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Original article

Reductions in tree-ring widths of silver fir (*Abies alba* Mill.) as an indicator of air pollution in southern Poland

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ABSTRACT

The aim of the study was to investigate how the emission of pollutants to the atmosphere from the late 19th century until modern times has been recorded in rings of silver fir trees growing in southern Poland. Samples were collected from 24 firs growing in the Beskid Niski Mountains (Western Carpathians). Using a Pressler borer, a single core was collected from each tree. Within the samples, tree-ring widths were measured. On this basis, reductions of tree-ring widths were calculated and subsequently divided into three classes according to their severity. Study results indicate that growth reductions at the site studied were influenced by the pollution emitted from the now-defunct Central Industrial Region, which developed most rapidly from 1920 to 1940, and began to decline after World War II. These emissions were probably responsible for reductions in the trees sampled in the years 1928–1947. On the other hand, reductions of tree-ring widths dating from 1951 to 1989 were caused by the post-war development of heavy industry throughout Poland, and in particular in the Upper Silesian Industrial Region, which developed at its most rapid rate from 1960 to 1990. The results obtained demonstrate that reductions of tree-ring widths in the silver firs studied are related to industrial air pollution in the 20th century. As industrial production declined and environmentally friendly technologies were introduced in the early 1990s, air pollution levels decreased and an increase in tree-ring widths followed in the silver firs studied. Further reductions of tree-ring widths have been observed in recent years (since 2009), which may be caused by air pollution due to low-stack emissions from domestic boilers. The analysis conducted demonstrates that a reduction in tree-ring widths in silver fir is a sensitive bioindicator of air pollution.

KEY WORDS: tree ring reductions, air pollution, environmental monitoring, southern Poland

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1. Introduction

The degrading impact of air-polluting emissions on forests is a widely studied phenomenon (WIMMER, 2002; DANEK, 2007; SZYCHOWSKA-KRĄPIEC, 2009; MALIK ET AL., 2011). The first works on this subject were published in the 19th century (e.g. STOECKHARDT, 1871). The extensive destruction of tree stands which occurred during the period of rapid industrial development (from 1960 to 1980) resulted in intensified interest in studies on the impact of pollution on trees (KRĄPIEC & SZYCHOWSKA-KRĄPIEC, 2001; DANEK, 2007; MALIK ET AL., 2011), this research initially focused on changes in stem morphology or the impact of parasites (e.g. fungi) on individual trees weakened by the presence of pollution (DUSZYŃSKI, 2014).

Trees in an environment strongly contaminated by toxic substances are prone to disruptions in physiological processes (GODZIK, 1981; EMBERSON, 2003) and, consequently, their radial growth may be slowed down or inhibited altogether. In the dendrochronological record, this manifests itself as a reduction in tree rings or as missing rings (SZYCHOWSKA-KRĄPIEC, 2009). These relationships can be used as a tool to enable the dendrochronological reconstruction of environmental pollution, and the advantage of this method is that it makes it possible to analyse the variable impact of environmental factors on tree-ring widths at an annual or seasonal resolution (GÄRTNER, 2007).

Tree rings started to be used as a source of environmental data and data indicating human pressure on the environment in the 1970s (e.g. ASHBY & FRITTS, 1972; NASH ET AL., 1975; EVERTSEN ET AL., 1986) when emissions of industrial pollutants rose sharply. In Poland, studies of the dendrochronological record of changes in air quality as a result of industrial pollutant emissions began around 20 years later. Scientific research using dendrochronological methods mainly concerned the impact of local factors (e.g. pollutant emissions from nearby industrial plants) on changes in tree-ring widths (EVERTSEN ET AL., 1986; SZYCHOWSKA-KRĄPIEC & WIŚNIEWSKI, 1996; KRĄPIEC & SZYCHOWSKA-KRĄPIEC, 2001; MALIK ET AL., 2010). However, FELIKSIK (1995), ELLING ET AL. (2009) and MALIK ET AL. (2012) have also demonstrated the impact of broader, regional factors on reductions of tree-ring widths. They point to a relationship between reductions in tree-ring widths and reduced air quality during the same period. Therefore, the reduction in radial growth in trees is a good bioindicator of air pollution as well as being useful in geographical studies concerning issues related to human impact on the natural environment.

