests actively create low-pressure regions that draw in moist air from the oceans, thereby generating prevailing winds capable of carrying moisture and sustaining rainfall far within continents.

The biotic pump concept explains why moist winds blow readily from oceans to well- forested land. This flow can decline and reverse when forest cover is absent or depleted. Deforestation reduces this pressure difference, weakening or removing the coast-to- interior moisture transport. Reliable rainfall in the continental interiors of Africa, South America, and elsewhere (EuroAsia) may thus be dependent on maintaining relatively intact and continuous forest cover from the coast.

The Šumava (Czech Republic) and Böhmerwald (Germany – Bavaria and partly Upper Austria) Mountains represent the largest forest complex in Central Europe on the boundary between Atlantic and continental climates. The Šumava National Park was declared in 1991 on 68,060 ha (ha), of which 55,000 ha are forested. An unmanaged regime for wilderness development was adopted and up until 2017 up to 17,000 ha of adult spruce forest declined or had to be cut due to bark beetle infestation, which represented roughly 6 million dead adult trees (note: as a large calamity is considered more than million m^3 of dry wood; one dead tree represents approx. 1 m^3 of wood) The expansion of the unmanaged zones continues to be promoted, with the aim of achieving a wilderness cover of 51% in the NP territory. Over the last several decades, a heated discussion has taken place among the media, Parliament, local communities, and among scientists on the effects of declining adult forests on hydrology and regional climate. The administration of the Šumava National Park, nature conservationists, and scientists advocate the thesis that hydrological function of a declined adult forest is compensated for by the ground vegetation. Foresters, most of the local people, communal politicians, and some scientists warn against the long-term slow process of drying linked with mountain deforestation. In order to assess effects of the decline of adult forest on regional climate following has been done:

- Assessment of long-term changes in surface temperature of the deforested areas, thermal data of Landsat satellites were evaluated for August of 1991, 1998, 2004, 2005, 2009, and 2016 and compared with Corine Land Cover data.
- For detailed evaluation of surface temperature differences between living and dead adult forest, ground thermal pictures were made in situ.
- The long-term trends of air temperature in the period 1988–2017 were evaluated for the meteorological station located in the mountain area where adult spruce forest declined and compared with the data of other meteorological stations located in undamaged areas.
- Time periods of snow cover duration in forested areas and in dead adult forest were evaluated.
- The data and results are discussed in terms of distribution of solar radiation (latent heat, sensible heat), evaporation and water cycle, and tree ecophysiology. Effects of deforested areas on valuable peat land mountain ecosystem are considered.

2. Specification of the area of interest, data and methods

The Šumava National Park (NP) was proclaimed in 1991 with an area of 680.6 km^2. The subjects of protection are forests, peat bogs and other wetlands, glacial relief, and cultural non-forested areas. Forest stands occupy 80% of the area, and the most valuable are mountain spruces reaching the forest boundary (1100–1300 m above sea level). In these plots, a non-intervention strategy was introduced in the 1990s, with the assumption of no bark beetle propagation. Ecological experts, unlike foresters, claim that these areas are resistant primeval forests, where the bark beetle is a natural part of the entomofauna and its overgrowth is impossible because of the presence of natural predators. However, bark beetle reproduction significantly increased from 2007 to 2011 after hurricane Kyrill. As a result of the non- intervention strategy, 17,000 ha of forest were lost in the Šumava NP (ÚHUL[1]) and 6500 ha of forest were lost in the neighbouring Bavarian NP, which is an estimated 8 million trees. Despite these events, the expansion of the non-intervention areas continues to be promoted, with the aim of achieving 51% wilderness cover in the NP territory.

The area of interest extends on the subset of Landsat satellite scene covering 544 km^2 (27.66 × 19.65 km), with the coordinates 49°05′53″ N, 13°19′34″ E and 48°55′34″ N, 13°42′34″ E. It is the transboundary area (Bavaria), however, only the Czech part was assessed (383 km^2).

From the Landsat data archive (https://earthexplorer.usgs.gov/), six free-clouds scenes (number 192-026) were selected from the following years:

Satellite Landsat 5: 7. 8. 1991, 10. 8. 1998, 10. 8. 2004, 29. 8. 2005, 24. 8. 2009
Landsat 8: 27. 8. 2016

The scanning time was 9:40 GMT (Landsat 5) and 9:57 GMT (Landsat 8).

Landsat satellites scan the electromagnetic radiation in the thermal portion of the spectrum in the channels:

Landsat 5-channel B6, wavelength 10.4–12.5 μm.
Landsat 8 – B10 channels (10.6–11.2 μm) and B11 (11.5–12.5 μm).

The spatial resolution of thermal data (that is, the size of the area capturing one pixel) for Landsat 5 is 120 m; while Landsat 8 is 100 m.

The data is suitable for analysis of larger territorial units. However, they capture vast territories of several hundred square kilometres at one point in time. The surface temperature is averaged for the smallest pixel from several surface types, in the case of very heterogeneous coverage. Using the intensity of the radiation that is recorded in the thermal channels, it is possible to calculate the surface temperature by means of

[1] ÚHUL – Forest Management Institute.

algorithms. To calculate surface temperature values for Landsat 5, the so-called single-channel algorithm was used (Chander and Markham (2003); Sobrino et al. 2005; Jiménez-Muñoz et al. 2014). The Landsat 8 satellite enables more accurate temperature calculation (based on the split window algorithm) because it has two thermal channels. However, in order to ensure the same processing method, the single channel algorithm was also applied on Landsat 8 data. The temperature calculation is based on the following calculations:

$$T = \frac{K_2}{ln\left(\frac{K_1}{L_\lambda} + 1\right)} \quad (1)$$

where T is land surface temperature (K), K_1 and K_2 are calibration constants for Landsat, L_λ is spectral radiance at the thermal channel in $W/(m^2.sr.\mu m)$, calculated as formula (2)

$$L_\lambda = \left(\frac{LMAX_\lambda - LMIN_\lambda}{Q_{max}}\right) + Q + LMIN_\lambda \quad (2)$$

where $LMAX_\lambda$ and $LMIN_\lambda$ are maximum and minimum spectral radiance in $W/(m^2 \cdot sr \cdot \mu m)$ that is scaled to $Q_{max/min}$, Q is quantified as calibrated pixel value in DN_s.

The algorithm (1) can also be corrected for emissivity or even atmospheric correction. No topography was taken into account when calculating the absolute values.

