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Forest dieback process in the Polish mountains in the past and nowadays – literature review on selected topics

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Abstract

Mountain forests constitute one of the most diverse ecosystems, not only in Europe but also all over the world. Mountain ranges, which frequently encompass multiple countries, constitute a unique link between various natural areas, which are very often completely different from the historical point, or which are characterized by different use and management types. Although the role of mountain forests is relatively well recognized nowadays, in the distant past, these areas were poorly penetrated, mainly due to the unfavourable climate and natural topography, which discouraged not only from settling down but also from moving around. Despite the fact that mountains had been the object of interest of mining, weaving, and glassmaking industries for hundreds of years, dramatic changes in the stands in these areas were sealed by the industrial revolution in the 18th and 19th centuries.

The purpose of this paper is the analysis of forest dieback process in the mountain ranges of Sudetes and Western Carpathians placed in Poland. Stress factors have been divided into three main groups, however, it should be remembered that it is a very simplified division and some factors could be partially found in the anthropogenic, as well as biotic, and even abiotic factor groups. Neither the beginning nor the end of deforestation process was defined precisely in the study, which was deliberate in taking into account constant changes in the ecosystems. Generally, three periods may be distinguished here, regarding the spruce forests dieback process. Typically anthropogenic deforestation, caused by the industrialization of the areas during the industrial revolution and earlier, deforestation in the years 1970–1980 and partially before the year 2000 (Western Carpathians) caused by a set of various stress factors and the latest period, that is, generally understood climate change.

The last several years have particularly contributed to the expansion of detailed knowledge about the dependencies and the influence of abiotic, biotic, and anthropogenic factors on the health condition of spruce trees. Although models have already been developed, which describe the course of insect outbreaks, the growth and health condition of spruces, or climate factors, no model has been developed so far that would allow to depict the process of hitherto deforestation, and to enable modelling the forthcoming changes. It seems that the development of such tool, not only from the forest management point of view, would constitute a milestone on the way to precision forestry.

Key words

deforestation, spruce, forests, Sudety, Beskidy

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Introduction

Mountain forests constitute one of the most diverse ecosystems, not only in Europe but also all over the world. Mountain ranges, which frequently encompass multiple countries, constitute a unique link between various natural areas, which are very often completely different from the historical point, or which are characterized by different use and management types. Apart from that, their high productivity along with high biodiversity are also key factors of the carbon cycle (Schulp et al. 2008). Taking the above into account, it may also be stated that they constitute a specific 'insurance' for humankind and for future generations.

Although the role of mountain forests is relatively well recognized nowadays, in the distant past, these areas were poorly penetrated, mainly due to the unfavourable climate and natural topography, which discouraged not only from settling but also from moving around. Despite the fact that mountains had been the object of interest of mining, weaving, and glassmaking industries for hundreds of years, dramatic changes in the stands in these areas were sealed by the industrial revolution in the 18th and 19th centuries.

The purpose of this paper is not a general description of deforestation in the mountains of Europe, but only in their small part, that is, in mountain ranges of the Sudetes and the Western Carpathians (Beskid Śląski and Beskid Żywiecki) in Poland. Stress factors have been divided into three main groups, however, it should be remembered that it is a very simplified division and some factors could be partially found in the anthropogenic, as well as biotic, and even abiotic factor groups. Neither the beginning nor the end of deforestation process was defined precisely in the study, which was deliberate. Generally, three periods may be distinguished here, that is, typically anthropogenic deforestation, caused by industrialization of the areas during the industrial revolution and earlier, deforestation in the years 1970–1980 and partially before the year 2000 (Beskid Śląski and Beskid Żywiecki) caused by a set of various stress factors known as spiral disease (Manion 1981), and the latest period, that is, generally understood climate change (Allen et al. 2010). It should be emphasized though that the individual adopted periods overlap, as, for example, the entire Anthropocene may be directly related to climate change.

Anthropogenic factors

Historical Human Impact on Mountain Areas

The Western Sudetes, and the Karkonosze/Krkonoše in particular, have been colonized relatively late. These mountains, called the 'Giant Mountains' in the past, constituted a natural barrier between Silesia and Moravia. Mining played a significant role in the development of settlement in this area, which resulted in economic and settlement processes supported by the rulers of this area in the period of feudal fragmentation. Due to mining, two industries began to develop, that is, thermal metallurgy of ores mined in the mountains, as well as glassmaking industry. At the same time, the Sudeten forests were exploited for purposes related to mining of non-ferrous metals, that is, copper and tin. Since charcoal was the most widely available 'fuel' at that time, and deciduous trees were the most suitable for its burning (due to the highest temperature obtained), natural beech and sycamore forests were gradually disappearing in line with the development of industry. Historical sources report that in the years 1566–1610 the forests of the Krkonoše Mountains provided approximately 1.5 million m^3 of wood for the needs of the royal silver mines, steel mills, and the state mint in Kutná Hora (Czech Republic). At that time, the damage was already so significant that in 1609, a royal commission was sent from Prague to examine the condition of forests in the Krkonoše Mountains. They stated that it would take 80 years to rebuild the damage (Jadczyk 1994). Iron ores also directly contributed to the industrial expansion in the area of Żywiec and later in Węgierska Górka, where the largest ironworks in Galicia was built in the second half of the 19th century.