The purpose of this research was to identify reductions of tree-ring widths in silver fir (*Abies alba* Mill.) growing in the Beskid Niski Mountains (in southern Poland) and to compare temporal relationships between reductions of tree-ring widths and variations in atmospheric pollution.

2. Study area

The study was carried out on the eastern slope of Kamień Mt. (714 m a.s.l.) in the Beskid Niski Mountain range, which is part of the Outer Western Carpathians (Fig. 1A, B). The study site is located in a moderately cold climate belt (HESS, 1965). Southern and south-western winds dominate in the area (HESS ET AL., 1977). Average annual rainfall in the study area ranges between 800 to 900 mm. The area is covered by natural beech and fir forests, with the largest part being occupied by fertile Carpathian beech forest (MICHALIK, 2003).

The study area is located within the now-defunct Central Industrial Region and is 200 km southeast of the Upper Silesian Industrial Region (Fig. 1A), which used to be the main source of industrial air pollution in the Polish part of the Carpathians in the 20th century.

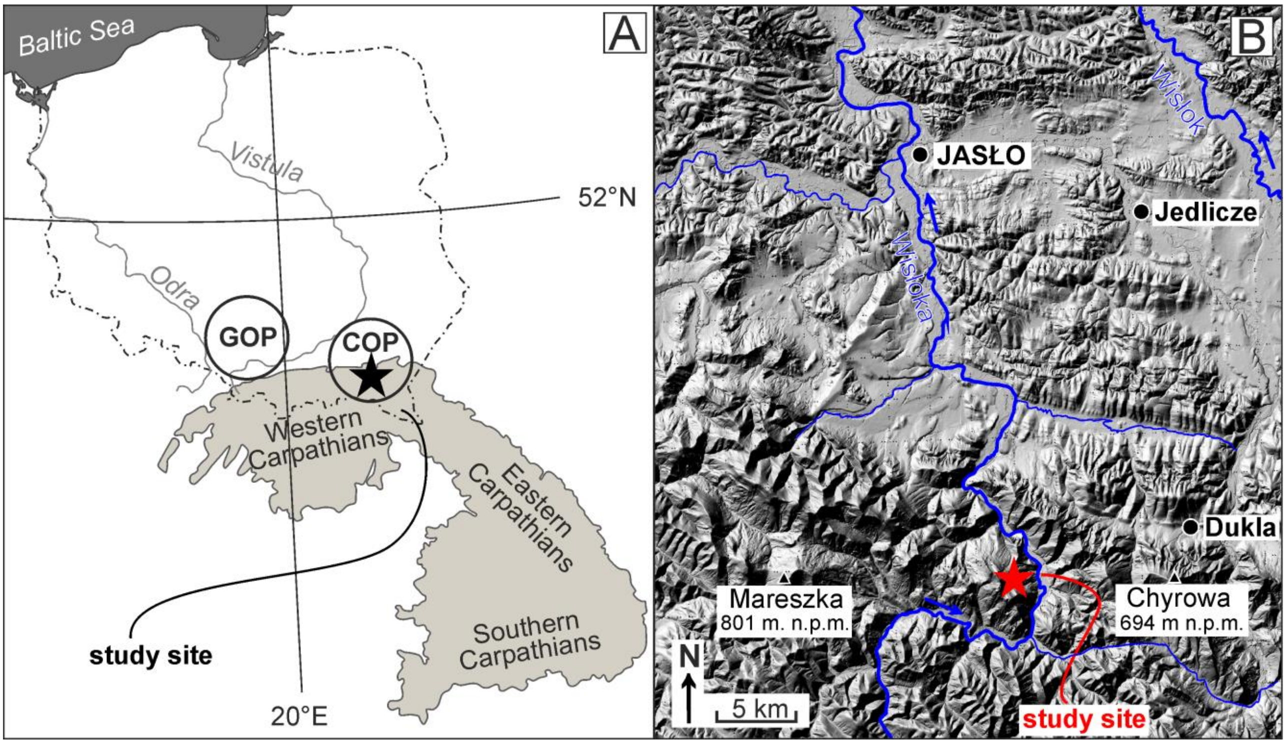

Fig. 1. Situation of the study site in Poland and within the Carpathians in relation to the main sources of pollution – the Upper Silesian Industrial Region (abbreviated GOP) and the Central Industrial Region (abbreviated COP) (A) and in the Beskid Niski Mountains (B)