The study evaluates the temperature of the landscape coverage in six different years. Although all images were taken in the same month of August, it is not objective to compare absolute surface temperature values with each other because data would be obtained under different environmental conditions (atmospheric, seasonal, etc.). When analysing time changes, we can only compare the relative temperature values obtained by standardization. The z-scores method was used to standardize the data. The method uses an approach introduced by (Brom et al., 2012). Eq. (3) was used for data standardization:

$$T_s = \frac{T_i - \overline{T}}{SD} \quad (3)$$

where T_i is land surface temperature of pixel i, T is mean image temperature, and SD is standard deviation.

Vector information on land cover was obtained from the CORINE Land Cover database for 1990, 2000, 2006 and 2012. This European classification database is based on the visual interpretation of the IRS-6 and SPOT 5 satellite data. As complementary data, the LPIS database, topographic maps and aerial orthophotomaps were used. The basic map layers are available at a scale of 1:100,000. The data was used only for the territory of the Czech Republic. For the purpose of the study, the original 11 classes of land cover were grouped into 5 categories – coniferous forest, mixed and deciduous forests, fields and meadows, transitional woodland-shrub, and peat bogs. The transitional woodland-shrub is the area where the coniferous forests died after the bark beetle attack. The area of merged Corine classes is shown in Table 1.

Table 1
Changes in landcover classes area between 1990 and 2012 in the model area.

Year (area in hectares)				
Land cover (Numbers of Corine classes)	1990 (ha)	2000 (ha)	2006 (ha)	2012 (ha)
Urban areas (112)	103,8	103,8	135,5	135,5
Evergreen forest (312)	25 633,30	24 777	24 872,20	18 084,40
Mixed and deciduous forest (311, 313)	1 454,2	1 507	1 642,4	2 370
Fields and meadows (211, 231, 243, 321)	5696,4	5662,3	5302,4	5281
Transitional woodland-shrub (324)	4 517	5 360,8	5 195	11 272,40
Peatbogs (411, 412)	9 17,5	9 11,7	1 181,5	1 181,5

The land cover masks were created based on the vector data; consequently, they were used to calculate the relative temperature of the land cover category. The relative temperature characteristics of land cover classes are shown in Figs. 1 and 2 for 1991 and 2016.

Assessment of surface temperature change mainly focused on the evergreen forest category. 1991 was used as the reference year for temperature and forest occurrence. Images for the year of interest were compared with images from 1991 to assess temperature change in areas where coniferous forest remained and areas where it has decayed. The results are presented mainly in graphical form, which allows for spatial visualization of temperature changes in relation to land cover. Fig. 3 shows land cover and the relative surface temperature change. For the detailed temperature change assessment, two sites affected by bark beetles in different years were selected (Figs. 4 and 5). The ground thermal images complete the temperature comparison between green and decayed mountain spruce forest (Fig. 6).

3. Results

3.1. Surface temperature assessment based on Landsat satellite data

Evergreen and mixed, and deciduous forests belong to the coldest categories of landscape cover (Fig. 1) with the typical values between −1.6 and 1.6. Conversely, fields and meadows, and transitional woodland shrubs are not able to lower the surface temperature due to water scarcity and these landscapes reach the highest temperature values 0–2.5). The transitional woodland shrub area was characterized by low temperatures in 1991 (−0.4; at that time, it was represented only by grassland and shrubs). However, during the 25-year period the transitional woodland shrub area expanded into the area of decayed forest with dead trunks. This was accompanied by a temperature rise of nearly 1 °C in the transitional woodland shrub area (Fig. 2). Number of pixels (frequency) in Fig. 1 also shows the significant decrease of forest area accompanied by the increase of transitional woodland shrubs territory. A specific case of landscape cover is peat bogs. If their surface layer (acrotelm) is adequately supplied with water and does not dry out, it is one of the coldest types of landscape cover due to the evaporation of water (evapotranspiration) (Hesslerová et al. 2013, Huryna et al. 2014). However, if the surface layer is dry, the dry vegetation acts as a bare surface and the peat bogs appear warm on the thermal images.

Changing land cover is accompanied by surface temperature changes (Fig. 3). When the mountain spruce ecosystem collapses, the surface temperature increases, as confirmed by Hojdová et al. (2005) and Hais and Kučera (2008, 2009). In 1991, mountain spruce forest was the dominant land cover category, covering nearly 257 km^2. Healthy forest stands can cool the landscape due to evapotranspiration, which is reflected in low surface temperatures. The relative temperature values ranged from −2.1 to 3.9, with the lowest at the southern border ridge area (around −1.8). Between 1995 and 1998 the first extreme bark beetle attack occurred in the southern part of the study area (around the borderline Grosser Rachel – Lusen – Černá hora Mountain). The forest area decreased by 9 km^2, which was accompanied by a temperature increase of 1–2 °C; however, in the damaged forest the temperature increased by nearly 4 °C. Consequently, the area of transitional woodland shrubs increased by 8 km^2, extending into the area of decayed forests, which was reflected by a temperature increase of less than 1 °C. When the spruce forest collapses, there is a gradual change in the vertical structure of the forest as the trees begin to die. However, the dead forest has a certain amount of longevity with which it is able to maintain the temperature-humidity conditions of the habitat. The rapid rise in temperature occurs with a certain delay, which is evident in 2004, 2005, and 2009. There was an abrupt temperature increase in the area of Grosser Rachel – Lusen – Černá hora by at least 4 °C. In January 2007, the Czech Republic was affected by hurricane Kyrill that resulted in an extreme number of windfalls and windthrows. The hurricane hit the top of the Šumava NP; in particular, the border ridges from Plesná

