DOI: 10.2478/frp-2018-0011
Available online: www.lesne-prace-badawcze.pl

Leśne Prace Badawcze / *Forest Research Papers*
Czerwiec / June 2018, Vol. 79 (2): 105–112

ORIGINAL RESEARCH ARTICLE

e-ISSN 2082-8926

Influence of climatic conditions and air pollution on radial growth of Scots pine (*Pinus sylvestris* L.) in Szczecin's city forests*

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Abstract. The aim of the present work was to characterize the growth – climate relationship of pines growing in the Szczecin city forests in intensively used recreational areas and to identify the effect of air pollutants emitted by a nearby chemical factory on tree- ring width. Our research area was located in the Głębokie forest complex, which is one of the most frequently visited. The chemical factory Police that produces fertilizers is located at a distance 11 km away from the study plot. The largest emissions of pollutants from the factory in terms of volume occurred in the 1980s and early 1990s.

Wood samples were collected from Scots pine (*Pinus sylvestris* L.) with the Pressler borer from 30 trees and examined using standard dendrochronological methodology. The result was a local chronology of 169 years from 1848–2016. Dendroclimatological analyses indicated that the weather conditions at the turn from winter to spring are the dominant factors influencing radial growth. For example, higher than average temperatures in February, March and April result in a wide tree-ring in the upcoming growth season. Following Nowacki and Abram's method, we also determined the relative growth change in order to delimit the timeframe when air pollution potentially alters tree-ring width. Due to the lack of data for the period 1848–1945, the increasing and decreasing relative growth could not be linked to specific events. For the period 1944–1972 however, we observed and increase in the tree-ring width, which in this case can be attributed to favorable weather conditions. The final period, 1973–1991, on the other hand showed the strongest decline in annual growth throughout our chronology and this was largely due to the nearby chemical factories, which released huge amounts of pollution into the atmosphere during this period.

At present, despite new technologies and a decrease in overall production by the nearby chemical factory, we found a negative trend in ring width dynamics indicating a need for pollutant monitoring and further research.

Keywords: tree-ring width, dendroclimatology, industrial emissions, *Pinus sylvestris*, recreational areas, Szczecin

* The points made in this article were presented at the 3rd National Conference 'Climatic conditions of forest life', organised by the Warsaw University of Life Sciences (SGGW), Faculty of Forestry, on 1–3 June 2017 at CEPL in Rogów.

1. Introduction

Szczecin is a large city that encompasses forests, forest lands (17% of the city area) and urban vegetation including that within parks, cemeteries, green spaces and street greenery (2%). The Urban Forests (2,764 ha) are part of three large forests: the Wkrzańska Forest, the Bukowa Forest and the Goleniowska Forest. The Urban Forests comprised of 13 forest complexes, the largest of which are the Arkoński Forest, 976.90 ha; Dąbie, 465.56 ha; Głębokie, 351.77 ha; Mościęcino, 281.46 ha; and Zdroje, 151.03 ha (Meyer 2011). Szczecin's urban greenery is one of the factors that determine the comfort of living in the city and shape residents' well-being and health. Urban green areas fulfil various ecological, protective and aesthetic functions. They absorb and neutralise pollutants, create noise suppressing barriers, improve local microclimate and regulate thermal-humidity relations in the environment. Furthermore, they ensure contact with nature and regenerate human physical and mental strength. As a general rule, forest areas create free-of-charge, attractive

Submitted: 20.11.2018, reviewed: 4.02.2018, accepted after revision: 15.02.2018.

conditions for recreation and leisure as well as for hiking or cycling. In the busy and overcrowded city, even small forest areas are of great importance.