Maximum levels of industrial production within the Central Industrial Region were reached between 1920 to 1940 when numerous steel mills, chemical and power plants as well as automobile and aircraft factories were built (SAMECKI, 1998). After World War II, the Central Industrial Region entered a period of decline (GOŁĘBIOWSKI, 2000). Currently, the area exhibits one of the lowest pollutant emission rates in Poland (RAPORT O STANIE..., 2013). In 2012, dust emissions in Podkarpackie Province (which covers the area of the former Central Industrial Region) accounted for 3.2% of national emissions, and gas emissions were less than 1.55% of the national emissions (RAPORT O STANIE…, 2013). The Upper Silesian Industrial Region developed at the end of the 19th century and its most important resource was hard coal (TKOCZ, 2012). A particularly significant increase in industrial production in the region took place from the 1960s onwards, reaching a maximum in the late 1970s and early 1980s. Heavy industry functioned on a large scale within the Upper Silesian Industrial Region until the late 1980s and early 1990s, when both industrial production and the emission of pollutants into the atmosphere decreased as a result of political and economic transformation. During that period, a significant number of mines and other industrial plants were closed, and the remaining ones were forced to introduce environmentally friendly technologies (KARPIŃSKI ET AL., 2013).

3. Methods

Samples were collected from 24 silver firs (*Abies alba* Mill.), with the oldest one being 154 years old (the oldest tree ring in the samples dates back to 1860). From each tree, a single core was collected at breast height using a Pressler borer. The samples were collected in a direction transverse to the slope to exclude the effect of mass movements on tree growth from further analysis.

The cores collected were glued to wooden holders and polished with abrasive paper to reveal the wood structure. Subsequently, tree-ring widths were measured with an accuracy of 0.01 mm using a LinTab 6 linear tree-ring measuring stage. On the basis of the measurements conducted, reductions of tree-ring widths were determined for each sample collected. The method used was based on the analysis of characteristic years and of sudden changes in tree-ring widths (MALIK ET AL., 2011). According to the methodology developed by SCHWEINGRUBER ET AL. (1985), the degree of reduction was calculated as the ratio of the sum of tree-ring widths calculated for the period in question to the sum of tree-ring widths calculated for the period preceding the reduction. Tree-ring width in any given year was compared to the average tree-ring widths in the three previous years. Where tree rings turned out to be narrower than the average for previous years, the degree of reduction was expressed as a percentage. The reductions calculated were divided into the following classes: 1) moderate reductions: 30–50%; 2) strong reductions: 51–70%; 3) very strong reductions: >70%. Reductions below 30% were not included in further analysis.

The method used made it possible to determine the temporal distribution of reductions of tree-ring widths (Fig. 2), which was subsequently compared to data on hard coal production, since these indirectly reflect the scale of pollutant emissions to the atmosphere. Comparisons of dendrochronological results with directly measured changes in air pollution levels were not possible, because the data series concerning atmospheric pollutant emissions from the Central Industrial Region and from the Upper Silesian Industrial Region are too short and do not cover the period before 1989, when emissions were the highest. There are no data on the pollutants released by individual sources of pollution (industrial plants) either. Therefore, a decision was made to use indirect data on hard coal production in the Upper Silesian Industrial Region since 1948 (Fig. 5) (based on literature: MALIK ET AL., 2012). To determine the relationship between hard coal production levels and the average tree-ring widths we have calculated the Pearson correlation coefficient.

