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PÔVODNÁ PRÁCA – ORIGINAL PAPER

Influence of selected factors on bark beetle outbreak dynamics in the Western Carpathians

Vplyv vybraných faktorov na vývoj kalamitného premnoženia podkôrneho hmyzu v západných Karpatoch

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Abstract
In the period from 1992 to 2013, more than 3.8 million m^3 of spruce wood from an area of 55 thousand ha of forests in the Kysuce region (Western Carpathians) was affected by bark beetles. This region has had the highest volume of salvage fellings in Slovakia. While before 1991, bark-beetle outbreak usually occurred after snow and wind disturbances, since 1992 they have occurred in the years with extremely warm and dry growing seasons and the years following them. These years were also characterised by high volumes of wood affected by honey fungus (*Armillaria* spp.), which only rarely took part in the calamities before 1992. Extreme deterioration of the situation occurred after 2003. In fragmented and sparse stands, the volume of wood damaged by wind increased. Artificial origin of spruce stands, their high occurrence, high age and even-agedness are likely pre-disposing factors of spruce forest decline. Bark beetles have become the most important factor of spruce decline. The most important factors driving the bark beetle attack on forest stands in the period 1973–2013 were the amount of unprocessed wood in the previous year; the amount of wood affected by honey fungus, precipitation total, and average temperature in the current growing season. Another important factor that complicated the situation was also the inferior quality of forest management.

Keywords: *Ips typographus;* spruce decline; regression modelling; weather condition; salvage felling

Abstrakt
V období rokov 1992–2013 bolo v regióne Kysúc (Západné Karpaty) napadnutých podkôrnym hmyzom viac ako 3,8 mil. m^3 smrekového dreva na ploche 55 tis. ha lesa. Tento región patrí dlhodobo k regiónom s najvyšším objemom náhodných ťažieb na Slovensku. Pokiaľ do roku 1991 dochádzalo k premnoženiu podkôrneho hmyzu predovšetkým po snehových a vetrových kalamitách, od roku 1992 dochádza ku vzniku kalamít podkôrneho hmyzu v rokoch s extrémne teplými a suchými vegetačnými sezónami a v rokoch po nich nasledujúcich. Tieto roky sa vyznačujú zároveň vysokým objemom dreva napadnutého podpňovkou, ktorá sa podieľala na kalamitách pred rokom 1992 len zriedkavo. K extrémnemu zhoršeniu situácie dochádza po roku 2003. Vo fragmentovaných a prerieďených porastoch dochádza následne k nárastu objemu dreva poškodeného vetrom. Nepôvodnosť smrekových porastov, ich vysoké zastúpenie, vysoký vek a rovnovekosť sú predispozičnými faktormi odumierania smrečín. Podkôrny hmyz sa stal najvýznamnejším činiteľom odumierania smrečín. Faktormi najvýznamnejšie vplývajúcimi na napadnutie porastov podkôrnym hmyzom v období 1973–2013 boli množstvo nespracovaného dreva v predchádzajúcom roku; množstvo dreva napadnutého podpňovkou, úhrn zrážok a priemerná teplota vo vegetačnej sezóne v danom roku. Medzi ďalší faktor, ktorý významne skomplikoval situáciu bola zhoršená kvalita lesníckeho manažmentu.

Kľúčové slová: *Ips typographus;* odumieranie smrečín; Beskydy; počasie; náhodná ťažba

1. Introduction

In the last 7 years, bark beetles have been the most destructive disturbance agent in Slovak forests; in 2013, 1.5 mil. m^3 of processed spruce timber was infected by bark beetles (Kunca et al. 2014). The most important species from this group is Spruce bark beetle (*Ips typographus* L.), which accounted for 94% of this volume. Other important species are Six-toothed spruce bark beetle (*Pityogenes chalcographus* L.), Double-spined bark beetle (*Ips duplicatus* Sahlberg) and bark beetles on pine. The outbreaks of bark beetles on spruce have been initiated by wind-throws in the mountains of the Central Carpathians, and physiological weakening of Norway spruce (*Picea abies* L.) stands in the mountain ranges formed by flysch rocks (Vakula et al. 2014).

Bark beetle outbreaks generally last from 5 to 7 years, during which many trees are killed (Schroeder & Lindelöw 2002; Jakuš et al. 2003). The dynamics of outbreaks depend largely on insect abundance, tree susceptibility, weather conditions, and human measures (Wermelinger 2004). *I. typographus* prefers reproduction in the breeding material

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with non-existent or weak defences such as wind-thrown or otherwise damaged trees, cut slash and debarked felled timber.