The health and condition of forest stands, especially those coniferous, are determined not only by management measures undertaken but also by the impact of pollution. The proximity of large pollutant emitters can seriously damage forests, lower their value, affect their functions and modify planned silvicultural activities. Air pollution emitted by the chemical plant 'Police' (*Grupa Azoty Zakłady Chemiczne "Police" S.A.*) has always significantly impacted the health and annual growth of forest stands in Szczecin. Dendrochronology enables the assessment of historical patterns of annual growth in individual trees or tree stands as well as makes it possible to determine the influence of climate, pollutant emission and habitat changes on tree annual growth. Data on the amount of industrial emissions released a dozen or so years ago are hardly ever available; hence, trees can be treated as an archive of the changes and may well be used to reconstruct adverse events occurring in the past. Szychowska-Krąpiec and Wiśniowski (1996) and Borowiec et al. (2005a, b) conducted research on the impact of air pollution on the width of annual tree rings in Scots pine growing in the Wkrzańska Forest. The obtained results made it possible to determine the period and a range of impacts of pollutant emissions on forest ecosystems. Unfavourable changes in tree physiological and biochemical processes because of pollution can reveal after many years and can lead to degradation of forest ecosystems if combined with climate change impacts and harmful pests (insects and pathogenic fungi).

The aim of the study was to (i) characterise the 'growth–climate' relationship in Scots pine *Pinus sylvestris* L. trees growing in the Urban Forests in the city of Szczecin, the forest area intensively used for recreational purposes, and (ii) to determine the impact of air pollution emitted by the located nearby chemical plant 'Police' on tree rings.

2. Study area

The study plot was established in the Urban Forests of Szczecin in the part of the Głębokie Forest – situated in the macroregion Szczecin Pobrzeże, the mesoregion Wzniesienia Szczecińskie (Kondracki 2002) and 500 m north-east of a ribbon lake – Głębokie. The study was carried out in the forest compartments 90o and 90z (53°29'N, 14°28'E) (Fig. 1), at an altitude of about 20 m a.s.l. Within the fresh mixed forest site (on rusty and brown soils formed on weak loamy sands), there grow Scots pine-beech-oak forests (managed to fulfil forest protective functions). Scots pine trees (10–20% share) are 150–155 years old, reach a height of 29–31 m and a DBH (diameter at breast height) of 46–54 cm. The study plot is located within one of the most popular recreational areas in the city of Szczecin – with numerous hiking trails and forest glades. Especially at the summer weekends, this is a place readily chosen by the residents of downtown apartment buildings for walking, running, bike rides and forest picnics.

At a distance of 11 km north-east of the study area, there operates the chemical plant 'Police' that produces fertilisers. The plant has been emitting large amounts of pollutants into the atmosphere and water since the late 1960s because of the production of, amongst others, sulphuric acid, phosphoric acid, sodium fluorosilicate, ammonia and urea. The largest emissions, related to the volume of production and technologies used, took place in the 1980s and early 1990s (Borowiec et al. 2005a, b; Mazurkiewicz, Podlasińska 2014).

3. Climate

The climatic conditions of Szczecin and its surroundings are primarily shaped by the advection of polar–marine air masses. The proximity of large water reservoirs (the Baltic Sea and the Szczecin Lagoon) brings about local breeze circulation that influences the weather.

Sunshine duration per year is, on an average, 1,588 h (from 1212 to 1971 h in 1965–2016). In the annual course, the minimum sunshine duration is observed in December (29 h) and the maximum in May (232 h). Sunshine duration greater than 200 h/month occurs from May to August. According to the division into the regions by Koźmiński and

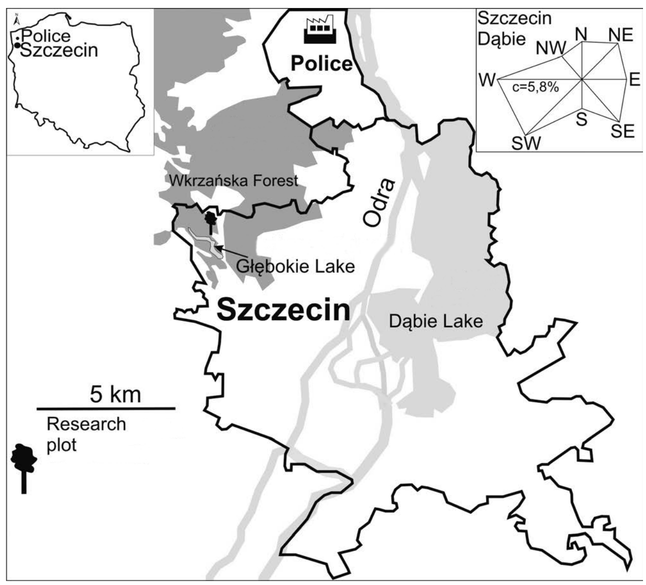

Figure 1. Location of the research plot and Chemical Factory Police. Wind rose for Szczecin-Dąbie station in 1956–1980, c – percentage share of calm, (Koźmiński, Michalska 2008 – modified).