Apart from mining, another important element of the colonization of the Western Sudetes was glass industry. Initially, it was associated in these areas with the so-called migratory glassworks whose existence depended on access to streams and wood. When the transportation of wood became uneconomic, the glassworks was moved further upstream. Similarly, in the process of melting glass, the most energetic, that is, deciduous species were valued most. Thermal metallurgy also flourished in Ustroń, significantly affecting the Vistula River. In the Silesian Beskid Mountains, the progressing industrialization had a slightly different course than in the Sudetes, since it was initially the cause of the afforestation of vast pastures used by highlanders.

The last element that had the impact on mass harvesting of high-energy deciduous species was the production of potash. This product, obtained from wood ash through leaching, was widely used for cleaning wool and bleaching linen, as a washing and bleaching agent. Due to the more demanded so-called white ash, the most valuable deciduous species, such as beech, were selected for combustion (Jutarski 2000). Also, in the Silesian Beskid Mountains, weaving and production of potash were popular activities, and sometimes entire places, such as Jabłonków, dealt with weaving and bleaching linen or cloth making, which contributed to the development of Bielsko (Barański 2007).

Both industries, that is, metallurgy and weaving, competed with each other for potash, and thus for wood (Wiater 2003). In the Sudetes, in the 16th century, a glassworks was established on Český Brod in 1575, as well as in Szklarska Poręba (Biała Dolina) in 1617, the Karlstal glassworks in Szklarska Poręba (Orle) in 1754, and the most famous 'Józefina' glassworks in 1842 (Chrzanowska et al. 1974).

Although the need to limit harvesting and regulate forest management was recognized in then Prussian and Austro-Hungarian territories, the process was relatively slow. In 1713, a paper was published by H. von Carlowitz entitled 'Silvicultura oeconomica', which promoted sustainable forest management (Klocek 2006). The plundering exploitation of mountain forests in the Sudetes was restrained by the virtue of an act issued in 1750, while it was not until 1776 that the Sudeten larch from Moravia was introduced in the Karkonosze (Zoll 1958). The first restrictions on the use of wood resources were introduced in the act on forests issued in the middle of 18th century by Frederick the Great. Based on the mentioned laws, the first measurement of the Sudeten forests was carried out in the years 1754–1757, and the extent of use was determined, which was to be controlled by competent state authorities. According to the performed measurements, non-renewed areas were estimated at the level of approximately 20% of the total forest area.

Similarly, in the area of the Beskidy Mountains, under the Austro-Hungarian Empire, the need was recognized to regulate forest management, which was partially carried out by forest companies, often managed by the representatives of contemporary Polish aristocracy (Kawecki 1939).

In addition, the situation at that time was not improved by the fact that in the 19th century German forestry primarily focused on profit maximization (e.g., W. Pfeil, M. Faustmann), which fostered accelerated rotation, among others (Klocek 2006; Kant 2014). The industrialization of mountain areas, both in the Prussian lands and in the lands of the Austro-Hungarian Empire, resulted in the selection of the most 'cost-effective' species, that is, Norway spruce [*Picea abies* (L.) Karst.] (Grodzińska and Szarek-Łukaszewska 1997; Turnock 2002; Sitková 2010). Spruce wood was considered universal, and was used in large quantities, including as mine timber for nearby mines or in the Prussian part of Upper Silesia. The introduction of spruce on such a large scale caused the shortage of seeds, which started to be imported regardless of their provenance. There was a gradual monotypization of the lower wooded section both in the Sudetes and the Western Beskids (Bytnerowicz 2002; Faber 2007).

Despite the plundering economy that was dictated either by the development of industry or by the conduct of wars, relatively many natural or semi-natural mountain forests survived into the 19th century (Holeksa et al. 2009; Veen et al. 2010). The main reason for that was the lack of access and the inability to harvest wood, although even in these distant places, traces of charcoal burning, selective logging or grazing may still be found (Peterken 1996).