Physiological weakening of spruce stands or so called contemporary spruce decline (Hlásny & Sitková 2010) is accompanied by the outbreaks of honey fungus (*Armillaria* spp.), which attacks physiologically weakened trees. The trees are consequently attacked by bark beetles. The analysis of the trees from salvage felling in the Kysuce region revealed that honey fungus occurred in 68% of salvage wood (Longauerová et al. 2010). A specific feature of this type of decline is an accompanying occurrence of invasive species of Double-spined bark beetle (*Ips duplicatus*), which was reported from Slovakia in 1996. In subsequent years, an expansion and outbreak of this bark beetle occurred (Vakula et al. 2007). Locally, Double-spined bark beetle (*Ips duplicatus*) is more abundant than Spruce bark beetle (*Ips typographus*). This type of spruce forest die-back occurs also in the border regions of the Czech Republic and Poland (Holuša 2004; Grodzki 2007), where it started at the beginning of 90s, but especially after 2003. Health condition of spruce forests was affected by several predisposing factors, the most important of which is the allochthonous character of spruce growing at unsuitable sites (Holuša 2004; Grodzki 2010). Forest stands that are insufficiently adapted to currently changing environmental conditions, such as secondary Norway spruce stands growing outside their natural occurrence, are particularly susceptible to disturbances (Seidl et al. 2008). The largest die-back in the north-western part of Slovakia began after 2003, which was an extremely warm and dry year. The forests started to be physiologically weak. The weakened spruce stands were easily attacked by honey fungus. In the trees affected by honey fungus, bark beetles were excessively propagated. Later, bark beetles started to be the primary die--back factor (Vakula 2012).

Warm and dry weather can increase the frequency of bark beetles in two different ways: directly – drought affects physiological conditions of trees and makes them susceptible to bark beetle attack, indirectly – high temperatures create favourable conditions for mass bark beetle swarming, and for their searching for host trees, and accelerate the juvenile development. Christiansen & Bakke (1997) found that except for scarce cases of long-term droughts, it is more probable that the dynamics of bark beetle propagation is directly affected by spring weather rather than indirectly by the physiology of host tree species. The analysis of long-term data from the south-eastern Alps showed that spring drought increases the next-year damage caused by bark beetles, while warm spring affects its phenology (Faccoli 2009). Climatic extremes can accelerate chronic declines associated with human management (Jurskis 2006).

Trees affected by honey fungus are preferably attacked by bark beetles (Tkacz & Schmitz 1986). Due to the production of volatile substances, trees affected by *Armillaria* spp. are attractive to bark beetles (Madziara-Borusiewicz & Strzelecka 1977). Root systems affected by fungi contribute to a gradual damage of sap flow resulting in qualitative and quantitative changes in sap and bark. These changes also modify the attractiveness of affected individuals for bark beetles (Rudinský et al. 1970).

The goal of this work was to describe the time course of bark-beetle outbreaks since 1973, and to assess the impact of selected factors on the volume of wood affected by bark beetles in the part of the Western Carpathians.

2. Material and methods

2.1. Study area

The study area is located in the north-western region of Slovakia called Kysuce. The region is situated at the border of three countries: Slovak Republic, Czech Republic and Poland, within two Slovak districts of Čadca and Kysucké Nové Mesto (Fig. 1). The forest cover is about 55,000 ha, of which 40% is owned by state and 60% by non-state companies. Forest area constitutes 59% of the total area of the region. In the area, the Norway spruce *Picea abies* L. (71%), common beech *Fagus sylvatica* L. (14%), silver fir *Abies alba* Mill. (7%) and Scots pine *Pinus sylvestris* L. (2%) are the dominating tree species. Other species occur only occasionally. Non-native spruce stands (*Picea abies* L.) grow in 4th and 5th vegetation zones. Orographically, this region belongs to the Beskid Mts., Javorníky Mts. and the Kysuce Highlands mountain ranges of the western Carpathians. Geologically, the region is located mainly at the palaeogenetic flysch. An elevation of the region varies between 400 – 1,200 m a.s.l.

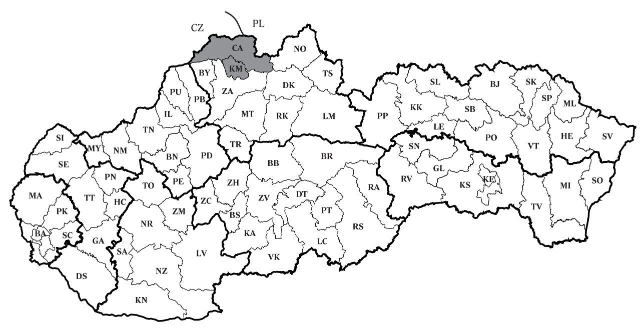

Fig. 1. Position of the study area in northwestern part of part of Slovakia (districts Čadca and Kysucké Nové Mesto).

2.2. Data collection

The information on the volume of salvage felling timber was obtained from the register, which is managed, checked, and evaluated for the whole Slovakia by the Forest Protection Service Centre in Banská Štiavnica. The data were obtained for the period from 1973 to 2013. The data on the volume of affected, processed and unprocessed wood were recorded separately. The data on the volume of wood damaged by bark beetles (hereafter as BB) represents summary data for the following species: Spruce bark beetle (*Ips typographus* L.), Six-toothed spruce bark beetle (*Pityogenes chalcographus* L.), and other species. The group of other bark beetle species includes Double-spined bark beetle (*Ips duplicatus* Sahlberg), Eight-toothed spruce bark beetle (*Ips amitinus* Eichhoff), and Small spruce bark beetle (*Polygraphus poligraphus* L.), which are not recorded separately. In the examined period, Spruce bark beetle was the dominant species, which accounted for 92% of the wood amount affected by BB. The data on the other analysed factors, i.e. on honey fungus, wind and snow were obtained in the same way.