Michalska (2005), the area under the study is situated in the Region III with the average sunshine duration.

The average annual temperature is 8.7°C – from 7.1 to 10.9°C (1948–2016, data from the weather station of the Institute of Meteorology and Water Management IMGW in Szczecin-Dąbie). The hottest month in the year is July, with an average temperature of 18.1°C (15.2–22.7°C), and the coldest month is January, with an average temperature of −0.4°C (from −8.8 to +5.1°C). The absolute maximum temperature was recorded in July 1959 (+36°C), and the lowest (−30°C) was recorded in January 1987 (Czarnecka 1996).

The long-term annual precipitation is 544 mm, ranging from 347 mm in the driest years to 796 mm in the wettest years. The driest month is February with an average precipitation of 31 mm, and the wettest month is July with 71 mm (then precipitation can range from 5 to 185 mm). Precipitation in the summer constitutes 35% of the sum of precipitation, whereas that in the winter constitutes 20%. The fall is more humid when compared to the spring (Czarnecka 1996). Owing to the frequent thaws, the snow cover is characterised by low durability and high variability over time. The dominant wind directions are western and south-west, and the wind speed ranges from 3.1 to 4.5 m/s (Koźmiński, Michalska 2001, Fig. 1).

4. Research methodology

Field observations were carried out in January 2017, when tree samples were taken from trunks of a total of 30 Scots pine trees (1.3 m above the ground), with the use of the Pressler increment borer. The resultant injuries were covered with Lac -Balsam (insecticide and fungicide) as well as protected with wooden pins. In order to achieve clear images of the rings, under the laboratory conditions, the extracted tree sections were fixed into dried slats and then cross cut with a preparatory knife. The examinations were carried out under a binocular combined with an increment measuring device (with an accuracy of 0.01 mm) and using the computer program DendroMeter (Mindur 2000). Then, the chronology of ring widths was determined with the use of tree rings (Krawczyk 1995), DendroGraph (Walanus 2001) and Cofecha (Holmes 1983) as well as the conservative cross-dating method (Cook, Kairiukstis 1992; Zielski, Krąpiec 2004). In further analyses, we used the residual chronology. In order to accentuate the short-term variability, long-term trends and autocorrelation were erased (in the first stage, the least-squares method was used, and in the second stage, spline function was performed using the ARSTAN program (Holmes 1994). The expressed population signal (EPS) – describing the representativeness of the measured sequences – was calculated as well (Wigley et al. 1984). In the dendroclimatic analyses, climatic factors with the greatest effects on tree rings, that is, air temperature, precipitation and sunshine, were taken into account. Identification of the indicator years was carried out using the TCS program (Walanus 2002). For at least 10 trees, The positive years (characterised by an increase in the ring width) and the negative years (with decreased ring width as compared to the previous year) were determined (Schweingruber 1989; Kaennel, Schweingruber 1990; Meyer 1997–1998; Zielski; Krąpiec 2004). The indicator years were those when more than 90% of the examined trees showed the same incremental tendency. The analysis of temperature and precipitation conditions was carried out for 25 indicator years (from 1936), whereas the analysis of sunlight conditions was carried out for 15 years (from 1969). The analysis of correlation and response function were carried out for the residual chronology using the RESPO program (Holmes 1994), with the aim to demonstrate the 'growth–climate' relationship. The analysis was carried out for 16 months, from June of the year preceding the growth measurement until September of the subsequent year of vegetation (based on the temperature and precipitation in the period 1948–2016, 69 years, and on the sunlight in the period 1965–2016, 52 years). Correlation, multiple regression and determination coefficients were calculated. In dendroclimatic analyses, data from the Szczecin-Dąbie weather station (IMGW Meteorological Yearbooks) for the period 1948–2016, archival German meteorological records (Deutches Meteorologisches Jahrbuch 1938–1948) and all other available materials were used.