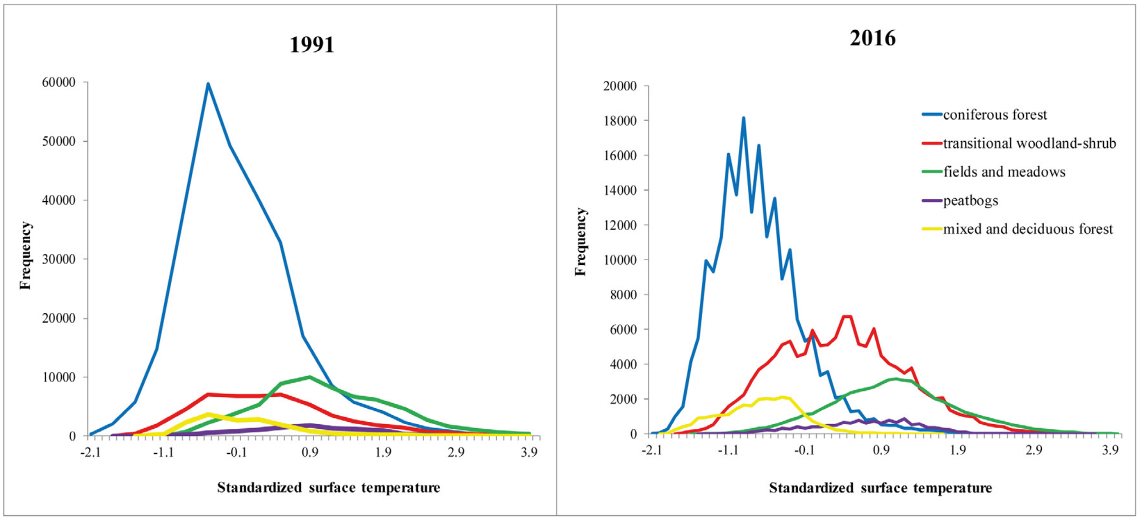

Fig. 1. Relative surface temperature of land cover.

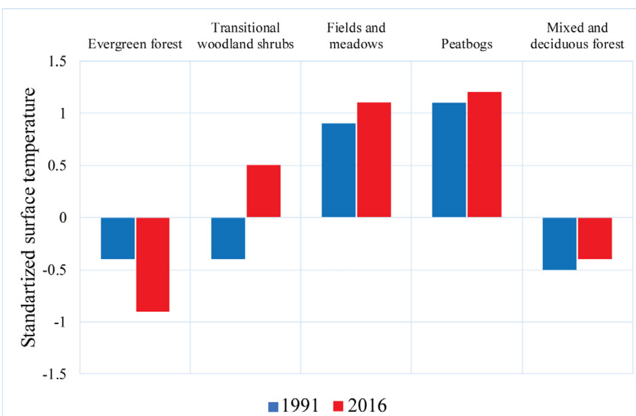

Fig. 2. Modus values of relative surface temperature for land cover categories.

in the western part of the park, Ždánidla and Poledník, then towards Modrava, in the southern part of the National Park, and the peaks in the vicinity of České Žleby and Trojmezná Mountains (out of model area). About 1 million fallen trees were removed and about 217,000 trees were left in the forests without processing. Unprocessed windfalls became the source of bark beetle propagation in the surrounding area. With regard to the number of destroyed trees, the greatest development of the insects in the modern history of the Šumava region occurred after 2007. The harvesting of affected trees from 2008 to 2010 exceeded the historical maxima. In the forests left for spontaneous development, hundreds of thousands of adult spruces died again. In the model area the mountain spruce forest occupied 180 km^2 in 2012 (in 1991 it was 256 km^2) and transitional woodland shrubs area significantly increased (from 45 km^2 in 1991 to 113 km^2 in 2012), which involved the areas of windfalls. This significant land cover change was accompanied by a temperature increase of 2–4 °C. Like transitional woodland shrubs, non-forest vegetation, such as meadows and pastures, are warmer surfaces. In the event that the original spruce is replaced by grassland after its decay, it is not possible to assume a significant decrease in the surface temperature to the level before the decay.

The change in surface temperature between the reference year 1991 and others is following: The slight temperature increase (0.2 °C) was observed from 1991 to 1998. However, over the following 6 years, the temperature increased sharply and the difference reached more than 0.9 °C in comparison with the initial state. From 2004 to 2009, the dead trees were removed and replaced by transitional woodland. This resulted in a temperature decrease of 0.3 °C. However, after hurricane Kyrill the temperature began to rise again. The temperature difference was around 0.7 °C by 2016.

Detailed temperature assessment

For the detailed development of the relative temperature in relation to change in land cover, two localities (see Fig. 3) – the area around the Poledník Mountain – locality 1 (1315 m a.s.l.) and the Špičník Mountain – locality 2 (1351 m a.s.l.) – were selected.

Locality 1 – Poledník mountain

The area of interest (553 ha) is defined by the coordinates 49°03′58″ N, 13°22′36″ E and 49°02′47″ N, 13°24′41″ E. In 2007, it was affected by Hurricane Kyrill, which caused extensive windfalls. The temperature development is shown in Fig. 4. From 1991 to 2005 no change in temperature was apparent in this locality. In 2009, because of large windfalls and consequent bark beetle calamity and total decay of forest, the temperature increased. The temperature increase between 1991 (green forest) and 2016 (grassland, dead trunks) was 2.3 °C.

Locality 2 – Blatný vrch – Špičník Mountains

The area Blatný vrch – Špičník (325 ha) is defined by the coordinates 48°58′14″ N, 13°26′18″ E and 48°57′39″ N, 13°28′39″ E. In the mid-1990s there was extensive bark beetle calamity and decay of the forest stand. Presently, the dry torso of the trunks prevails with the Calamagrostis sp and the blueberry (*Vaccinium myrtillus* L.). Fig. 5 shows the relative temperature development. In 1991, the values were lowest (−1.8); with the progressive decay of forest stands the temperature increased until 2009 (1.2). Gradual grassing of the locality resulted in slight temperature decrease to 0.6 in 2016.

3.2. Ground thermal measurements

Differences between landscape surface temperatures captured on the satellite images (Fig. 3) are likely much higher. This is due to the spatial resolution of the data. In order to provide detailed temperature measurements, ground thermal measurements are taken by a thermal camera (FLIR ThermaCamS65 HS). Images taken by the Thermovision Camera in the Třístoličník area in August 2016 captured detailed temperature distribution (Fig. 6). In the clearings, where fallen stems lie, temperatures ranged from 22 to 60 °C while the temperature of trunks was around 40 °C. The temperature in the forest was around 22 °C, with temperature inversion showing slightly higher temperatures