As of 1880, sowing was increasingly replaced by planting, and of 1914, the exclusive manner of carrying out forest management was clear-cutting, renewed with artificially planted spruce. Only after 1914, strains of foreign origin have been excluded from forest production even though spruce has still remained the main forest-making species. However, in the attempts to maximize economic effects coming down to obtaining the highest land rent, the Sudeten forests are still being transformed into more and more equal age spruce monocultures (Lenart 1998).

The *coup de grâce* to the Sudeten and Beskid forests before 1945 were also Napoleonic Wars (1815), World War I, and World War II. All of the above had a dramatic impact on both forest area and health condition (Zoll 1958; Capecki 1993).

In the years 1906–1928, the average annual harvest from one hectare of forest area in the Western Sudetes was 4.90 m^3 of gross merchantable wood (including 3.40 m^3 in final cutting products, 1.50 m^3 in intermediate cutting products). The excess of the normal capability adopted at that time was approximately by 14%. Annual harvesting was very uneven, and for example, in 1909, probably as a result of wind and snow breaks, as much as 57,600 m^3 were obtained, whereas only 15,400 m^3 were obtained in 1916 during World War I. An economic plan for the discussed forests, developed in 1928, assumed the annual harvest of net merchantable wood in the amount of 25,000 m^3 (approx. 4.2 m^3/ha), including 18,600 m^3 cut-offs (approx. 3.2 m^3/ha) and 6,400 m^3 pre-cutting (approximately 1 m^3/ha). The adopted amounts exceeded the then estimated volume increase by about 16%. The exceeding was explained by a significant number of overmature stands. In fact, in the years 1929–1941 a total of 455,339 m^3 were harvested (347,863 m^3 in cut-off, 107,476 m^3 in pre-cutting), which indicates that the assumed volume was exceeded by approximately 35% (Pietruńko et al. 1999a).

World War II caused not only deforestation, but also droughts and fires as a consequence of devastating logging. An inevitable result of the above disasters were insect gradations. During World War II, Germans did not perform sanitary cuts, and in the last year of war, they did not bark the cut trees, as well as they did not manage to remove the cut wood from the forest. Such negligence resulted in the outbreak of the spruce bark beetle *Ips typographus* (Linnaeus, 1758) in the years 1946–1951 in both the Sudetes and the Western Carpathians (Jadczyk 1994; Capecki 1969, 1993).

Modern Times

The post-war years brought a slowdown in economic activity in the Sudeten and Beskid forests. The period immediately after the end of the war was spent, on the one hand, dealing with the bark beetle outbreak situation, which was neglected during the war, and on the other hand, on the gradual inventory of resources or organizing forest administration on so-called 'Recovered Territories'.

In the first years, the Polish foresters mainly performed sanitation and accidental cuts in order to prevent further outbreak of insect pest in the newly created forest districts in this area (Pietruńko et al. 1999b). It was only in 1952 that the situation began to stabilize slowly along with publishing Regulation No. 109 of the Minister of Forestry on the management of new, more complex and environmentally friendly cutting. Despite the introduction of the abovementioned legislation, spruce, with trace amounts of other species, still remained the main regeneration species. This type of forest management, that is, inappropriate for environmental conditions, carried out for years, would eventually lead to changes in forest ecosystems of both mountain areas, in particular in the Western Sudetes. For this area, species composition of stands already showed the significant incompatibility in relation to habitat types. The excessive switching from habitats to coniferous habitats takes place, to a small extent, in approximately 5,000 ha, and to a medium extent, in approximately 3,000 ha. In general, however, the sanitary condition of forests in the years 1950–1975 was satisfactory. Locally, the only damage recorded was caused by winds and insect pests (mainly spruce bark beetle, striped ambrosia beetle, and pine web-spinning sawfly in the 1960s).

Another breakthrough for mountain forests, initially mainly for the Western Sudetes, was brought by 1970s and 1980s. What counted most for the socialist heavy industry was increasing coalmining and electricity production, while nature conservation matters receded into the background. Four mining and power complexes built in the 1950s in Czechoslovakia, the German Democratic Republic and Poland started to operate at full capacity and became the main polluters in the region. The total production capacity of the plants at the crossing point of three borders reached 16,000 MW (Germany 10,000 MW, Czechoslovakia 4,000 MW, and Poland 2,000 MW), and due to their bad reputation, they were finally called 'Black Triangle'. The first symptoms of pollution impact on spruce stands were observed in the 1970s. Pollutants were transferred mainly along with the transport of atmospheric sediments (rain, fog, rime) and without their participation (Błaś et al. 2010; Błaś et al. 2012; Weathers et al. 2006).