Regrettably, no relevant data concerning the study plot have been available. In some cases, there lacked data from the first years after 1945, as, at that time, forestry activities in Poland's forests were just organised after the war. Information with reference to the past three decades of the 20th century was obtained from retired managers of the Urban Forests: Mr. Wojciech Tomczak and Mr. Tomasz Krowicki. Available meteorological and forest management data used in the study concerned not more than the period after 1945.

The relative growth change was determined using the method by Nowacki and Abrams (1997). A comparison of tree-ring width in the subsequent 10-year periods was made to detect permanent changes, indicating disturbances of tree site conditions. At the same time, short- and long-term effects of changing weather conditions as well as the age trend of trees found in a series of tree-ring widths were eliminated. The percentage of growth change (% GC) was calculated at annual intervals using the following formula:

$$\% GC = [(M2 - M1) / M1] \times 100$$

where
M1 is the mean from 10 years preceding a given year,
M2 is the mean from subsequent 10 years (Nowacki, Abrams 1997, Läääldaid et al. 2014).

5. Results

The LM chronology is based on 28 individual growth curves and comprises a period of 169 years (1848–2016) (Fig. 2). The average tree-ring width in the studied Scots pines is 1.81 mm and ranges from 1.04 to 2.39 mm for individual trees. The standard deviation (SD) for the real and indexed chronology (RES) is 1.059 and 0.176, respectively; the first-order autocorrelations (A1) are 0.795 and 0.110, respectively; and the mean sensitivity (MS) is 0.269 and 0.211, respectively. The EPS index for the period 1880–2016 is 0.94, which indicates the representativeness of the chronology (Wigley et al. 1984, Wilczyński 2010).

Correlation analysis and response function analysis show that tree growth response in the forthcoming growing season is influenced by weather conditions in the period between the winter and the spring (Fig. 3). Higher than average temperatures in February, March and April contribute to the formation of a wide tree ring in the forthcoming season. Precipitation in February has a positive effect on Scots pine incremental dynamics. The amount of precipitation in May and, especially, in July, positively correlates with the annual growth change. Also the sum of sunshine in August has a positive effect on the size of tree-ring width. In the year preceding the vegetation season, negative values of regression coefficients for air temperature in autumn months (September and October) as well as negative values of correlation and regression coefficients for sunshine in November are observed (Fig. 3).

There are 49 indicator years: 21 positive (characterised by an increase in tree-ring width as compared to the previous year) and 28 negative (characterised by a decrease in tree-ring width as compared to the previous year). This analysis confirms the results obtained in correlation and regression analyses: the warm end of winter and early spring warms cause wide tree rings in Scots pine trees in the forthcoming growth season, whereas frosts in February and March, as well as low temperatures in April, cause growth reduction. In Figure 4, the positive and negative indicator years are summarised and the temperature course in February, March and April in the years 1943–2013 is compared to the average values for these months. In the majority of the negative years (12 of 13 analysed), the average February temperature is below the long-term average; in March, the analogous situation is observed in 7 years, and in April, it is observed in 9 years. For the positive years (analysis of 12 years), the average air temperature is above the long-term average in 8 cases in February, in 10 cases in March and in 7 cases in April; in 1 year, both the temperatures are equal (Fig. 4).

Relative changes in tree-ring width can be used to reconstruct the history of the examined stand (Fig. 5). The periods characterised by a decrease in the relative growth change,

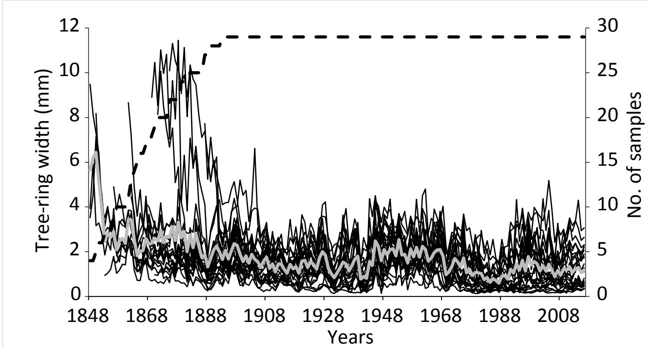

Figure 2. Individual sequences of tree-ring width (thin black line) making up the local chronology of pine (LM, thick gray line) from Szczecin City Forests; number of samples in a local chronology (dotted line)