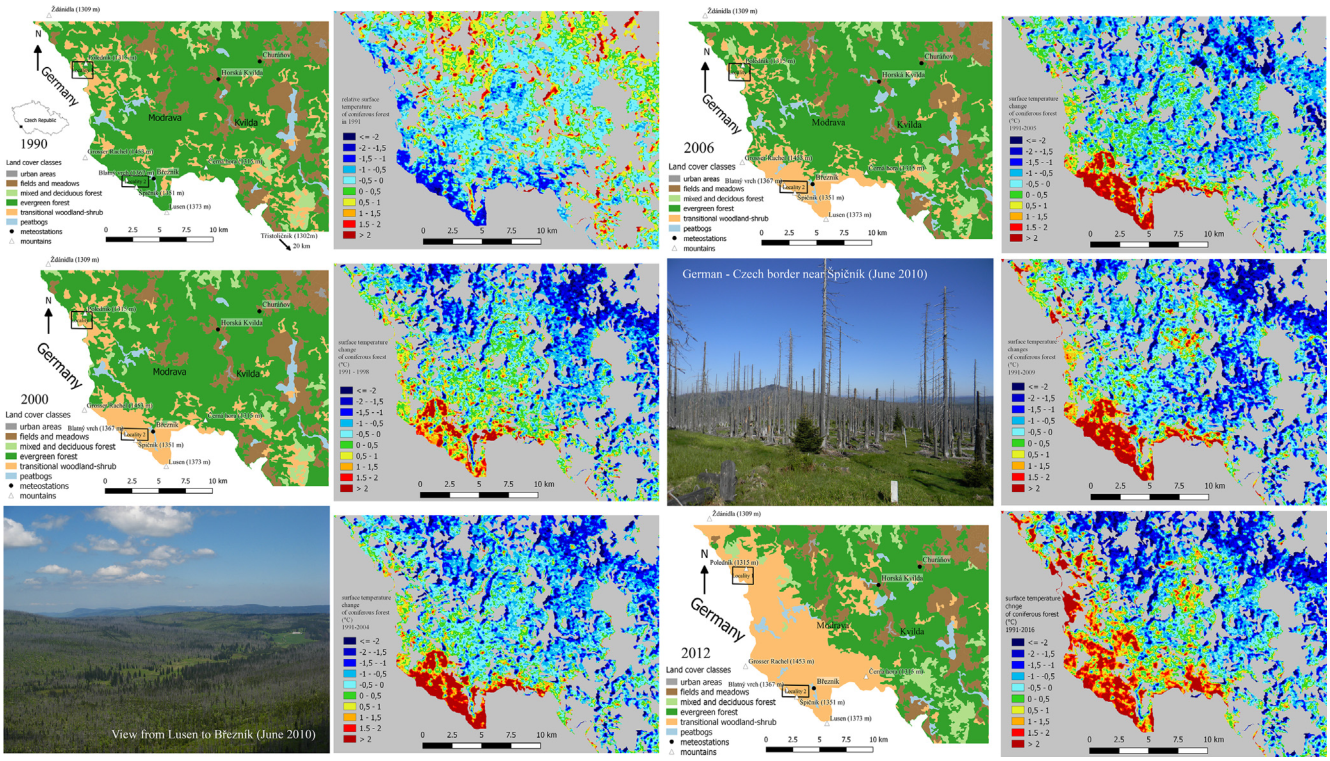

Fig. 3. The mosaic of images shows the land cover changes in the years 1990, 2000, 2009 and 2012 (based on Corine Land Cover database); The surface temperature changes of coniferous forest are based on comparison temperature difference between reference year 1991 and following years 1998, 2004, 2005, 2009 and 2016.

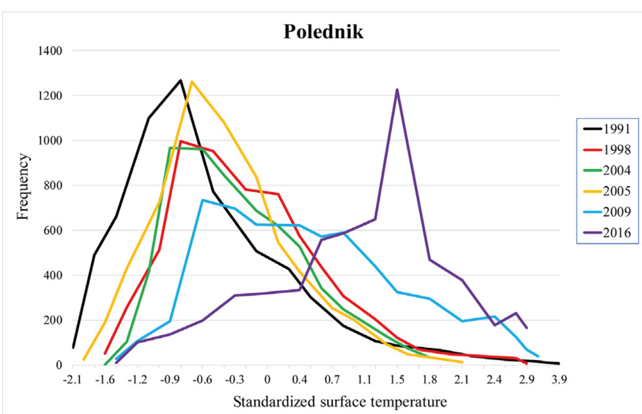

Fig. 4. Relative surface temperature changes in Poledník Mountain area.

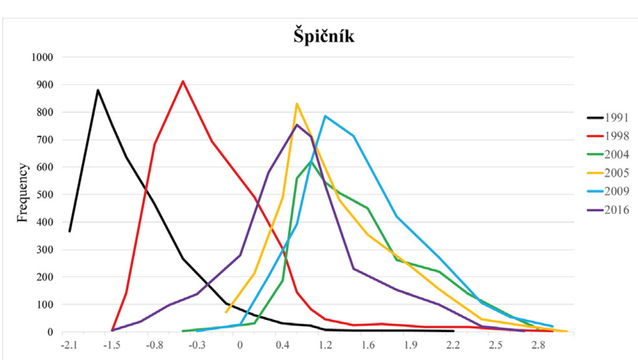

Fig. 5. Relative surface temperature changes in Blatný vrch – Špičník Mountains area.

in the canopy (23 °C) and one degree less in the undergrowth. Forest grasslands reached 27 °C.

3.3. Long term trends in air temperature

In addition to surface temperatures, the long-term trends of air temperature from 1988 to 2017 were evaluated at three meteorological stations. Březník is located in the heart of mountain spruce forests damaged by the disturbance on the tree floor. In the shallow valley, an amateur meteorological station has been in operation since 1987, which supplies data to the climatological network of the Czech Hydrometeorological Institute (CHMI). Therefore, it is possible to monitor the air temperature before the bark beetle calamity occurred, during the calamity, and at the current stage of gradual forest regeneration. To better document the described changes, a comparison was made between the meteorological stations. The second station was Churáňov (1118 m a.s.l., station of the CHMI), which is at a similar elevation, at the top of the hill 15 km NE from Březník outside the core area affected by bark beetle. The third station was the amateur station Horská Kvilda (1055 m a.s.l.) lying similarly to Březník in shallow depression, but between wooded flat ridges 11 km NNE from Březník.

