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Effect of canopy density on the defoliation of the European silver fir (*Abies alba Mill.*) due to heavy industrial pollution

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Abstract: Until recently, the level of industrial air pollution in the Sudetes (a mountain range extending on the Czech Republic and Poland border) was very high. This caused a large-scale forest decline, especially in the western part of the Polish Sudetes: in the Izerskie and Karkonosze Mts. An analysis of data on fir defoliation in that area, collected directly after the period of heavy industrial pollution, showed a clear dependence of the degree of defoliation of the primary crown on canopy density: the lower the density, the higher the degree of defoliation.

Additional key word: air pollution, crown defoliation, crown regeneration, ecology

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Introduction

As a result of the substantial reduction of industrial pollution in most of Europe, its influence on forest trees has recently aroused less interest, but there are some areas where effects of pollution are still very significant, even in the situation of its gradual abatement. On the other hand, trees subjected to a strong stress can show some features related to their survival strategy, which in other conditions have been considered unimportant. The study area used to belong to the so-called Black Triangle, including the Czech-German-Polish borderland, where industrial air pollution was extremely high (Dmuchowski and Bytnerowicz 1995, Vancura et al. 2000).

Pollution impacts on the forests of the Sudetes Mountains were noted early in the 20th century in areas surrounding the coal mines and other small industrial plants in mountain valleys (Capecki 1989). After World War II, rich deposits of soft (brown) coal were discovered in the region where the borders of south-west Poland, Germany and the Czech Republic meet. This region represents the largest basin of soft coal in Europe, with approximately 200–220 Mt ware extracted annually (25% of the total production in Europe). The coal were burned locally in 17 major power stations with a total output over 15,000 MW. As a result, in this relatively small area (less than a quarter of the territory of the Netherlands), 3 Mt of SO_2 and approximately 1 Mt of NO_x were emitted each year. Adverse effects of air pollution developed throughout the Sudetes region (in all three countries). Large-scale effects of pollution were detected at the end of the 1960s (Capecki 1989), and in the 1980s large-scale forest disturbances (mostly involving Norway spruce) affected more than 46,000 ha in Poland. In 1984 alone in just one small part of the Sudetes Mountains, forest decline affected 3800 ha of Norway spruce. It was the first such large decline in Polish mountain forests (Vancura et al. 2000).

In the late 1980s and early 1990s, concentrations of most of the monitored types of pollution greatly exceeded the limit values there, and oscillated around 60 ìg/m^3 for SO_2, 40 ìg/m^3 for NO_2, and 90 ìg/m^3 for particulates (Abraham et al. 1999; Filipiak 2002a; Filipiak and Ufnalski 2004). In the 1990s, the levels of major pollutants started to decline gradually, because some power stations were closed and modern filters were applied in the others. At present, pollution levels in the study area generally do not exceed the limit values. The greatest reduction was recorded for sulphur oxides. Their emission in the immediate neighbourhood of the Sudetes declined from 1.9 million tonnes in 1989 to 0.2 million tonnes in 1999, while mean air concentrations from 50–60 to 5–6 ìg/m^3 (Abraham et al. 1999). In recent years, a remarkable improvement of fir health has been observed (Filipiak 2005; 2006). In the period of heavy pollution, the greatest forest damage was caused by short episodes of particularly high concentration of pollution in some parts of slopes, as a result of specific weather conditions (Zwoździak et al. 1998). Research conducted in the Karkonosze Mts (part of the western Sudetes) in 1995 (Zwoździak et al. 1998), i.e. when emissions have already been greatly limited, show that for 2–4 hours SO_2 concentrations often exceeded 120 μg/m^3 near summits and 80 μg/m^3 at lower altitudes. At the same time, in the Czech part of this mountain range (Krkonoše), its concentration increased to 194 μg/m^3 (Kubizňak and Kubizňaková 1998). That study was conducted in early autumn, whereas the highest concentrations of pollutants and greatest damage are usually observed in winter (e.g. Davison and Barnes 2004; Mills 2004). In the cold season the emissions increase because of a greater demand for heating and electricity. Thus it is nearly certain that the concentrations mentioned above are not the highest possible. This means that till the end of the last century, the Sudetes were within the zone where pollution very strongly affected forest ecosystems, including fir trees, which are sensitive to pollution (e.g. Keller 1978; Jaworski and Zarzycki 1983; Boudot et al. 1994). Consequently, the natural resources of this species, strongly limited due to the principles of forest management in the past (which favoured spruce plantations), were additionally reduced by pollution (Wilczkiewicz 1976; Vancura et al. 2000; Filipiak 2002a). At the end of the 20th century, fir was threatened with extinction in that region. It no formed already forest stands, occurred individually or in small groups; and the mean degree of its defoliation reached 45% (Filipiak 2002a). In this situation, the main principles for a programme of fir protection and restitution in the Sudetes have been worked out (e.g. Barzdajn 2000; Filipiak and Barzdajn 2004). This program, currently implemented, is based on results of a complex inventory and assessment of resources of this species. For this purpose, many studies and surveys were carried out (e.g. Filipiak 2002b; Filipiak and Barzdajn 2004; Filipiak 2005; Filipiak and Komisarek 2005). The estimated parameters include the degree of defoliation of fir crowns as well as canopy density in the forest stands where fir trees were found. The surveys were conducted in the year 1999–2000, i.e. in the period when the level of emitted pollution was already reduced, but the negative effects of pollution were still conspicuous (e.g. Filipiak 2005). Observations made in that period suggested that the degree of defoliation depends on canopy density to a large extent. The aim of the present report is to characterize this phenomenon more precisely, on the basis of materials collected during the studies mentioned above.