Pollutants emitted by the abovementioned plants, mainly SO_2 and NOx, fell down in the form of dry and wet deposition. These compounds were spread by wind, undergoing transformation into other compounds along the way. Sulphur and nitrogen compounds penetrated the soil, causing the formation of weak acids (sulphur, nitric, hydrochloric, hydrofluoric), which, in the dissociation process, released hydrogen (H +) displacing nutrient cations (K+, Ca2+, Mg2+) from the sorption complex. This resulted in faster soil acidification and impoverishment. These phenomena also took place in the air, where weak acids had a stinging effect on the assimilation apparatus.

The acid deposition rates recorded in the Western Sudetes were very high and reached > 1500 mol H +/ha/a. The gradual modernization of production processes in 'Black Triangle' plants, installation of electrical filters and systems for the desulfurization of flue gases allowed to downsize the level of acid deposition to 700 mol H +/ha/a (Galos et al. 2003).

In mountain stands, the impact of pollutants was intensified by heavy rainfall and fog deposition. In acidified soils, an excessive activation of aluminium, iron, and manganese was recorded, which could have been absorbed up by plants in significant amounts, blocking paths for other cations. These elements destroyed the hairs of plant roots and germinating seeds, causing the decline of mycorrhizae. All these phenomena led to the degradation of forest soils and destabilization of stands (Walendzik 1994).

As a result of industrial emissions and a number of stressors, such as insect outbreaks, over 4,000 hectares of forest died before the end of the 1970s and the beginning of 1980s, only in the areas of Szklarska Poręba Forest District and Świeradów Forest District alone. The extent of forest dieback in that period may be deduced from the increase in the area of final and intermediate cutting products both in the Szklarska Poręba and Świeradów Forest Districts (Fig. 1). Wood harvesting in the worst period exceeded six times the harvesting plans. It is worth mentioning that by default, the amounts reached tens of thousands of m^3 for each forest district, while in the top years of the disaster, the values were close to two million m^3. In addition, it

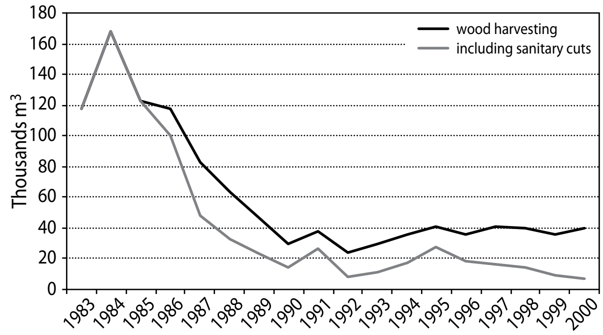

Figure 1. Area of final cutting products and intermediate cutting products in Szklarska Poręba and Świeradów Forest Districts, in the period of 1978–2004 (Bałazy, 2015)