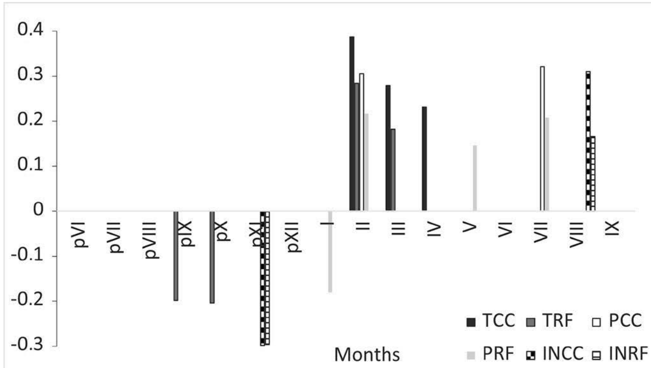

Figure 3. Results of correlation and response function analyses for index pine chronology (LM) from Szczecin City Forests; the correlation coefficients (TCC – temperature, PCC – precipitation, INCC – insolation) and regression (TRF – temperature, PRF – precipitation, INRF – insolation) are shown; only significant values (α=0.05); p – previous year

that is, 1854–1871, 1886–1893, 1904–1920, 1929–1943, 1973–1991 and 2001–2016, as well as the periods with an upward trend, that is, 1872–1885, 1894–1903, 1921–1928, 1944–1972 and 1992–2000, can be distinguished. In the years 1944–1972, in the chronological order, an increase in the width of annual tree rings (Fig. 2) and an increase in the relative growth change from −70% to 40% are observed (Fig. 5). During the latter period, the studied Scots pines were 100–130 years old and reached their optimal development. Notwithstanding very cold winters occurring in the years 1944–1972 (negative indicator years: 1947, 1954, 1960 and 1969), as well as relatively dry years (e.g. 1963, 1971 and 1972), there prevailed weather conditions that favoured wide tree-ring increments (which is reflected in, amongst others, five positive indicator years: 1943, 1945, 1953, 1957

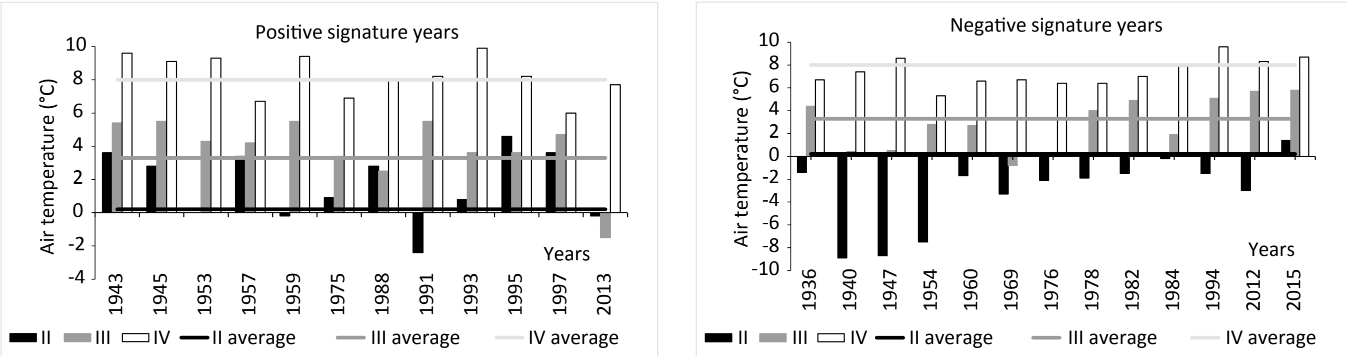

Figure 4. February, March and April temperature (bars) in positive and negative signature years in comparison to average February, March and April temperature from 1948–2016 (line)