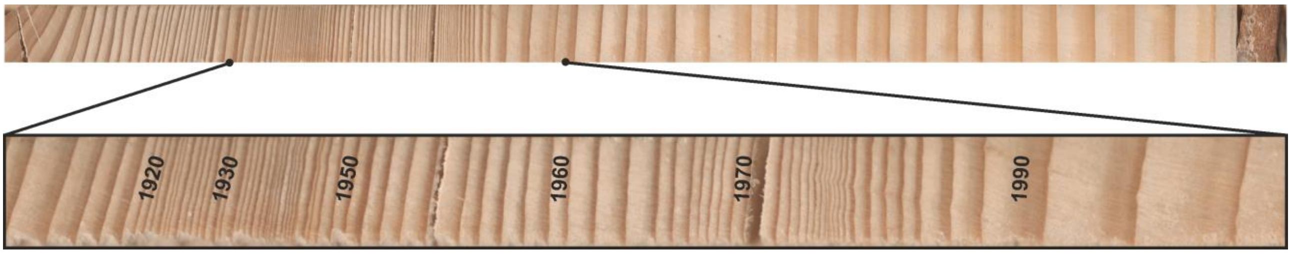

Fig. 2. Part of the core collected from the stem of a fir growing on the study site. Periods when tree rings were relatively wide (e.g. after 1987) as well as reduced tree rings (e.g. in the 1920s, 1930s, 1940s and 1980s) are visible

4. Results

It was found that in the silver fir population studied almost yearly reductions of tree-ring widths occur. In the years when reductions occurred, these were recorded for at least 4.17% of the trees studied. Periods with a particularly high prevalence of reductions of tree-ring widths were 1918–1947 (1928–1947 in particular) and 1951–1989 (1951–1956 and 1961–1989 in particular), when reductions were found in nearly 70% of trees, and also recent years after 2009 (Fig. 3). The strongest negative response (reductions of tree-ring widths) was recorded between 1967 and 1980. Single strong reduction signals were also found in the years 1996, 2000 and 2003, when reductions of tree-ring widths were recorded for as many as half of the trees sampled (Fig. 3).

The analysis of variability in the average tree-ring widths in the trees sampled (Fig. 4) indicates a gradual decline starting in the 1880s, with a minimum from 1900 to 1920 and also with a shorter and less pronounced depression in the mid-1950s. Subsequently, by the second half of the 1960s the average tree-ring widths increased again, reaching the same level as that from the early period of the trees' lives in the late 19th century, only to decrease again in the 1970s (Fig. 4). From the 1980s onwards, tree-ring widths in firs on the Kamień site gradually increased, especially after 1990, reaching a maximum at the turn of the 21st century (Fig. 4).