At these three stations, the average annual air temperatures were compared between 1988 and 2017. Compared to the Churáňov and Horská Kvilda stations, there was a significant increase in the average annual air temperature at the Březník station in the last few years beginning in 2007–2008 (Fig. 7). If the differences between stations Churáňov – Horská Kvilda and Churáňov – Březník are compared, a similar trend will appear. The difference in average annual temperatures between Churáňov and Horská Kvilda remains roughly the same, between 1.5 and 1.8 °C, while the average difference between Churáňov and Březník changed. In the first two decades of observation, this difference was between 3 and 4 °C, but in the last decade there was a gradual decrease (Fig. 7). In the last five years, the average difference was 2 °C.

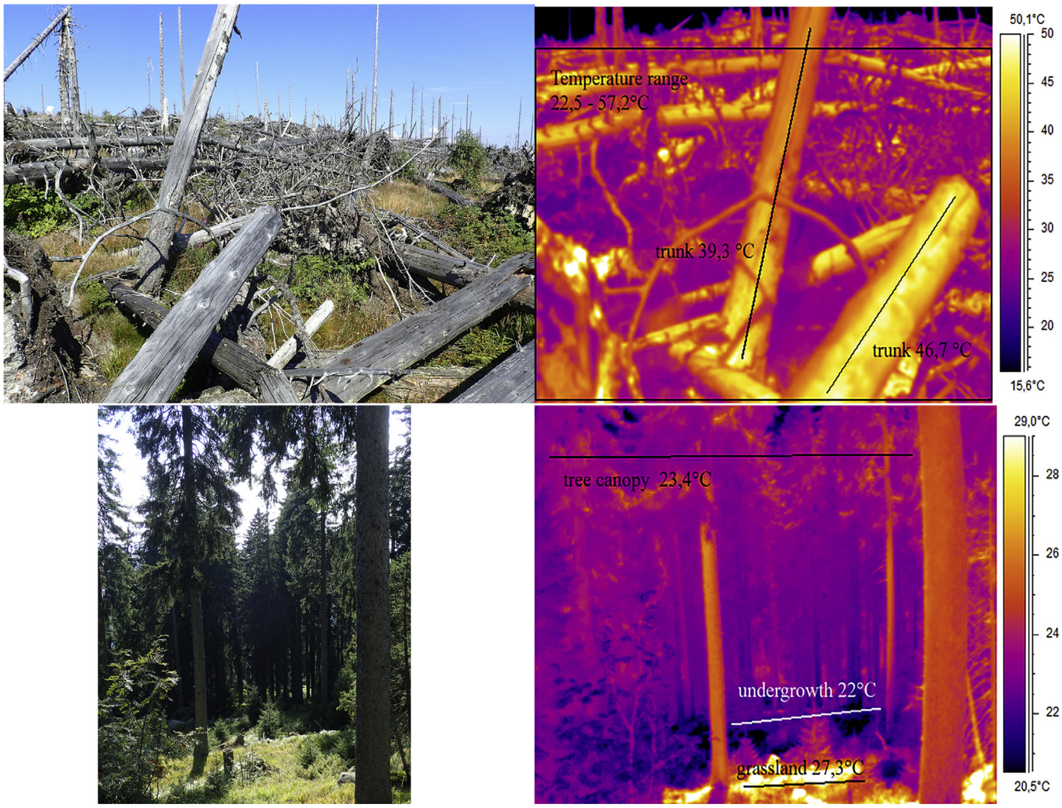

Fig. 6. Examples of images taken by the Thermovision Camera in the Třístoličník area in August 2016. Surface temperature differences in forest reach 4 °C, while in clearings with dead trunks reach nearly 35 °C.

3.4. Earlier snow ablation in the disturbed forest

Areas with disturbed forest experienced faster snowmelt and increased spring runoff. These areas included the entire narrow border zone on the Bohemian side of the Šumava Mountain at the highest elevations (about 1250–1378 m a.s.l.), the mountain ranges from Jezerní hora and Svaroh in the west, to the Trojmezná ridge with the highest peak, and Plechý in the southeast. One of the few border peaks where mature forest is still present is the Smrčina region at about 1330 m a.s.l. (out of model area). From here, it is possible to compare snowmelt and snow accumulation at the highest elevations of the Šumava where adult living forests are still present with places where the forest has decayed, in this case, the area around the peak of Poledník (about 1310 m a.s.l.).

Forest disturbance affects not only surface and air temperatures, but also influences timing and rate of snowmelt and runoff of water from the river basin. The climatic network of the CHMI is very sparse in the Šumava region, but in recent years, it has been possible to carry out regular monitoring of the height of the snow cover and air temperature in many places in the Šumava Mountains (Procházka et al., 2017). This monitoring, thanks to new technologies, also includes the highest elevations of the Šumava. Results from the Poledník and Smrčina summits during the last four winter periods show clear differences in spring snow ablation on bare surfaces after forest decay compared to forested areas that are positively affected by the tree floor microclimate (Fig. 8). The accumulation of snow in early winter is always very similar. During the winter, due to the influence of known factors of the thaws (temperature, rain, wind) and solar radiation, the differences begin to show and peak in the spring season when snowmelt begins. The duration of permanent snow cover on forested peaks over the last four years was, on average, 11 days longer than on the peaks without trees.

4. Discussion

Healthy forest stands (deciduous and mixed, coniferous) are surfaces that cool the landscape due to evapotranspiration, which is reflected in low surface temperatures. The category of transitional woodland-shrub partly replaced the coniferous forest. It is characterized by high surface temperatures and temperature increase, on average, by 4 °C. Hais and Kučera (2008) compared surface temperature of living spruce forest with decayed forest (standing dry trees) and clear-cuts in the similar model area from Landsat data. The results show an average increase of surface temperature by 3.5 °C and 5.2 °C, respectively.

Non-forest vegetation such as meadows, pastures, and fields also belong to the warmest areas. Therefore, grassland vegetation that appears in deforested localities as a compensation for the forest, cannot significantly decrease the surface temperature. A specific case is peat bogs. If acrotelm has an adequate water supply, it is one of the coldest types of land cover due to evapotranspiration (Huryna et al., 2014). If the surface layer is dry, dry vegetation acts as a bare surface and peat bogs appear warm on the thermal images (Hesslerová et al., 2013). When the spruces break down, the surface temperature increases. This fact is evident in the entire border area (Fig. 3). The difference between forested and deforested localities can reach 10 °C (ground measurements).