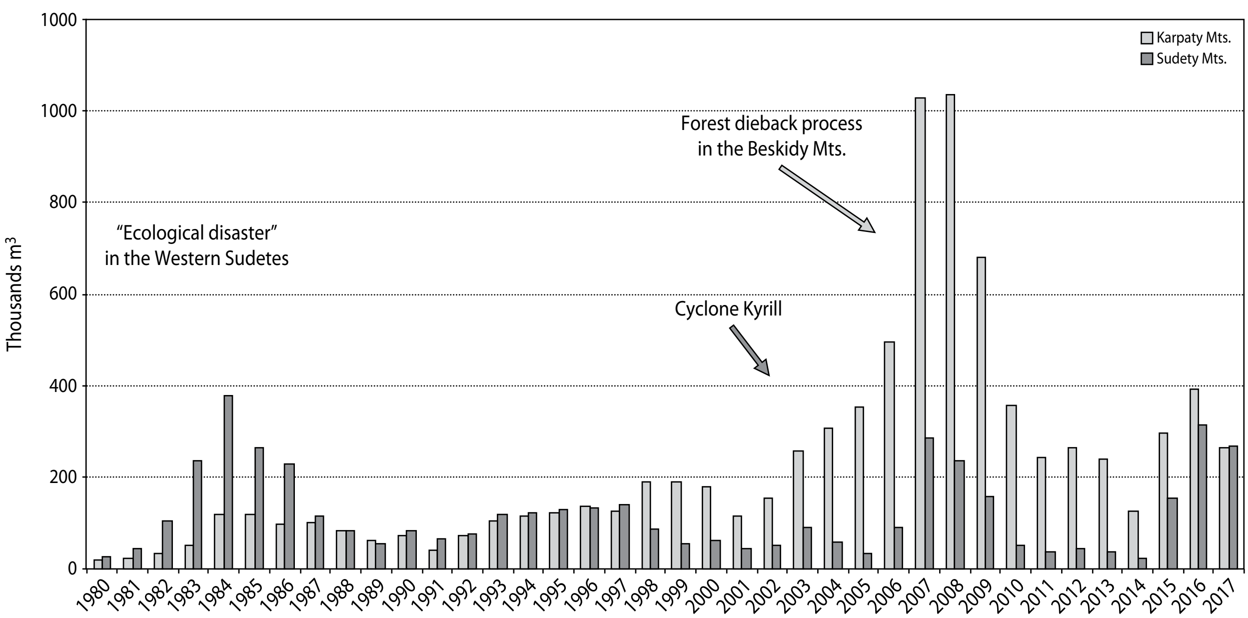

Figure 2. Wood harvested due to sanitation cutting in Sudety and Beskidy Mts. (Grodzki, 2018)

should be remembered that the above records included exclusively cut down dead stands over 21 years of age. Not included were tree stands, whose dieback did not entail cutting down all the trees (where no open area for regeneration was created), and no young trees were included, many of which died as well. Despite a huge area that was affected by forest dieback in the Western Sudetes (nearly 15,000 ha of fully deforested areas), the decay of spruce forests in the Carpathians was even greater, leaving huge surfaces of the Beskid Śląski and Żywiecki (Fig. 2).

The process of forest dieback or, more widely, land use and land use-change in the mountains has been examined by a number of authors. With the use of satellite imaging, these studies, for obvious reasons, concerned mainly the second half of the 20th century (Main-Knorn et al. 2009; Feranec et al. 2010; Grffiths et al. 2013; Prishchepov et al. 2013), while the analyses covering longer periods were based on the use of archival cartographic studies (Skokanová et al. 2012; Munteanu et al. 2014; Lieskovský et al. 2018). It should be noted that while there are relatively many studies on the Carpathians, very few have been carried out on the Sudetes. What is more, all publications on land use changes are usually based on relatively large spatial units, such as several dozen meters in the case of analyses based on Landsat imaging (Main-Knorn et al. 2009), or even a kilometre in the case of analyses based on archival cartographic materials (Lieskovský et al. 2018). The above-mentioned studies are supplemented by an analysis based on both historical data (Landsat) and contemporary data (orthophotomap and LiDAR), which enables comparing the course of the forest dieback process in the past and today (Bałazy et al. 2019a).

Biotic factors

Biotic factors, as well as anthropogenic and abiotic ones, have had a combined effect on mountain ecosystems, which was described as 'spiral disease' in the previously cited work by Manion (1981). It could be claimed that while anthropogenic factors had a negative impact on mountain ecosystems as early as from the beginning of settlement, which became even more intensive from the industrial revolution, the biotic factors operated most severely at the last stage of forest dieback (Baltensweiler 1985; Christiansen 1989). Among many biotic factors, insect pests definitely played a very important role (Schelhaas et al. 2003; Svoboda et al. 2010; Zhao et al. 2011), although weakening of forest stands by fungal pathogens, and ultimately also the negative role of rodents and large ungulates was also significant.

Damage from Primary and Secondary Insect Pests

Insect pests, and in particular bark beetle (*Ips typographus;* Linnaeus, 1758), have a huge, if not essential, impact on forest management not only in Europe but also in other areas as well. The enormous damage caused by this insect makes a thorough understanding of its formation and outbreak progression one of the major challenges of modern forestry (Walter and Platt, 2013). The most important factors that influence the development of this insect's population include the age of stand, the history of disturbances in a given area, solar radiation, whereas climate and weather are considered the primary factors that trigger outbreaks. (Dutilleul et al. 2000; Becker and Schröter 2001; Gilbert et al. 2005; Klopcic et al. 2009; Kautz et al. 2013; Ogris and Jurc 2010; Lausch et al. 2011; Marini et al. 2012; Overbeck and Schmidt 2012; Albrecht et al. 2012; Thom et al. 2013; Mezei et al. 2014).

Insect outbreaks are a natural phenomenon both in primeval and man-transformed forests. Forests are usually perfectly able to defend themselves against outbreaks (Jakuš et al. 2011a), unless one of the abovementioned factors or many of them occur simultaneously (Jakuš et al. 2011b; Kautz et al. 2013), as it happened both in the Sudetes and the Beskids.

Behind the outbreaks both in the Sudetes and the Beskids were anthropogenic transformations of mountain stands, as well as their age (Guderian 1977; Hais 2003). It seems that in the case of the Sudetes, air pollution played a slightly more important role (Modrzyński 2003), and in the case of the Beskids, it was the age of stands.