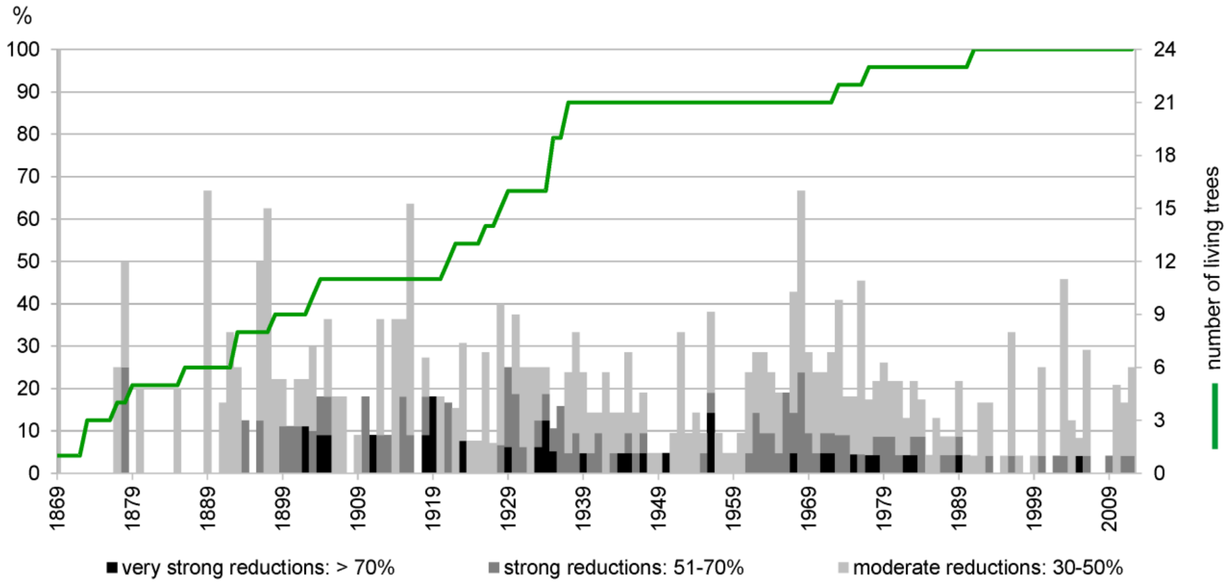

Fig. 3. Percentage of trees sampled which exhibited reductions of tree-ring widths broken down into three severity classes

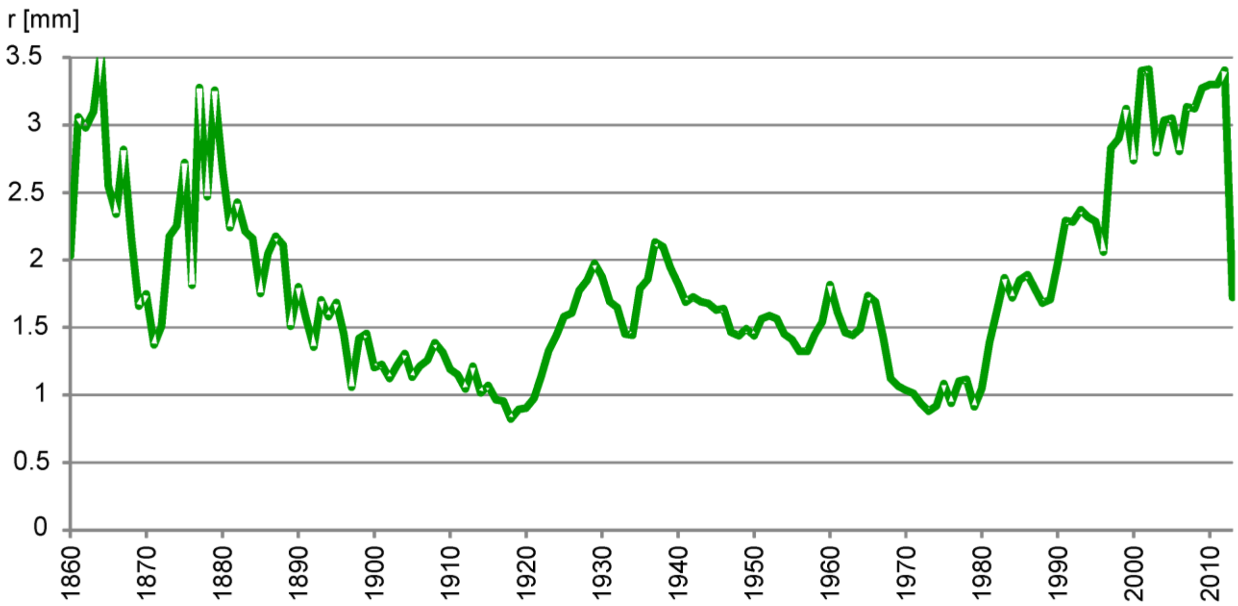

Fig. 4. Average tree-ring widths of silver firs sampled at the study site

For the comparison of the occurrence of reductions of tree-ring widths (Fig. 3), the average tree-ring widths (Fig. 4 and 5) and industrial production data (Fig. 5) demonstrate that the decrease in tree-ring widths in the firs studied occurred at more or less the same time as the increase in the production of hard coal in the Upper Silesian Industrial Region (Fig. 5). The inverse relationship between the industrial production levels and the tree-ring widths of the trees studied is clear. From 1967 to 1988, high levels of hard coal production in the Upper Silesian Industrial