Meteorological data were obtained from Čadca meteorological station (source SHMÚ). The data were obtained for the period from 1951 to 2013. Each year was characterised by the average temperature and precipitation total in the growing season (from April 1st to September 30th). The data were compared with the long-term average (hereafter as LTA) temperatures and total precipitation representing the period from 1951 to 1980. The occurrence frequency of above-average temperatures was calculated as a ratio (%) of the years with the temperatures higher than LTA. The occurrence frequency of below-average temperatures was calculated as a ratio (%) of the years with the temperatures lower than LTA.

We analysed two time periods. The first period between 1973 and 1991 (hereinafter as 1st period) represents the period prior to the spruce forest decline. The second period between 1992 and 2013 (hereinafter as 2nd period) is the period of the large-scale spruce forest decline in the examined region.

2.3. Data analyses

Statistical evaluation of the results was performed in Statistica 10 software (Stat Soft, CR, s.r.o.). Factor analysis, method of principal components with the rotation of Varimax normalised, was used to assess the relations between the analysed factors (independent variables) and to reduce the number of independent variables entering the multiple regression analysis applied afterwards.

Factor scores were subsequently used in multiple linear regression, in which wood volume affected by BB in year "n" was the dependent variable. Independent variables were the unprocessed wood affected by BB in year "n-1", wood volume damaged by wind and snow in year "n-1", wood volume affected by honey fungus in year "n", average temperature, and precipitation total in the growing season in year "n". Regression parameters were estimated using least squares method.

3. Results

3.1. Bark beetle outbreak dynamics

During 1st period (Fig. 2a) we observed the first increase in the volume of wood affected by BB in 1977, which culminated in 1979 (9 thousand m^3 of affected wood). The next increase in the volume of wood affected by BB occurred in 1984 (5 thousand m^3), and culminated in 1989 (6 thousand m^3). The average annual volume of affected wood was 3.5 thousand m^3.

During 2nd period (Fig. 2b) we observed the first slight increase in the volume of affected wood in 1992 (7 thousand m^3) with the weak culmination in 1995 (47 thousand m^3). The next increase in the volume of affected wood was observed in 1998 with the culmination in 1999. Another increase of salvage trees affected by BB was recorded in 2003 with the culmination in 2004 (181 thousand m^3). In 2007, a further increase in the volume of wood affected by BB (263 thousand m^3) with the culmination in 2009 (668 thousand m^3) was observed. The year 2009 was the year with the highest volume of wood affected by BB since 1973. After 2009, there was a gradual decrease in the volume of wood affected by BB, with a significant decrease after the year 2010. In 2012, we observed a slight increase in the volume of wood affected by BB. The reason for this development was the substantial reduction and locally even the total absence of spruce stands with the age above 60 years. Considering the calamities, the period between 2003 and 2013 was the most critical since 1973, as during this time salvage fellings accounted for 77–99% of the total felling amount (Fig. 3). The annual average volume of salvage fellings was 462 thousand m^3 per year. In this period, a large amount of wood affected by BB was left unprocessed at sites (43 thousand m^3 on average), which had a negative impact on the amount of wood affected in the following years.

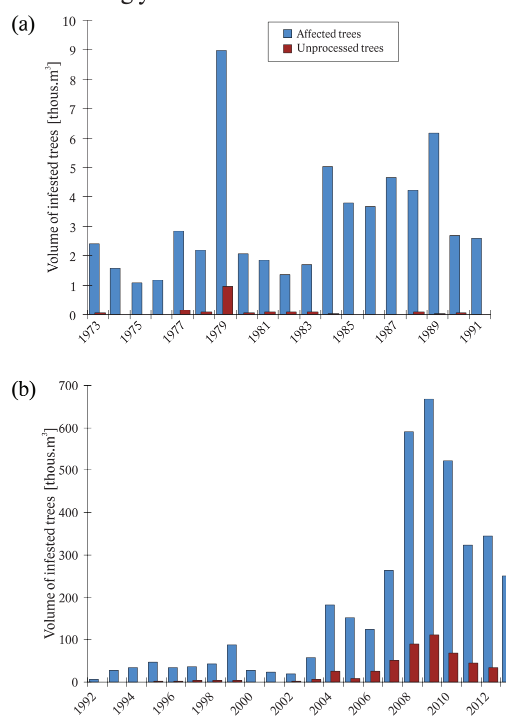

Fig. 2. Volume of trees infested by bark beetles in 1st period between 1973 and 1991 (a) and in 2nd period between 1992 and 2013 (b) in the Kysuce region (National Forest Centre - Forest Protection Service, Slovakia; internal data).