In the area of the Western Sudetes, they were also noted previously. Outbreaks in the Sudetes in the years 1944–1950 (Capecki 1995) were caused by drought and numerous windfalls. Following the damage due to weather conditions, further devastation was brought by cambium-feeding insects and fungi. The above three factors caused thinning of stands, fostered their weakening, and improved the conditions for the development of pests.

Contrary to the Beskids, the larch tortrix (*Zeiraphera griseana;* Hübner, 1799) played a huge role in the Sudetes. The caterpillars of this butterfly were found feeding for the first time in the Jizera Mountains and the Karkonosze Mountains in 1934, however, the extent of damage was not recorded. The butterfly was earlier known mainly in the Alps, where its outbreaks recurred periodically every 7–8 years. Mass occurrence of the larch tortrix was recorded in the Jizera Mountains and the Karkonosze Mountains in the years 1977–1982, when it had disastrous consequences. 44,450 ha of forests were damaged in Świeradów, Szklarska Poręba, Śnieżka, Kamienna Góra and Wałbrzych Forest Districts, 3,211 ha in the Karkonosze National Park, that is, a total of 47,661 ha (Jadczyk 1995a; Oleksyn et al. 1994; Grodzki 1995).

With the disappearance of the larch tortrix, damage from industrial emissions and drought in the years 1982–1983 paved the way for the outbreak of cambio- and xylophages. These pests attacked single, strongly shaded trees, and created favourable conditions for the propagation of the bark beetle (*Ips typographus;* Linnaeus, 1758). In 1982, a significant increase in its number was observed (Jadczyk 1995b).

Weather conditions, especially long, hot, and dry growing seasons, constituted an important factor in the development of secondary pests. As a result of intensive sanitation cutting, exposed stand's walls of stands of considerable lengths were formed, which were susceptible to adverse operation of winds. Under these conditions, the spruce bark beetle often 'behaved' like a primary pest, and attacked healthy trees and stands as well.

Apart from the spruce bark beetle, a considerable threat was stated from the spruce wood engraver (*Pityogenes chalcographus;* Linnaeus, 1760), which in many cases played the role of the main secondary pest of spruce (Grodzki 1995b).

Several years after subduing the outbreak in the Western Sudetes, tree dieback began to increase significantly in the Beskids (Schelhaas et al. 2003; Svoboda et al. 2010, 2012; Zhao et al. 2011), eventually reaching the catastrophic volume. Although the older, often overmature, Beskid stands were considered more resistant to anthropogenic factors, such as pollution (Faber et al. 2007; Pietruńko 2004; Małek 2005), their age was not an advantage in the fight against root pathogens or bark beetle (Grodzki et al. 2014). Also, exclusive stands of world-famous spruces of Istebna ultimately fell victim to the bark beetle (Faber et al. 2007; Sabor 1996).

In fact, by the end of the 20th century, very few studies focused on large-scale changes in outbreaks, their spatial course, intensity, or dependence on topography. Increasingly common access to remote sensing data, including topographic, climate, and quantitative data, make the analyses of bark beetle outbreaks comprehensive.

Research by Grodzki (2007) and Klopcic et al. (2009) proved that the damage caused by bark beetle outbreaks in the mountains depended on altitude, aspect, and topography. Furthermore, the authors managed to work out the impact of the abovementioned elements on individual stages of outbreak development, which is of fundamental importance for building better forecasting models.

Damage from Fungal Pathogens

Spruce trees in the Jizera Mountains and the Karkonosze Mountains, weakened by industrial emissions, formed an ideal base for fungal parasites such as: bleeding conifer crust (*Sterum sangoinolentum;* Alb. & Schwein, 1826) butt rot of conifers (*Heterobasidion annosum;* Bref, 1888) and honey fungus (Ar*millaria mellea,* Kumm, 1871) (Jadczyk 1995). Both in the Sudetes and the Beskids, the honey fungus (Ar*millaria mellea,* Kumm, 1871) was of economic importance, especially in the lower wooded sections of richer habitats (Żółciak et al. 2009; Sierota 2011), as well as the butt rot of conifers (*Heterobasidion annosum;* Bref, 1888) occurring throughout the Jizera Mountains and the Karkonosze Mountains. On the other hand, needle cast of larch (*Meria laricis Vuill,* 1896) caused little damage in plantations.

It seems that while fungal pathogens were of tremendous importance in the case of both mountain areas, an additional factor that could have influenced the extent of damage in the case of the Beskids was the age of stands. The oldest parts of the Beskid forests were entering the stage of their natural decay.