Region were accompanied by low average tree-ring widths in firs growing in the Beskid Niski Mountains (Fig. 5). Since 1989, the production of coal in the Upper Silesian Industrial Region has been declining and the average tree-ring widths in the trees studied has been simultaneously increasing. Additionally, at the end of the 1970s, there was a noticeable increase in tree-ring widths alongside a sudden, albeit slight, decrease in coal production (Fig. 5). Earlier, from 1958 to 1965, this relationship is not as clear, but it is discernible (Fig. 5). Since the beginning of the 1980s, as industrial plant production declined, the average tree-ring widths in the trees studied increased noticeably. There is a moderate negative correlation between hard coal production levels and average tree-ring widths for the period 1948-2013 (66 years). Pearson's correlation coefficient is -0.38.

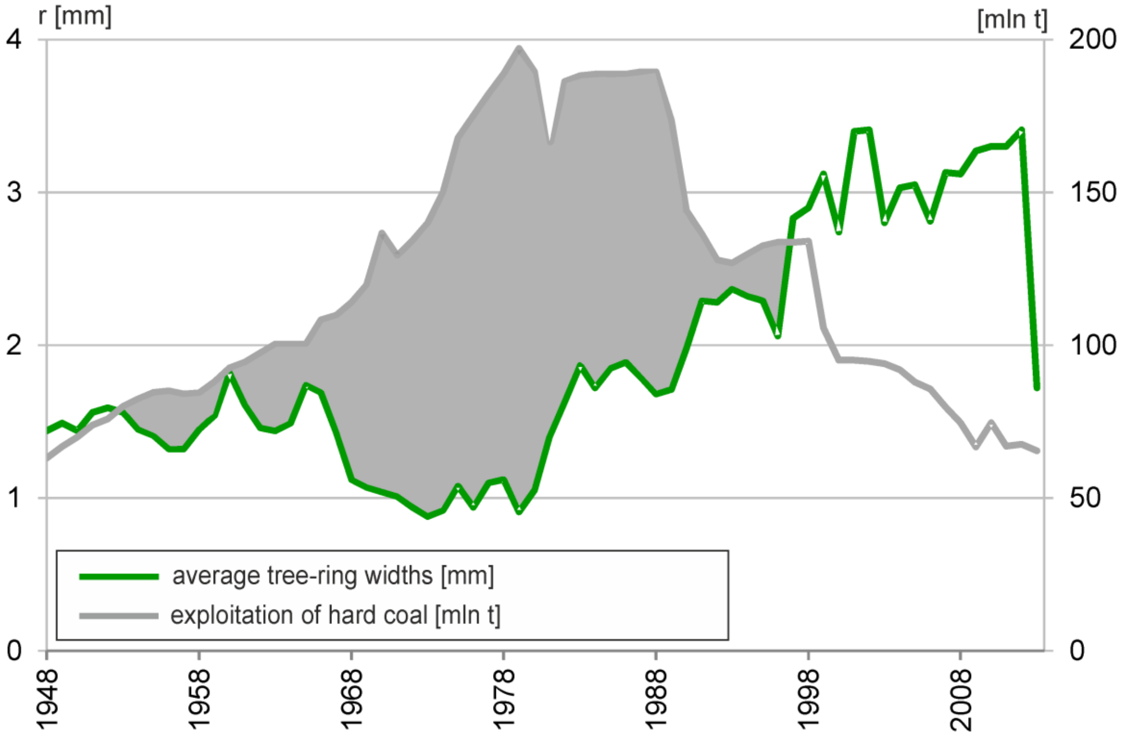

Fig. 5. Average tree-ring widths in firs at the study site in the Beskid Niski Mountains from the mid-20th century compared to hard coal production levels in the Upper Silesian Industrial Region (source data from Malik et al., 2012). Periods of inverse proportionality are marked by *a grey* colour