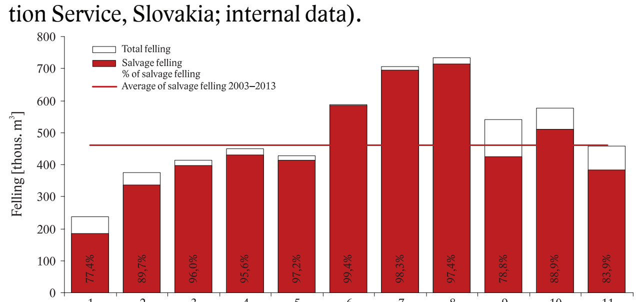

Fig. 3. Volume of felling between 2003 and 2013 in the Kysuce region (National Forest Centre - Forest Protection Service, Slovakia; internal data).

On the basis of the observed results we can say that during 1st period two smaller bark-beetle gradations occurred, after which the maximum annual volume of affected wood did not exceed 9 thousand m³. In the second period we recorded 4 bark-beetle gradations with the maximum annual volume of 668 thousand m³ of affected wood. Until 1991, the average annual volume of wood affected by BB was only 3 thousand m³, while after 1992 it was 176 thousand m³, which is 56-times more (Table 1).

Table 1. Average annual volume (thousand m³) of trees damaged by the most important pest agents in the studied periods in the Kysuce region (National Forest Centre - Forest Protection Service, Slovakia; internal data).

Time period	Bark beetles	Honey fungus	Wind	Snow
1973–1991 (19 years)	3,162	1,829	20,050	20,437
1992–2013 (22 years)	175,866	93,284	36,890	10,735

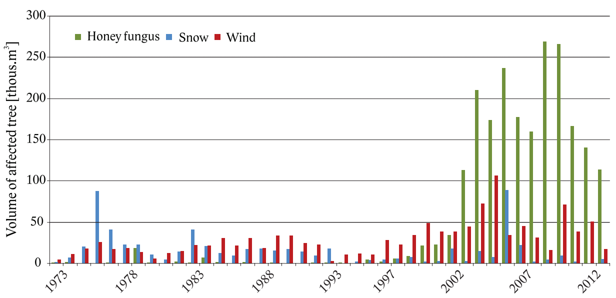

Fig. 4. Volume of trees affected and damaged by honey fungus, snow and wind in the period 1973–2013 in the Kysuce region (National Forest Centre - Forest Protection Service, Slovakia; internal data).

3.2. Honey fungus, wind and snow damage

The comparison of the annual average amount of wood damaged by most harmful factors since 1973 can be made using the data in Table 1 and Fig. 4. During 1st period, honey fungus attacked the largest volume of wood in 1979 (18 thousand m³) and in 1984 (7 thousand m³). The average annual volume of affected wood was 1.8 thousand m³. During 2nd period, honey fungus attacked the largest volume of wood in 2009 (269 thousand m³) and in 2010 (266 thousand m³). The average annual volume in 2nd period was 93 thousand m³, which is 50 times more than the volume of wood affected in 1st period. The volume of wood affected by honey fungus started to increase in 1996, with the sharp rise in 2003.

During 1st period, wind damaged the largest amount of wood in 1990 (34 thousand m³) and in 1989 (33 thousand m³). The average annual volume of wood was 20 thousand m³. During 2nd period, wind damaged the largest amount of wood in 2005 (106 thousand m³) and in 2004 (73 thousand m³). The average annual volume in 2nd period was 37 thousand m³, which is 1.8 times more than the volume of wood damaged in 1st period.

Snow damaged the largest amount of wood in 1976 (87 thousand m³) and in 1983 (41 thousand m³) during 1st period. The average annual volume of wood damaged by snow was 20 thousand m³. During 2nd period, snow damaged the largest amount of wood in 2006 (89 thousand m³) and in 2007 (22 thousand m³). The average annual volume of wood damaged by snow in 2nd period was 11 thousand m³, which is 53% of the volume of wood from 1st period.

3.3. Temperature and precipitation

Figure 5 shows average annual temperatures and precipitation totals in the growing seasons since 1951. The long-term average temperature in the growing season was 12.7 °C and the long-term precipitation total was 568 mm. During 1st period, the average annual temperature in the growing season was by 1 °C lower than during 2nd period (Table 2). In 2nd period, 96% of the seasons were above average warm, while in 1st period only 63% were above average warm. In 2nd period, 6 years (27%) were extremely warm (by more than 1.5 °C than LTA), and 7 years (32%) were very warm (by more than 1–1.5 °C than LTA), while in 1st period only 1 year (5%) was extremely warm. The results point to a marked warming and high frequency of extremely warm growing seasons in 2nd period.

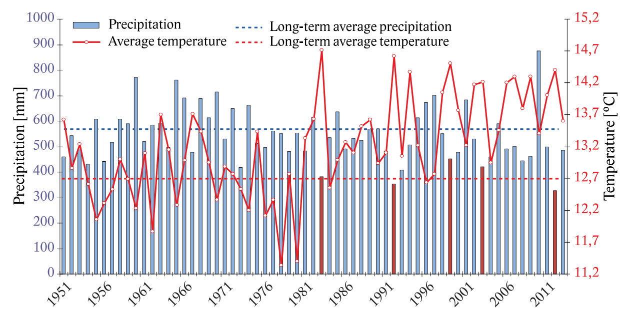

Fig. 5. Average temperatures and precipitation totals in the growing season in the years 1951–2013 at the meteorological station of Čadca (data source Slovak Hydrometeorological Institute).