Damage from Rodents and Ungulates

The removal of dead trees and spruce stands, and the growth of grass vegetation favoured the mass development of rodents. In the Western Sudetes, common voles

(*Microtus arvalis;* Pallas, 1779), field voles (*Microtus agrestis,* Linnaeus, 1761) and bank voles (*Clethrionomys glareolus;* Schreber, 1780) played an essential role. During the disaster in the Western Sudetes, two outbreaks of these rodents were recorded and no effective methods of reducing their population on large areas of regeneration could be developed. Outbreaks faded spontaneously.

The processes of large area forest dieback were usually accompanied by the intensive growth of herbaceous plants. The observed dependence, particularly in the first succession phase, created very favourable conditions for herbivorous mammals, that is, deer and roe deer. Along with the expansion of deforested areas, a dynamic development of the herbivore population, especially ungulates, took place. At the subsequent stage, the disappearance of many species of dicotyledons was observed in favour of grass plants, especially reed grass which is not preferred by cervids. The expansion of deer in open biotopes goes hand in hand with the efforts usually made by foresters to restore disaster areas as quickly as possible, using as many different species as possible. While such an action is certainly right to increase biodiversity, it also favours deer, diversifying their food base.

Similarly, as in the case of bark beetle outbreak, also in the case of deer, the volume of damage depends not only on the age of stand, but also on the altitude above sea level, aspect, and even the slope of terrain (Bałazy et al. 2016).

Abiotic factors

Abiotic factors are understood to mean both climate features and topography of an area, which have had or still have an impact on deforestation of spruce stands in the mountains. Given the role of air pollution in generally understood climate features and topography, it has been presented in the chapter on abiotic, not anthropogenic factors. It should also be mentioned that while the land topography invariably works to the same degree, the climate with pollution may be analysed in at least three different dimensions: the climate itself with precipitation, winds, temperatures, and so on, long-term climate changes (climate warming), which definitely play an important role in the dieback of mountain spruce trees, and air pollution itself.

The last of these elements is primarily the effect of strong industrialization both at the junction of the three borders (the so-called 'Black Triangle') and in the coal field of Upper Silesia. It was the air pollution, apart from changes in species composition and monotypization of stands, which contributed to the weakening of mountain ecosystems and, as a consequence, to outbreaks. In the Western Sudetes, it started with larch bud moth (*Zeiraphera griseana*) and then bark beetle (*Ips typographus*) (Nowicki 1995; Oleksyn and Reich 1994; Grodzki 1995b). Despite the fact that due to the efforts of all three countries, air pollution in this area was reduced to levels acceptable by national standards (Wawrzoniak et al. 2000; Modrzyński 2003), the process of disintegration of spruce trees in the Western Carpathians commenced at the beginning of the 1990s (Kozak 1996; Badea et al. 2004; Grodzki et al. 2004). At the moment, the situation in the Beskid Śląski and Beskid Żywiecki seems to be under control, however, massive deforestation has been observed in the Eastern Sudetes for several years. There is no doubt that a set of various factors is usually behind large-scale deforestation (Tesche 1992; Saxe 1993; Capecki 1995; Liwińska and Wawrzoniak 1995; Modrzyński 1984, beginning from climate change (Althoff 1985; Hais 2003) through air pollution (Baltensweiler 1985; Christiansen 1989; Vacek et al. 2015) or heavy metals carried by winds and precipitation (Guderian 1977; Shparyk and Parpan 2004). Studies carried out by some scientists in the Jizera Mountains (Glina and Bogacz 2013; Gamrat and Ligocka 2018) confirmed that the content of sulphur and heavy metals in soil and needles may still be considerable, despite the fact that nearly thirty years have passed since the ecological disaster. There is no doubt that apart from anthropogenic factors, especially in mountain ecosystems, the following play a significant role: the climate (Sobik et al. 1998; Błaś 2000), precipitation, temperature drops, and droughts (Grodzki 1998). A substantial part, or even the most of adverse climate factors and deposited pollutants are a direct consequence of land topography (Dore et al. 2000; Sobik et al. 1998; Sobik and Błaś 2008), ultimately affecting the health condition of spruce stands. In all three areas, western, south, and north-western winds are predominant. What may be important for health condition of the stands is the wind strength and the amount of carried pollutants, as well as periods when winds are the strongest. In the Beskids, winds are the highest from November to March when the health of stands may be affected adversely (Małek 2005; Barszcz and Małek 2008).