5. Discussion

The presence of reductions in tree-ring widths in the years after World War II in the trees studied demonstrates that firs growing in the Beskid Niski Mountains were affected by pollution transported over long distances, probably originating from the Upper Silesian Industrial Region with its numerous steel mills (19) and non-ferrous metal smelters (3), coking plants (9), power plants and combined heat and power plants (43) and chemical plants (3), and also from the Czech Republic and Germany (Pukowska-Mitka & Tkocz, 2008, Elling et al., 2009, Tkocz, 2012). This confirms a clear relationship between industrial production levels in the Upper Silesian Industrial Region (which indirectly reflects the scale of pollutant emissions to the atmosphere) and the average tree-ring widths and the prevalence of reductions of tree-ring widths in the silver firs growing at the studied site in the Beskid Niski Mountains. The inversely proportional relationship between these two elements (industrial production and tree rings) is clear, not only before 1989, when levels of pollution were high and fir tree rings narrow, but also after 1989 when the situation changed (Fig. 5).

After 1990, many industrial plants were closed in the Upper Silesian Industrial Region as a result of political and economic transformation, e.g. Huta Batalion, Huta Gliwice or Huta Jedność (Karpiński et al., 2013). Industrial production levels decreased (Fig. 5) and environment-friendly technologies had to be introduced at those plants which continued to operate. As a result, the emission of pollutants to the atmosphere declined, and firs in the Beskid Niski Mountains responded rapidly by increasing tree-ring widths. Similar trends, i.e. the reduction of radial growth in trees from the mid-20th century onwards followed by recovery starting from the 1990s as the condition of tree stands improved, have been observed in many regions of Poland, e.g. in the Silesian Upland (MALIK ET AL., 2012), in the Iłża Forest (BIS & DOBROWOLSKA, 2012) and in the Świętokrzyskie Mountains (PODLASKI, 2003). Similar relationships were also observed in Germany, the Czech Republic and Slovakia (ELLING ET AL., 2009; HAUCK ET AL., 2012; RYDVAL & WILSON, 2012; BOŠEĽA ET AL., 2014). HAUCK ET AL. (2012) noticed that the rapid growth increase of Norway spruce in the Harz Mountains (Germany) since the 1990s was mainly caused by a decrease in atmospheric SO_2 concentrations. BOŠEĽA ET AL. (2014) observed that during the last two to three decades there was a rise in tree-ring widths of silver fir in four sites in Slovakia (Western Carpathians). They suggested that the increase in the width of fir growth occurred when there was a decrease in pollution to the atmosphere (NO_x and SO_2 emissions).

The results obtained for the second half of the 20th century indicate a clear relationship between industrial production levels, treated as a proxy for pollutant emissions to the atmosphere, and changes in the radial growth of silver firs growing at the studied site in the Beskid Niski Mountains. Studies on the relationship between tree rings and changes in industrial pollution emissions have so far been conducted in the Sudetes (ZAWADA, 2001; FILIPIAK, 2002), in the Świętokrzyskie Mountains (JAWORSKI ET AL., 2000), on the Kielce Upland (WERTZ & WILCZYŃSKI, 2012) and in the Ojców National Park (KRĄPIEC & SZYCHOWSKA-KRĄPIEC, 2001). Similar to the results obtained for the Kamień site in the Beskid Niski Mountains, in the aforementioned articles, a strong negative impact of air pollution and its long-distance transport (including cross-border transport from Germany and the Czech Republic) on tree-ring widths at the beginning of the 20th century and from the early 1960s onwards was identified. According to ELLING ET AL. (2009) local SO_2 emissions could have influenced fir growth. The authors observed a continuous increase in SO_2 emissions since 1880, which reached a maximum between1970-1980. They also suggested that air pollution was the most important factor which played a key role in the growth reductions of silver fir in the period 1960-1980.

Results of comparisons between industrial production in the second half of the 20th century and tree-ring widths in the firs studied, supported by data from the literature (JAWORSKI ET AL., 2000; KRĄPIEC & SZYCHOWSKA-KRĄPIEC, 2001; ZAWADA, 2001; FILIPIAK, 2002; WERTZ & WILCZYŃSKI, 2012), make it possible to reconstruct changes in levels of atmospheric pollution also in periods for which no industrial emissions monitoring data or industrial production data exist, on the basis of calculated reductions of tree-ring widths. As a result, the oldest period in which reductions of tree-ring widths were identified for the silver firs studied, corresponds to the interwar years and to World War II, and can be associated with the impact on the trees studied of the pollutants emitted in the Central Industrial Region within which the study site is situated. The Central Industrial Region developed rapidly from 1920 to 1940 and it included industrial plants which emitted significant amounts of pollutants such as Huta Stalowa Wola (a steel mill), the chemical plant in Nowa Sarzyna or Elektrociepłownia Rzeszów (a combined heat and power plant) (KALDA & ŁOPUSZYŃSKA, 2014).