Material and methods

The objects of this study were 857 fir trees found in the Karkonosze and Izerskie Mts. (longitude 15°16'–15°55'E, latitude 50°38'N–50°53'N) i.e. those parts of the Polish Sudetes that were the most exposed to industrial pollution. The trees were located at altitudes of 550–800 m, in habitats assigned to one forest site category "LMG" (montane mixed broadleaved forest), which in most cases corresponds potentially to the plant association – acidophilous montane beech forest *Luzulo luzuloidis-Fagetum*, but within the study area such sites were often dominated by planted spruce. Only the trees older than 50 years were taken into account. According to forestry records, their mean age reached 86 years. For each tree, the degree of crown defoliation was estimated, as well as canopy density of the forest stand in the place where the tree was found. Crown was assessed on the basis of the atlas of damages to tree crowns (Borecki and Keczyński 1992) according to the following classification: healthy crowns (no defoliation) = loss of assimilative apparatus up to 10%; slight defoliation = loss of assimilative apparatus >10 up to 25%; moderate defoliation = loss of assimilative apparatus >25 up to 60%; severe defoliation = loss of assimilative apparatus > 60%. The classification presented above is based on the classification approved by the United Nations Economic Commission for Europe, which is widely used (Bussoti and Ferreti 1998; Modrzyński 2003; Badea et al. 2004; Podlaski 2005; Božic et al. 2006). Also canopy density was estimated according to widely accepted principles. Five levels of the stand canopy density were distinguished: dense canopy = crowns touch, sporadically slightly overlap one on the other (0.9–1.0); closed canopy = crowns do not touch but are close to one another (0.7–0.8); broken canopy = gaps in the canopy could be filled by crowns of single trees (0.5–0.6); open canopy = crowns widely spaced, gaps in the canopy could be filled by more then one tree (0.4) (Włoczewski 1968). Considering that in the study area the fir trees were hardly ever found in forest stands with strong canopy = crowns are crowded and overlap one on the other (1.1–1.2), this level was omitted. In contrast, one lower level was added - no canopy = trees solitary or very widely spaced (0.3 and below). On the brackets they gave average ratio of crowns projections area to stand area. The differences between distributions for individual levels of canopy density (Fig. 1) were tested by chi-square test. The differences between average degrees of defoliation of fir trees in forest stands with various levels of canopy density were analysed by Kruskal-Wallis and Tukey-Kramer tests. The mean defoliation (MD) for individual canopy density classes was calculated by equation – $MD_k = 1/n_k\Sigma_{(d_i}n_{ik})$ where: MD_k – mean defoliation kth canopy density class (no, open, broken, closed, dens) n_k – number of trees in kth canopy density class, d_i – mean defoliation in ith defoliation class (no, slight, moderate, severe), n_{ik} – number of trees in ith defoliation class of kth canopy density class.