Although a relation between the health condition of stands, pollution and topography was obvious for a long time, it was only in the 1990s that the necessary tools to study this phenomenon were developed. Using remote sensing methods (archival aerial photographs and Landsat imaging), it was possible, for the first time, to perform a large-scale analysis of deforestation in the Sudetes (Poławski and Zawiła-Niedźwiecki 1987; Zawiła-Niedźwiecki and Glasenapp 1994; Ciołkosz and Zawiła-Niedźwiecki 1995; Poławski and Zawiła-Niedźwiecki 1995). In the following years, relationships between the layout of mountain ranges, the height of peaks, and climate conditions accelerated, among others, due to the use of increasingly accurate topographic data. It was proven that the indirect role of climate and its impact on forests is mainly related to the capture of raindrops/fog by spruce stands, and this process is the most intensive on high-altitude, western, north-western and northern slopes (Błaś et al. 2012; Błaś et al. 2000). Similarly, as the deposition of pollutants from fogs affects significantly the deterioration of trees' health condition, the strong deposition of rime causes considerable mechanical damage to spruces (Błaś et al. 2000 Godek et al. 2012). The work of a team of authors has shed new light on a relation between the annual growth of spruces, and aspect and altitude. They compared, based of field data (tree rings), the results of the Western Sudetes, the Eastern Sudetes and the Beskids (Opała-Owczarek et al. 2019). It was proven that the correlation was weaker between the growth and aspect, if a given mountain range was closer to the then source of pollution (the 'Black Triangle') (Fig. 3).

The relationships between the growth in height and aspect, slope or altitude for the abovementioned areas were also demonstrated by other authors (Socha et al. 2017; Bałazy et al. 2019c, 2019d). The obtained results clearly show that although there is a number of similarities between the Western Sudetes, the Eastern Sudetes and the Beskids, there are numerous variables that operate differently in every mountain range. This is also confirmed by studies based on comparing historical and current remote sensing data, as well as studies based on time series of satellite imaging (Bałazy et al. 2019a, b).

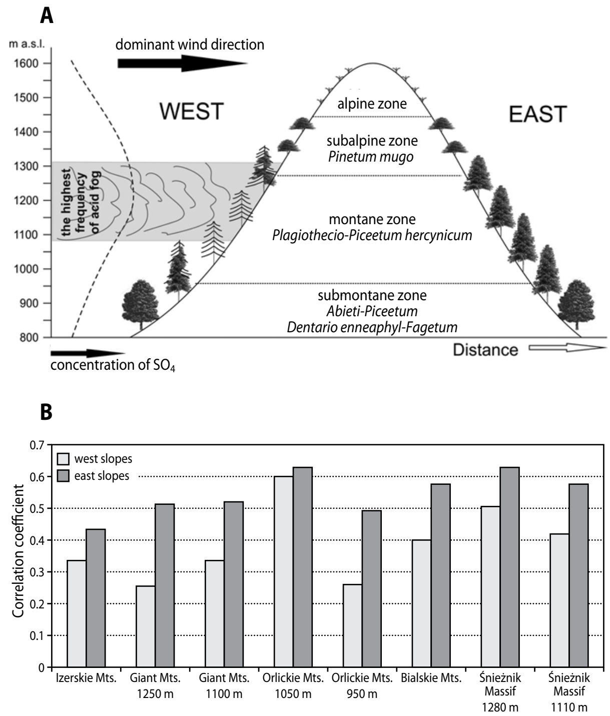

Figure 3. A – an east-west schematic cross section, showing vegetation zones of the Sudetes with selected elements of the pollutant influence on the forest dieback process on the west slopes; B – correlation coefficients between tree-ring chronologies from western and eastern slopes and April–July temperature. All values are statistically significant at $p < 0.05$ (Opała-Owczarek et al. 2019)

Summary

Large-scale deforestation in the mountains is an important economic problem, the impact of which goes far beyond the economic consequences such as the depreciation of wood raw material. The water-protection, soil-protection, and nature related role of those areas is of immense importance for Poland and for future generations. The changing role and share of pollution, climate changes, increased greening of management activities undertaken, they all influence mountain ecosystems. Investigations into the causes of the ecological disaster in the Western Sudetes, deforestation in the Beskids or the current situation in the Eastern Sudetes bring us increasingly closer to finding an answer to the question about the roles of individual factors, and how to express them mathematically in forecasting models. The last

several years have particularly contributed to the expansion of detailed knowledge about the dependencies and the influence of abiotic, biotic, and anthropogenic factors on the health condition of spruce trees. Although models have already been developed, which describe the course of insect outbreaks, the growth and health condition of spruces, or climate factors, no model has been developed so far, which would allow to depict the process of hitherto deforestation, and to enable modelling the forthcoming changes. It seems that the development of such tool, not only from the forest management point of view, would constitute a milestone on the way to precision forestry.

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