Landsat satellite acquires the images repeatedly approximately at 9:50 GTM (10:50 Central European Time) and therefore cannot capture afternoon maximums, yet the high temperature of the woodland-shrubs, as well as grasslands, is obvious. Differences in land cover temperatures as captured on the satellite images may actually be much higher. This is due to the spatial resolution of the data. For example, temperature information is the average pixel value for an area of 100 × 100 m in 2016, for others it is 120 × 120 m. If a given part of the territory is heterogeneous in terms of land cover, thermal information is

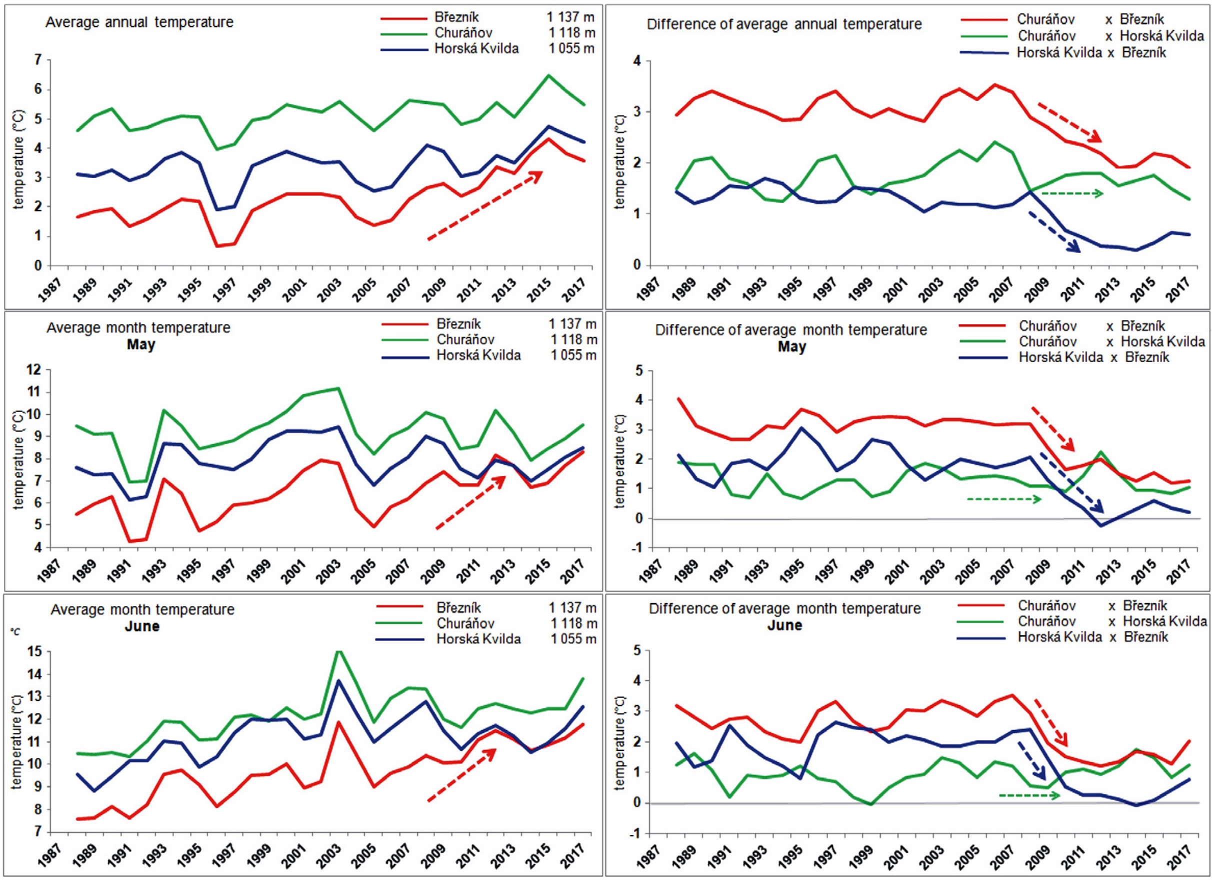

Fig. 7. Average annual temperature at the meteorological stations of Březník (1137 m a.s.l.), Churáňov (1 118 m a.s.l.) and Horská Kvilda (1055 m a.s.l.). Air temperature differences (in ˚C) between Churáňov station x Březník and Churáňov × Horská Kvilda between 1988 and 2017 (Data source: CHMI and A. Vojvodík – operator of amateur meteorological stations).

also heterogeneous; i.e. it is the average temperature of different types of surfaces. The pixel heterogeneity and topography effects on surface temperature are discussed in Hais and Kučera (2009). Despite this fact, changes in temperatures due to extensive changes in land cover are clearly visible on Landsat satellite imagery.

The current outbreak of bark beetle in the part of the southwest territory of the Czech Republic with overlapping to Austria and Bavaria was preceded by three calamities the largest in 1868–1878 and then the end of the First and the Second World Wars. Afterwards, the bark beetle spread in Germany and throughout the central Europe. There have been