Table 2. Statistical characteristics of the temperature in the growing season in the two time periods in the Kysuce region (mean ± SD).

Time period	x±Sx	Min	Max	Sx%	Difference from long-term average	% of years with a temperature above the long term average
1973–1991 (19 years)	12.8 ±0.8	11.3	14.7	6.3	0.2	63
1992–2013 (22 years)	13.8 ±0.6	12.6	14.6	4.4	1.1	96

Table 3. Statistical characteristics of precipitation in the growing season in the two time periods in the Kysuce region (mean ± SD).

Time period	x±Sx	Min	Max	Sx%	Difference from long-term average	% of years with a precipitation above the long term average
1973–1991 (19 years)	529.2 ±68.9	382.0	663.0	13.0	93.2	74
1992–2013 (22 years)	522.9 ±126.1	327.0	876.0	24.1	92.1	73

During 1st period, the average precipitation total in the growing season was by 6.3 mm higher than during 2nd period (Table 3). In 1st and 2nd period, 73% and 74% years, respectively, had a precipitation total lower than the long-term average. In 2nd period, two years (9%) were very dry (less than 70% of LTA), four years (18%) were dry (less than 70–80% of LTA), while in 1st period only one year (5%) was very dry, and one year (5%) was dry. These results show the higher frequency of dry growing seasons in 2nd period.

3.4. Weather, honey fungus, wind and snow calamities versus bark beetle outbreaks

During 1st period only two bark beetle outbreaks were observed. The first outbreak occurred after the snow calamities in the years 1976 and 1977. After the snow calamity in 1976, 27 thousand m^3 of wood remained unprocessed, which had the greatest impact on the bark beetle outbreak in the following years. The growing seasons in the years 1976–1977 were normal from the point of temperature and precipitation. The second outbreak occurred after the snow calamities in the years 1983 (41 thousand m^3), and 1985–1989 (18–3 thousand m^3 per year). The growing season in 1983 was the warmest and driest during 1st period, and this also contributed to an increase in the volume of wood affected by bark beetles in 1984.

During 2nd period, bark beetle outbreak occurred after the wind-throw in 1992 (22 thousand m^3), and other wind-throws in the years 1993–1995 damaging the volumes of 3–12 thousand m^3. During this period, snow calamities (0–18 thousand m^3 per year) also occurred. The growing season of 1992 was the warmest and the driest during 2nd period (by +1.9 °C warmer than LTA, 62% of LTA, respectively). Another increase in the volume of affected wood was observed after the wind-throw in 1997 (28 thousand m^3). The year 1999 was also extremely warm (LTA+1.8 °C) and dry (80% of LTA). In 1996, the first significant increase in the volume of wood affected by honey fungus (4 thousand m^3) was recorded. In 2003, we observed another increase in the volume of wood affected by BB. The growing season of 2003 was extremely warm (LTA+1.5 °C) and dry (74% of LTA). In that year, a significant increase in the volume of wood affected by honey fungus (2003 – 113 thousand m^3, 2004 – 210 thousand m^3) was observed. After this year, the volume of wood affected by honey fungus occurred every year (more than 100 thousand m^3 per year). In addition, wind-throws became regular events after this year damaging open forest edges and freshly thinned stands. The following increase in the volume of wood affected by BB occurred in 2007 (263 thousand m^3), and culminated in 2009 (668 thousand m^3). The year 2009 was the year with the highest volume of wood affected by BB since 1973. This period was characterised by the activation of honey fungus (more than 160 thousand m^3 per year), regularly repeated occurrence of wind-throws (more than 16 thousand m^3 per year), and also by the snow calamity in 2006 (89 thousand m^3). The years 2006–2009 were also very warm (by more than +1.1 °C compared to LTA) with below-average precipitation totals (less than 88% of LTA). After 2009, there was a gradual decrease in the volume of wood affected by BB, with a significant decrease after the year 2010 characterised by abundant precipitation (154% of LTA). Although the year 2012 was extremely warm (+1.7 °C more than LTA), and the driest in the entire examined period (57.6% of LTA), only a slight increase in the volume of wood affected by BB was observed. This was due to the substantial reduction and locally even the total absence of spruce stands with the age above 60 years.

On the basis of the results we can say that during 1st period two weak bark-beetle outbreaks occurred, after which the maximum annual volume of affected wood did not exceed 9 thousand m^3. Bark-beetle outbreaks occurred mainly after snow and wind calamities except for the year 1983, which was extremely warm and very dry. In the second period, four outbreaks of bark beetles occurred, which were preceded by warm and dry years, activation of honey fungus, and the occurrence of snow and wind calamities. Until 1991, the average annual volume of wood affected by BB was only 3 thousand m^3, while after 1992 it was 176 thousand m^3, which is 56-times more.