Results

Of the 857 surveyed trees, 145 grew solitary or in thinly wooded areas, 223 in forest stands with open canopy, 141 with broken canopy, 288 with closed canopy, and 60 with dens canopy. Crowns only of 15 trees were classified as healthy, the degree of defoliation was slight in 136 trees, moderate in 467 and severe in 239. Figure 1 shows contributions of trees with various degrees of defoliation in forest stands with various levels of canopy density. A decrease in canopy density is accompanied by a substantial increase in contributions of moderately and severely defoliated fir trees and reduced contributions of healthy and slightly defoliated trees. Distributions for individual levels of canopy density clearly differ and in most cases the differences are statistically significant (chi-square test). Insignificant differences in distribution were only observed between no canopy and open canopy and between broken and closed canopy.

The average degrees of defoliation for individual levels of canopy density (Fig. 2) clearly differ, and in each cases the differences are statistically significant ($p < 0.05$).

Discussion

Although there is a rich literature on tree decline under the influence of industrial pollution, there are few reports on the relationship described here. The poor health of fir trees in less dense forest stands was mentioned by Bernadzki (1983), Wilczkiewicz (1976), Filipiak (2002a), Filipiak (2005) and Oliva and Colinas (2007), but they did not provide more de-

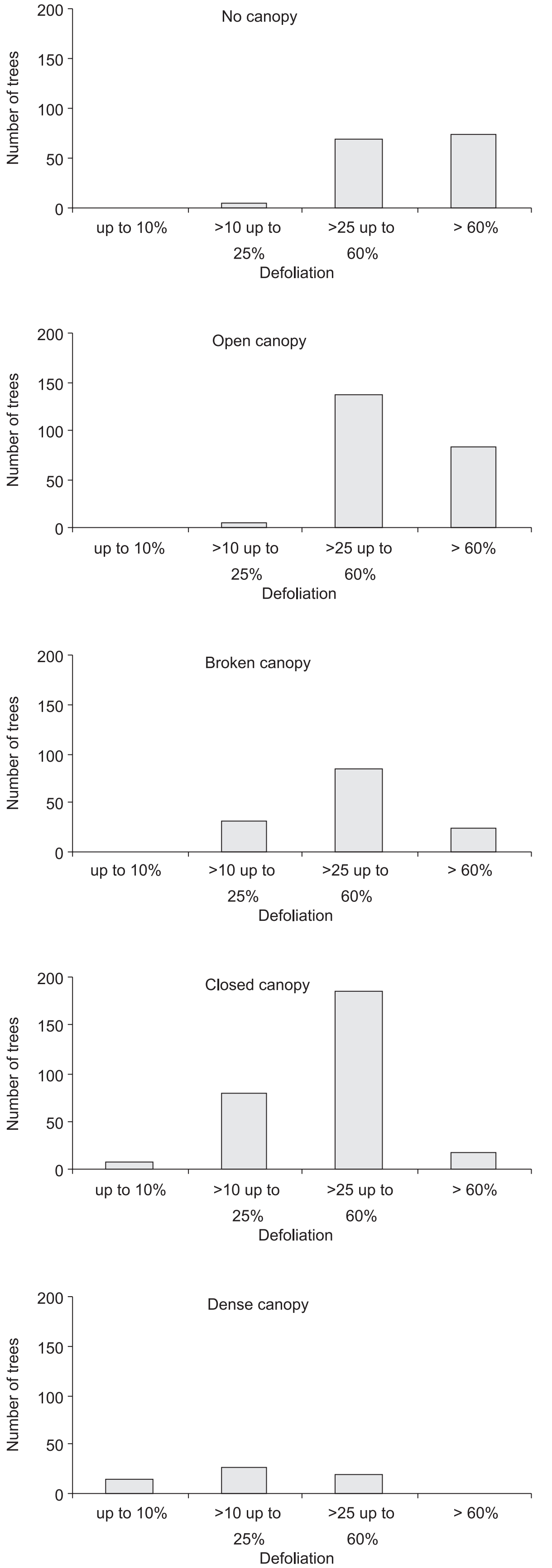

Fig. 1. Contributions of fir trees with various degrees of defoliation in forest stands with various levels of canopy density