The severity of the reductions of tree-ring widths in the firs studied caused by atmospheric pollution in the second half of the 20th century was slightly greater than in the case of previous reductions, despite the fact that in the 1920s and 1930s, the sources of pollution were situated much closer to the study site. However, the period after World War II was characterised by a particularly rapid development of industry not just in Poland, but throughout Europe as well. The scale of pollution transported over long distances was high as at that time the Upper Silesia Industrial Region was the area with the highest concentration of industrial plants in Poland (PUKOWSKA-MITKA & TKOCZ, 2008), and thus emitted the largest amount of pollutants to the atmosphere. Moreover, reductions of tree-ring widths in the firs studied in the second half of the 20th century were less severe than the reductions found by MALIK ET AL. (2012) who studied the impact of individual pollution sources on radial growth in pine trees growing from 5 to 20 km from a chemical plant and from a zinc and lead smelter. However, this comparison is made more difficult by the difference in the tree species studied.

Apart from the long-term reductions of tree-ring widths related to the development of industry, in the firs studied single years were found as well in which a large percentage of the trees sampled produced narrower rings, e.g. 1918, 1952, 1956, 1996, 2000 or 2003. It would appear that reductions in those individual years were caused by short-term factors other than industrial pollution, e.g. unfavourable climatic conditions, according to FELIKSIK ET AL. (2000), OPAŁA (2009) and BIS & DOBROWOLSKA (2012), these include severe winters and inclement weather in June with low temperatures and precipitation. According to the aforementioned authors, such conditions prevailed in Poland from the 1920s to the mid-1960s. During that period, the negative impact of climate could have overlapped with the adverse effects of pollutants in the firs studied, which in the dendrochronological record obtained could have been expressed by particularly narrow tree rings. Bis & Dobrowolska (2012) stated that unfavourable weather conditions from the 1920s to the 1960s were recorded by the majority of firs. Additionally, Elling et al. (2009) argued that there were no healthy firs at all in Poland in the 1970s, which was caused by various factors, but the dominant one was air pollution from sulphur dioxide.

A reduction in tree rings at the study site was also found for recent years (after 2009). It appears that this phenomenon may be related to the increase in low-stack emissions from domestic boilers in this period (Raport o stanie..., 2013; Rutkiewicz et al., 2016). This points to the considerable sensitivity of firs as bioindicators of air pollution and to the usefulness of this tree species not just for dendrochronological reconstructions of pollution conditions, but also for the ongoing monitoring of air quality.

6. Conclusions

Reductions in the tree-ring widths of silver firs are a good indicator of air pollution, which enables not only the historical reconstruction of changes in air pollution, but also its ongoing monitoring.

Dendrochronological analysis of silver fir trees growing in the Beskid Niski Mountains, facilitated the detection of changes in their annual growth rate over the past 154 years. The studies conducted allowed the detection of reductions of tree-ring widths during three main periods: in the 1930s and 1940s, from the 1960s to the 1980s, and in the post-2009 period. Reductions in tree-ring widths in the second half of the 20th century and the average tree-ring widths in the firs studied coincide with changes in industrial production in the Upper Silesian Industrial Region. The inverse relationship between production levels and the width of tree rings in firs indicates that the detected reductions of tree-ring widths were caused by severe industrial air pollution. In the first half of the 20th century, emissions of industrial pollutants from plants operating in the Central Industrial Region within which the study site is located had a similar impact on radial growth of the trees studied. In the 1990s due to the decrease of pollution into the atmosphere, tree-ring widths in the firs under study increased and the number of trees with recorded reductions of tree-ring widths decreased.

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