Factor analysis created three groups of factors (Table 4). The first group (F1) consisted of unprocessed amount of wood affected by BB in year n-1, and the amount of wood affected by honey fungus in year “n”. The second group (F2) comprised the average temperature in the growing season, and the precipitation total in year “n”. The third group (F3) contained the amount of wood damaged by wind in year “n-1”, and by snow in year “n-1”. The results of multiple regression analysis (Table 5) revealed that the amount of wood affected by BB in the years 1973–2013 was significantly affected by the first two factors, which together explained 88% of its variability ($R^2 = 0.88$, $p < 0.01$). Each of the two groups of factors contributed to the explanations of variability with approximately the same weight, although the first group (amount of unprocessed wood affected by BB in year “n-1”, and amount of wood affected by honey fungus in year “n”) had a slightly greater effect. From the first group, the factor of unprocessed wood affected by BB in year “n-1” had a similar effect as the amount of wood affected by honey fungus in year “n”. From the second group, precipitation total had a slightly greater effect than the average temperature in the growing season. The relationship between the amount of wood damaged by wind in year “n-1” and the amount of wood damaged by snow in year “n-1” was not significant.

Table 4. The results of factor analysis, method of principal components with the rotation of Varimax normalised.

Variable	F1	F2	F3
Unprocessed “n-1”	0.88	0.15	0.15
Temperature “n”	0.34	−0.71	0.33
Precipitation “n”	0.12	0.90	0.13
Wind “n-1”	0,64	−0.41	−0.09
Snow “n-1”	−0.02	0.01	−0.96
Honey fungus “n”	0.96	−0.10	0.00

Table 5. The results of multiple regression analysis, regression parameters were estimated using least squares method.

N = 40	Beta	Standard error Beta	B	Standard error B	t(37)	p-value
Intercept			43012.99	15430.00	2.79	0.01
F1	0.57	0.08	1.93	0.26	7.50	0.00
F 2	0.46	0.08	10.63	1.76	6.03	0.00

4. Discussion

Before 1991, the disturbances caused by bark beetles usually occurred after snow and wind calamities in the Kysuce region. The impact of extremely warm and dry years was marginal with the exception of the year 1983. During this period, only two minor outbreaks of bark beetles occurred. Snow and wind were the most harmful factors until 1991.

The average annual volume of wood damaged by snow was 2-times higher than after 1991. This result may be affected by the lower age of spruce stands during 1st period, which are damaged by snow at a higher rate. The analysis of the snow calamities in the years 2005/2006 and 2009 revealed that in the Moravia-Silesian Beskids the snow damage primarily depends on stand developmental stage, volume, age, height, and diameter (Hlásny et al. 2011). The impact of density and slenderness ratio on stand damage was not proven. According to Konôpka (2007), in the Kysuce region snow breakage mainly occurred at elevations from 601 m to 1,000 m a.s.l., where the highest amount of wet heavy snow fell. Large-scale storm-fellings are one of the most important initiators of *I. typographus* outbreaks, since they provide a surplus of breeding material with non-existent or weak defence (Schroeder & Lindelow 2002; Nikolov et al. 2014).

After 1992, four outbreaks of bark beetles occurred, while the calamities of BB occurred in the extremely warm and dry years (1992, 1999, 2003, 2008) or in the years following them. In these years, a strong activation of honey fungus was also recorded. BB have become the most harmful factor since 1992. Honey fungus was the second most important factor. Wind and snow were other factors significantly contributing to calamities. The most critical period since 1973 was between 2003 and 2013. In the years 2003–2008, a similar progress of spruce forest die-back was recorded in Poland at the borders with Slovakia and the Czech Republic, in the Śląski and Żywiecki Beskids. The predisposing factors of spruce decline in the Beskids are selected stand characteristics (species composition, age) and the *Armillaria* sp. root rot. Inciting and contributing factors are the climatic drivers, and also the wind damage and stress to trees are considered. The main contributing factors that drive spruce decline are bark beetles (Grodzki 2010). The process of forest decline can be described by the Manion's spiral forest decline concept (Holuša 2004; Grodzki 2010).

The occurrence of BB outbreaks in the years 1973–2013 was significantly related to the amount of unprocessed wood affected by BB in the previous year, the amount of wood affected by honey fungus in the given year, precipitation total and average temperature in the growing season. The amount of unprocessed wood affected by BB in the previous year had the greatest impact on the amount of affected wood. Salvage felling of affected trees is the most widespread measure to defeat *I. typographus* (Wermelinger 2004).

In the years 1992–2013, the average annual volume of wood affected by honey fungus in Kysuce was almost 50 times higher than in the years 1973–1991. Honey fungus is one of the important factors causing spruce forest die-back in the Beskids. Grodzki (2010) showed 2-fold increase of the area affected by honey fungus in the Polish Beskids in 80s and the years 2005–2009. In the Slovak part of the Beskids, Kulla & Hlásny (2010) found that the older stands with a higher proportion of spruce situated in the vicinity of the locations with biotic pests, were most affected by the decline. Drought has very often been considered as an inciting factor, and pathogens such as *Armillaria* sp. as contributing factors (Desprez Lousteau et al. 2006). Honey fungus is not only a problem of Europe; in North America (south-central Utah) an association of bark-beetle outbreaks with honey fungus (*A. ostoyae*) was detected (Jenkins et al. 2014) on spruce trees (*Picea engelmannii*).