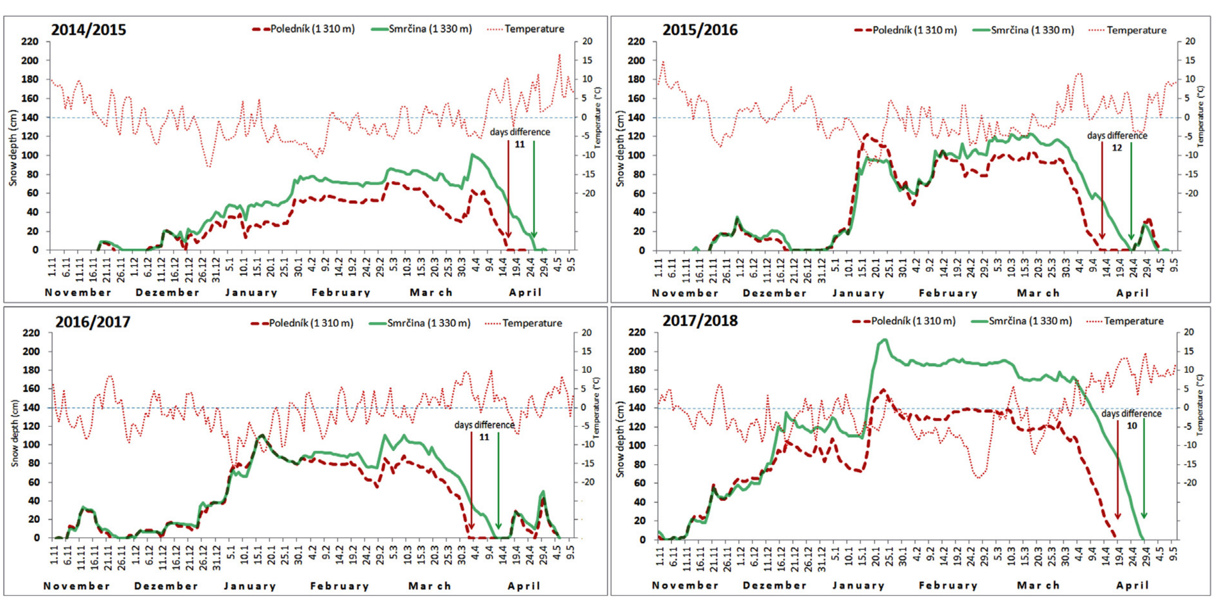

Fig. 8. Snow cover height (in cm) in winter seasons 2014/2015 to 2017/2018 at the peaks of Poledník (1 310 m a.s.l.) and Smrčina (1330 m a.s.l.). Average daily temperature at the meteorological station Plechý (1344 m a.s.l.). (Data source: CHMI and I. Rolčík, DiS. – operator of Plechý meteorological station).

numerous calamities since 1970 in various parts of Central and Eastern Europe, and have been culminating in recent years, which is linked to worse forest management (due to lack of people), water scarcity, drought and climate change. Similarly, bark beetle calamities occurred in Sweden, Norway, France, the Balkan peninsula, Ukraine, the Baltic republics. Extensive and less mentioned are calamities in the spruce forests of Russia from 55° to 63° N, in Ural region and in the western and eastern parts of Siberia. The individual calamities represented up to two tens of millions of m^3 of dry wood. Many original studies of spruce calamities have not been written in the world languages, and the papers in which they were published were, and are, hard to reach. Skuhravý (2002) quotes 400 citations from Europe, including less accessible works in the original language of the former Soviet Union, Poland and the Balkan countries.

Many authors interest mainly in the relationship of climate and climate change on bark beetle outbreaks (Fauria and Johnson 2009; Bentz et al. 2010; Berg et al. 2006). There is not much attention paid to direct effect of forest decay caused by bark beetle calamity on local climate in terms of active role of healthy forest in local precipitation and water cycle as described by Sheil and Murdiyarso (2009), Sheil (2018). Sagar and Waterhouse (2015) studied the changes in microclimate (air and soil temperature, frost events and snow-free days) in the Chilcotian Plateau in British Columbia in relation to partial cuts and clear-cuts, as well as with outbreak of pine beetle (*Dendroctonus ponderosae*). The effect of forest structure changes on microclimate due to human activity and natural disturbances (such as insect's outbreaks) reviewed by Chen et al. (1999). Classen et al. (2005) investigated the influence of herbivory insects on changes in vegetation (canopy change) and consequently on microclimate (soil moisture and temperature) and nutrient cycling in Northern Arizona. Deforestation caused by bark beetle outbreaks in Rocky Mountains (North America) was also responsible for water budget changes which caused decrease of transpiration with subsequent increase in groundwater contributions to streams (Bearup et al. 2014). The similar results provide Redding et al. (2008): "The current mountain pine beetle infestation and associated salvage harvesting have the potential to affect the amount, timing, and quality of water originating from British Columbia's forested watersheds". The authors elaborated the general recommendations for avoiding hydrological risks in management and planning for both the forested watersheds and the valley-bottom infrastructure.

The impact of bark beetle calamity on the hydrological balance of the Šumava national park territory is a widely discussed topic. There is the assumption that deforestation and decay of the tree floor will result in decreased evapotranspiration, which compensates for the loss of water caused by an eventual increase in runoff. In addition, dead trees have a smaller surface area (leaf area index) than live trees, so more rainfall will reach the upper soil layer, which supports groundwater supply. Beudert et al. (2007) studied hydrological balance in connection with bark beetle calamity in the Bavarian Forest. The forest decay caused significant changes in the soil water balance and runoff. Fast forest dieback, where 80% of trees died, resulted in a 39% decrease in evapotranspiration (ET) and a direct runoff increase of 162%. Additionally, fast and slow groundwater runoff reached 125%, and 132%, respectively, when compared to reference data. After alternative vegetation development, there was a significant increase of ET, up to 78% and direct runoff reached 70%. Despite the fact that both groundwater levels reached the normal level, the fast component decreased to 74%, whereas the slow increased to 136%, which confirms significant effects of deforestation on groundwater level. Bečka and Beudert (2016) discuss several examples of hydrological response to disturbance (bark beetle calamity) and climate change. In the Forellenbach catchment area in the Roklan-Lusen area, annual transpiration from 1996 to 1997 decreased from approximately 700 $l{\cdot}m^{-2}$ to 450 $l{\cdot}m^{-2}$ because of the decline in mountain spruce forest. Absence of evapotranspiration leads to an increase in the amount of infiltrating water and faster recovery of groundwater supplies and a consequent increase in runoff. Another study conducted from 1992 to 2013 examined changes in the hydrological balance of two streams lying in a non-intervention zone in the Roklan-Lusen area. After approximately 30% of spruce forests died in 1999, annual runoff increased in both catchments by 146 $l{\cdot}m^{-2}$ (Forellenbach) and 127 $l{\cdot}m^{-2}$ (Große Ohe). The amount of precipitation remained almost the same and evapotranspiration decreased by 120 $l{\cdot}m^{-2}$ and 90 $l{\cdot}m^{-2}$, respectively; at the same time, the groundwater reserves increased. The third example presented by the authors compared the water conditions of large watercourses around the Bavarian Forest National Park between 1978 and 2013. In areas with less than 36% of the forest vegetation, there was a decline in annual runoff, but the total rainfall remained unchanged. Unchanged annual runoff is also typical for river basins where more than 50% of the trees have died. The authors associate this change with increased evapotranspiration, which is caused by warming from May to August of ~2 °C (measurements at 4 meteorological stations), even in April by 4 °C. Reduced evapotranspiration from the dead stand is compensated for by increased evaporation from the surface enhanced by climate change. It is unlikely that the authors realized deforestation caused changes in evapotranspiration, resulting in a change in the dissipation of solar energy. Heat flows are directed to sensible heat instead of the latent heat of the vapour, resulting in rising surface temperatures and further loss of water. The difference in latent and sensible heat distribution of forest stands and in drained areas, on bright, hot days, is a matter of hundreds of $W{\cdot}m^{-2}$. The decline in evapotranspiration of 1 km^2 due to drainage or degradation of the forest for an equivalent to 100 $mg{\cdot}m^{-2}{\cdot}s^{-1}$ water vapour represents 250 megawatts of solar energy released from the area 1 km^{-2} into the atmosphere in the form of warm air (sensible heat). However, the real value of the sensible heat may be higher. From a thousand hectares (10 km^2) of dry forest, 2000 megawatts of energy are released into the atmosphere in the form of sensible heat on sunny days, resulting in changes in airflow and gradual drying. From 1990 to 2012 7500 ha of evergreen forest was lost (approx. 30%) in the model area. A minimum of 15,000 megawatts of energy is released in the form of sensible heat in hot summer days from this area.