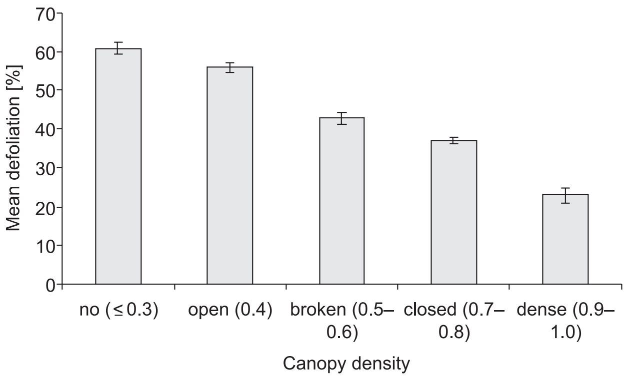

Fig. 2. Mean degree (± SE) of defoliation of fir trees in forest stands with various levels of canopy density. On the brackets – average ratio of crowns projections area to stand area

tails on this subject. Data presented by Jaszczak (2001) and Juknys et al. (2003) show that in pine stands growing on polluted sites, a decrease in canopy density generally has a positive influence on tree crown regeneration after injury by air pollution. Thought the severe defoliation of fir tree crowns is often naturally associated with its declining (e.g. Bernadzki 1983, Filipiak 2002a, Bigler at al 2004), in the Sudetes, in contrast to spruce, only seldom was a sign of approaching death of the tree. If the trees were not removed, they often lived for many years with severely defoliated crowns, but when the stress was reduced (a marked decrease in the level of pollution, mainly of SO_2 after 1995), the condition of fir trees improved (Filipiak and Ufnalski 2004). This was mainly caused by the development of epicormic shoots on the trunk, which formed a secondary crown after some time, so that their photosynthetic apparatus was increased. In the period of heavy pollution, the systematically damaged new shoots did not develop quickly, only maintaining the basic metabolism of the tree, but currently they grow intensively, so that the difference between primary and secondary crown is blurred (Filipiak and Ufnalski 2004, Filipiak 2005, 2006). According to Hasenauer and Monserud (1996), in Austria the fir trees that grow on sites with sparse canopy have on average longer crowns than in denser forest stands. Some of such crowns could have been formed as a result of development of epicormic shoots. It is noteworthy that opinions of many foresters about the development of epicormic shoots are very negative. Their appearance is associated with degeneration of the primary crown and a lower technical value of timber (e.g. Jaworski 1979). However, on the other hand, in the period of heavy pollution in the Sudetes, the development of epicormic shoots has enabled many fir trees to survive. Epicormic shoots use some of the nutrients that could otherwise reach the primary crown, so this may accelerate its weakening.

The severe defoliation of many fir trees found on sites with sparse canopy may be associated with the so-called edge effect, which consists in the greater deposition of pollution at forest edges (Lovet 1984; Jała and Błaś 2000). In forest stands, the trees that grow at the edges of stands are the major receptors of fog water deposition. This probably applies also to trees that are solitary or grow in thinly wooded areas. The Sudetes are characterized by a high number of days with fog, so high levels of acid deposition are recorded there more frequently than in other areas (Błaś and Sobik 2000; Jała and Błaś 2000). A destructive influence of acid fog water deposition on fir trees was reported, for example, by Igawa et al. (1997). European silver fir is a species with a very high level of interception of precipitation and deposits: it can stop in the crown from 40% to 80% of water contained in them (Jaworski and Zarzycki 1983). According to Ashenden (2004), concentrations of pollutants in fog and clouds may be even 10-fold higher than in precipitation. After deposition on the surface of leaves, the pH of water droplets is not constant, but it usually increases, up to 10-fold, as a result of evaporation (Ashenden 2004).

A reduction of the primary crown in less dense forest stands is noticeable not only in the Sudetes, but it was particularly conspicuous here due to the additional stress caused by heavy pollution. I observed the thinning of crowns of older fir trees also in other regions. This applies, for example, to the vicinity of the reserve Dobročski Prales in Slovakia with lower level of pollution. In the right, located on a slope reserve, on a deforested elevation at an altitude of ca. 1000 m, some old fir trees are branched nearly down to the ground, with dense conical crowns that resemble *Thuja* spp. This is probably a result of several decades of adaptation of the trees to environmental conditions (stronger wind, lower temperatures, frequent hoar frost). At lower altitudes, in dense forest stands, the shape of fir trees is typical of this species – wide crown with a characteristic 'stork nest' (Filipak 2006).

Results of this study suggest that forest management in fir stands should avoid sudden thinning, especially if the trees are exposed to stress (e.g. high level of pollution, strong winds, hoar frost, etc.). If canopy density is already reduced (e.g. as a result of windthrow, or decline of an accompanying tree species), and crowns are getting thinner, the partly defoliated trees should not be felled because it is highly probable that the crowns will be restructured, and the photosynthetic apparatus and tree growth will be restored (Filipak 2006). This is important mainly in the areas where fir is becoming a relic species, which are more and more numerous in Europe.

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