After 1992, the average annual temperature in the growing season was by 1 °C higher, and the average annual precipitation total in the growing season was by 6.3 mm less than before 1991. After 1992, extremely warm and dry growing seasons occurred more frequently than before 1991. Minďáš et al. (2000) consider the lack of precipitation and high evapotranspiration to be an important stress factor at sites below 1,000 m above sea level. The analysis of long-term data from the south-eastern Alps showed that spring drought increases the next-year damage caused by bark beetle, while warm spring affects its phenology (Faccoli 2009). Favourable thermal conditions and abundant breeding material in the form of wind-broken and -fallen, as well as standing – stressed trees, favoured the development of subsequent generations of *I. typographus*, which resulted in a dynamic outbreak (Grodzki 2007).

Another factor that complicated the situation was the inferior quality of forest management. After 1989, 60% of the forests managed by state were restituted to their original owners. New forest owners were not sufficiently prepared for managing forests, and did not have the specialised staff. New ownership relations were complicated, and in a large part of the forests the owners were unknown. Salvage fellings were carried out late or were not performed at all. Forest protection measures were insufficient. Fundamental legal regulations in forest protection were not followed, which also significantly contributed to the deterioration of the situation.

5. Conclusion

The paper analysed the data of forest managers on the amount of wood affected by BB, honey fungus, snow and wind in the Kysuce region since 1973. Before 1991, BB outbreaks usually occurred in the Kysuce region after snow and wind calamities; the occurrence of extremely warm and dry years was marginal. The greater volume of wood affected by honey fungus occurred only in 1979. Since 1992, the outbreaks of bark-beetles have occurred in extremely warm and dry years or in the years following them. These years were also characterised by high volumes of wood affected by honey fungus. Bark beetles were the most harmful factor followed by honey fungus as the second most important factor. Since the beginning of the 1990s, physiological weakening of spruce forests and the onset of the so called contemporary spruce decline has occurred.

The artificial origin of spruce stands, their high proportion, high age and even-agedness were pre-disposing factors of spruce forest decline. Extremely dry and warm growing seasons, which frequently occurred after the year 1991 put excessive stress on spruce stands. The resistance of stands was reduced which made them sensitive to the attack of honey fungus and BB. After salvage fellings had been processed, the stands became unstable, susceptible to wind-throws and to further bark-beetle outbreaks on mechanically damaged trees. The most important factors driving the bark beetle attack on forest stands in the period 1973–2013 were the amount of unprocessed wood in the previous year;

wood amount affected by honey fungus in the given year, precipitation total, and average temperature in the current growing season.

Before 2003, forest management dealing with processing calamities was sufficient; trees affected by BB were processed by the end of the year in which they were affected. After 2003, the volume of affected wood increased to such an extent that forestry operation failed to react flexibly to an extreme increase of calamities. Operating options were not adapted to such an abrupt increase in the volume of salvage timber. The large amount of wood affected by BB was left unprocessed in the stands till following years. After this period, unprocessed focal points of bark-beetle outbreaks occurred in the stands. This factor caused a further increase in the volume of affected wood in the years 2008–2010. A specific problem of Kysuce is calamitous outbreak of Double-spined bark beetle, which has been present in the region since the mid-90s. This species is a locally dominant pest in the stands older than 40 years. It is often more frequent than Spruce bark beetle, and has significantly contributed to spruce decline. A similar situation is in the border regions of the Czech Republic and Poland.

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References

Desprez-Loustau, M. L., Marcais, B., Nageleisen, L. M., Piou, D., Vannini, A., 2006: Interactive effects of drought and pathogens in forest trees. Annals of Forest Science, 63:597–612.

Faccoli, M., 2009: Effect of Weather on *Ips typographus* (Coleoptera, Curculionidae) Phenology, Voltinism, and Associated Spruce Mortality in the Southeastern Alps. Environmental Entomology, 38:307–316.

Grodzki, W., 2007: Spatio-temporal patterns of the Norway spruce decline in the Western Beskidy mountains in Poland. Journal of Forest Science, 53 (Special Issue):38–44.

Grodzki, W., 2010: The decline of Norway spruce *Picea abies* (L.) Karst. stands in Beskid Śląski and Żywiecki: theoretical concept and reality. Beskydy, 3:19–26.

Hlásny, T., Křístek, Š., Holuša, J., Trombik, J., Urbaňcová, N., 2011: Snow disturbances in secondary Norway spruce forests in Central Europe: Regression modelling and its implications for forest management. Forest Ecology and Management, 15:2151–2161.

Holuša, J., 2004: Health condition of Norway spruce *Picea abies* (L.) Karst. stands in the Beskid Mts. Dendrobiology, 51:11–15.

Christiansen, E., Bakke, A., 1997: Does drought really enhance *Ips typographus* epidemics? A Scandinavian perspective. In: Gregoire, J. C., Liebhold, A. M., Stephen, F. M., Day, K. R., Salom, S. M. (ed.): Proceedings: Integrating cultural tactics into the management of bark beetle and reforestation pests. USDA Forest service General Technical Report NE-236, p. 163–171.