It should be pointed out that air heated by warm surfaces that ascends into atmosphere contains water vapour. Landscapes lose water with this rising warm air driven by sensible heat. The amount of water in the air transported by sensible heat into atmosphere can be substantially higher than that released by evapotranspiration. For example, air at 100% relative humidity at a temperature of 40 °C contains 50 g of water vapour in 1 m^3 whereas air at 20% relative humidity contains 10 g of water vapour in 1 m^3. Air driven by sensible heat from 1 m^2 at a speed of 0.1 $m{\cdot}s^{-1}$ would transport 3.6 kg water into the atmosphere over the course of an hour, i.e. over 30 L per day. The effect is known as advection of energy (warming of relative dry air) from overheated dry surfaces. These are water losses that are not measured as flow rate in rivers. In the summer, "air rivers" can drain invisibly more water than water courses. Discharge in rivers decreases and water gets high in the atmosphere.

Common values of ET are several mm (several litres per m^2 per day). Very high values of ET are about 10 mm. From this point of view, ET can be considered as a process that slows down evaporation water losses from the landscape on regional level. ET binds surplus solar energy into latent heat of water vapour and reduces release of sensible heat; water vapour is not driven up and stays close to the canopy. Tesař et al. (2006) assessed temperature regimes of three mountain forest basins in the Šumava at various stages of development (dead spruce forest with herbaceous undergrowth, clearings covered by herbaceous vegetation, and mature spruce forest). Results showed that both soil and air temperature are influenced by plant cover and the extremes in day and night-time air temperatures are a function of transpiring vegetation height in hot and dry days, with higher daily maximums and lower night-time minimums for areas with smaller vegetation. For the period of the entire growing season, mean air temperature was independent of plant cover, but the magnitude of the dispersion variance followed the sequence in ascending order: mature forest – clearing – dead forest. Consequently, Bässler (2008), Bernsteinová et al. (2015), and Langhammer et al. (2015), observed increasing air temperatures in the Šumava for 80 years, most notably in the spring (+ ~4 K in April). As a result of climatic changes and forest decay, the Vydra basin showed changes in the seasonality and variability of runoff; a significant amount of runoff that historically occurred during the summer is now occurring in the spring period, when the melting of snow cover is accelerated by rising air temperatures. A number of studies have shown the positive influence of mature forest on slowing snowmelt and outflows from the catchment area (Troendle and Reuss, 1997; Kantor and Shach, 2002; Pomeroy et al., 2012). Even in extreme situations, as shown by Marks et al. (1998) with the Oregon flood (USA, February 1996), the forest areas in the Cascade Mountains retained a significant amount of rain in the snow compared to deforested ones. Hríbik et al. (2012) studied the influence of spruce (*Picea abies* (L.) *Karst.*) on the hydrophysical properties of the snow cover and results indicated that coniferous stands play an important role both in snowmelt and runoff formation. The results of a study conducted in Central Slovakia (in Polana Biosphere Reserve) showed a significant effect of spruce forests in slowing down snowmelt and spring runoff from the entire catchment area of the Hucava stream watershed. In the Šumava, the influence of spruce forests and the forest affected by bark beetle (*Ips typographus* L.) on snow cover, melting speed, and the formation of runoff are discussed by Buchtele et al. (2006), Bernsteinová et al. (2015), Langhammer et al. (2015), and Jeníček et al. (2017). The surveys coincide with faster melting of the snow cover and increased spring runoff from model river basins and areas affected by deadwood trees.

5. Conclusions

The analyses of thermal satellite images show an increase in surface temperature in the area where the forest canopy layer died, due to bark beetle outbreaks, in the order of 2–4 °C. The meteorological station located in the center of the dieback forest area recorded a twice as fast increase in the average air temperature than the stations in the green forest areas. Similarly, it has been documented accelerated melting of the snow cover (by 11 days).

High surface temperature in the decayed forest indicates production of sensible heat instead of evapotranspiration, which cools adult live forests. Sensible heat drives the turbulent movement of air into the atmosphere. The ascending warm air transports water vapour into the atmosphere and dries the surrounding landscape by the so-called advection effect. Production of sensible heat reaches several hundred Watts per m^2 on sunny days during the growing season. The area of c. 7500 ha, which lost high adult forest, and which shows an increase of surface temperature, produces at least 17,000 megawatts of sensible heat. This is transformed solar energy, which dries the landscape and affects movement of air on at least the regional scale.

Climate extremes are not moderated by water and vegetation. Water and vegetation form the climate, equalizing differences in temperatures and pressures that cause torrential rains and storms. Man has deforested and drained large areas. Warm air rises from dry areas, dissolving clouds, and the landscape becomes even more heated. Deforestation releases sensible heat (heated air from the overheated surface of the landscape) in the range of hundreds of watts per m^2. This has been known since the mid-20th century and can be easily measured. Increased concentrations of greenhouse gases caused an increase of radiation forcing by 1–3 $W{\cdot}m^{-2}$, which cannot be measured. Life is essentially immanent to balance differences in energy. In order to compensate for differences in pressure and temperature, life is maintained and developed from these differences. Average temperature may not always be an opposite variable for assessing climate change, as it not reflects daily and seasonal temperature dynamics and extremes and therefore cannot describe real effect of climate change. Even equal/balanced temperature is the end of motion. For example, air temperature in the forest is 18 °C in the morning and 22 °C in the afternoon. When we cut the forest down, the temperature is 15 °C in the morning and 25 °C in the afternoon. The climate has changed, however, the average temperature (20 °C) is still the same. Climate change caused by deforestation and, drainage is more significant than it can be seen from an increase in average global temperature.

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