Jakuš, R., Grodzki, W., Ježík, M., Jachym, M., 2003: Definition of spatial patterns of bark beetle *Ips typographus* [L.] outbreak spreading in Tatra Mountains (Central Europe), using GIS. In: Liebhold, A. M., McManus, M. M., Grodzki, W. (ed.): Proceeding Ecology, Survey and Management of Forest Insects. USDA Forest Service, General Technical Report NE-311, p. 25–32.

Jenkins, M. J., Hebertson, E. G., Munson, A. S., 2014: Spruce Beetle Biology, Ecology and Management in the Rocky Mountains: An Addendum to Spruce Beetle in the Rockies. Forests, 5:21–71.

Jurskis, V., 2006: Eucalypt decline in Australia, and a general concept of tree decline an dieback. Forest Ecology and Management, 215:1–20.

Konôpka, J., Konôpka, B., Nikolov, Ch., Raši, R., 2007: Damage to forest stands by snow with regard to altitude in Orava, Pohronie and Kysuce regions. Lesnícky časopis - Forestry Journal, 53:173–190.

Kulla, L., Hlásny, T., 2010: Multi-factorial analysis of spruce forests decline in the Slovak part of Beskydy region. Beskydy, 3:65–72.

Kunca, A., Finďo, S., Galko, J., Gubka, A., Kaštier, P., Konôpka, B. et al., 2014: Výskyt škodlivých činiteľov v lesoch Slovenska za rok 2013 a ich prognóza na rok 2014. Zvolen, NLC - LVÚ Zvolen, 89 p.

Longauerová, V., Vakula, J., Leontovyč, R., 2010: Coexistence of honey fungi and bark beetles in declining spruce stands in Kysuce region. Lesnícky časopis - Forestry Journal, 56:257–268.

Madziara-Borusewicz, K., Strzelecka, H., 1977: Conditions of spruce (*Picea excelsa*) infestations by the engraver beetle (*Ips typographus* L.) in mountains of Poland. Zeitschrift für Angewandte Entomologie, 83:409–415.

Manion, P., D., 1991: Tree disease concepts. Prentice Hall, Englewood Cliffs, New Jersey USA, 402 p.

Minďáš, J., Škvarenina, J., Střelcová, K., Priwitzer, T., 2000: Influence of climatic changes on Norway spruce occurrence in the west Carpathians. Journal of Forest Science, 46:249–259.

Nikolov, Ch., Konôpka, B., Kajba, M., Galko, J., Kunca, A., Janský, L., 2014: Post-disaster forest management and bark beetle outbreak in Tatra National Park, Slovakia. Mountain Research and Development, 34:326–335.

Rudinský, J., A., Novák, V., Švihra, P., 1970: Attractivity of the spruce bark beetle (*Ips typographus* L.) to terpenes and feromones. Lesnictví, 16:1051–1062.

Seidl, R., Rammer, W., Jager, D., Lexer, M. J., 2008: Impact of bark beetle (*Ips typographus* L.) disturbance on timber production and carbon sequestration in different management strategies under climate change. Forest Ecology and Management, 256:209–220.

Schroeder, L. M., Lindelöw, Å., 2002: Attacks on living spruce trees by the bark beetle *Ips typographus* (Col.: Scolytidae) following a storm-felling: a comparison between stands with and without removal of wind-felled trees. Agricultural and Forest Entomology, 4:47–56.

Tkacz, B., Schmitz, R. F., 1986: Association of an endemic mountain pine beetle population with lodgepole infected by *Armillaria* root disease in Utah. United States Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, Utah, Research Note INT-353, 7 p.

Vakula, J., Kunca, A., Zúbrik, M., Leontovyč, R., Longauerová, V., Gubka, A., 2007: Distribution of two invasive pests in Slovakia since 1996. In: Evans, H., Oszako, T., Alien Invasive species and International Trade, Proceedings, IUFRO UNIT 7.03.12, Jedlnia, p. 105–113.

Vakula, J., Gubka, A., Galko, J., Kunca, A., Zúbrik, M., Longauerová, V. et al., 2012: Stav a prognóza škodlivých činiteľov v Beskydoch. In: Sitková, Z., Kulla, L. (ed.): Rekonštrukcie nepôvodných smrekových lesov: poznatky, skúsenosti, odporúčania. Zvolen, NLC - LVÚ Zvolen, p. 6–13.

Vakula, J., Sitková, Z., Galko, J., Gubka, A., Zúbrik, M., Kunca, A. et al., 2014: Impact of irrigation on the gallery parameters of spruce bark beetle (*Ips typographus* L., Coleoptera: Curculionidae, Scolytinae). Lesnícky časopis - Forestry Journal, 60:60–66.

Turčáni, M., Vakula, J., Hlásny, T., 2006: Analýza populácii podkôrnych škodcov na Kysuciach, prognóza ďalšieho vývoja a rámcový návrh opatrení. In: Varínsky, J. (ed.): Zborník referátov z medzinárodného seminára Aktuálne problémy v ochrane lesa, Zvolen, LVÚ Zvolen, p. 84–93.

Wermelinger, B., 2004: Ecology and management of the spruce beetle *Ips typographus* a review of recent research. Forest Ecology and Management, 202:67–82.