and 1959). The late thinning treatments could also influence the observed increase in the width of tree rings. At the same time, the lack of industrial pollution emitters is conducive to high cambium activity. The next period, 1973–1991, was the period when the average tree-ring width was reduced (Fig. 2). A substantial decrease in the tree-ring width, that is, from about 40% to −80% in the course of chronology, is observed (Fig. 5). In the years 1992–2000, in the chronological order, an increase in the tree-ring width as well as the relative growth change (from −80% to about 20%) is again observed. From 2001 to the end of the chronology (2016), the period of slight decrease both in the width of tree rings as well as in the relative growth change is observed.

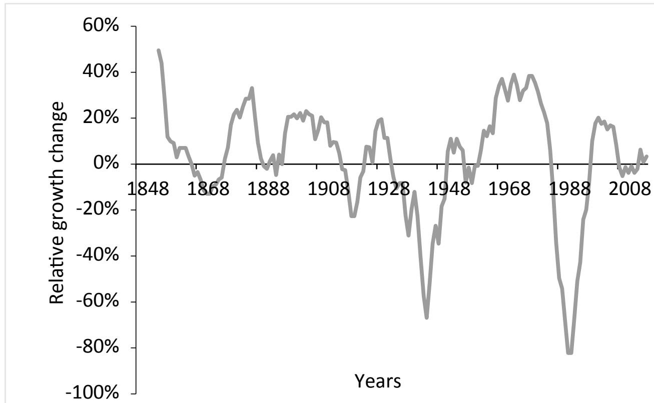

Figure 5. Relative growth change for pine chronology LM

6. Discussion

Under the conditions of the present study, the weather in February and March determined the growth of Scots pine. Predominantly mild and short winters, as well as warm rapidly beginning springs, favour the formation of wide ~~annual~~ tree-ring width in the forthcoming growing seasons. An additional factor with favourable effects on Scots pine good health condition and formation of wide tree rings is sufficient water supply in the growing site during the summer period. The dominant role of the weather in the period between winter and spring seasons in the process of shaping tree rings is also indicated by other authors, for example, in the studies carried out in the West Pomerania (Cedro 2004), Kujawy (Koprowski et al. 2012), the Niepołomice Forest (Muter 2012), the Drawskie Lakeland (Łodzińska-Jurkiewicz 2016), the coastal areas (Cedro et al. 2013, Olesiak et al. 2014,) Rogów (Bijak 2013), the Kielecka Upland (Wilczyński 2010) and the Tatra Mts. (Bzręk et al. 2014). So far conducted studies have confirmed a common climatic signal in the area of Central Europe, which differentiates the incremental tempo in Scots pine trees (Wilczyński et al., 2001). At the end of the winter and with increasing day length, Scots pine loses frost resistance and becomes sensitive to low temperatures. Frost damages (needle, branch and trunk freezing), frosty winds (drying out) and mechanical damages caused by snow loads negatively affect the tree health condition and impinge tree growth dynamics in the forthcoming growing season.

Scots pine is regarded as a species with high sensitivity to air pollution. The most frequently observed symptoms are needle damage (disturbing photosynthesis and photoresponse), tree-ring width decrease, reduced pollen germination, lower quality of seeds and loss of tree vitality (Kocięcki 1993, Oleksyn 1993). Trees weakened by harmful effects of air pollution are more sensitive to fungal diseases and harmful insect outbreaks (Karolewski, Lorenc-Plucińska 1993, Borowiec et al. 2005a, b), which, because of the poor health condition of trees, often lead to the decline in entire tree stands. Analysis of the relative growth change in the examined trees that grow in the vicinity of the chemical plant 'Police' that emits large amounts of pollutants into the atmosphere shows considerably high sensitivity of Scots pine to pollution. The largest reductions in the width of tree rings are interrelated with the period of the largest fertiliser production in the plant, with the use of outdated technologies (the 1970s to the beginning of the 1990s). During this period, especially in the 1980s, three factors contributed negatively to the growth of Scots pine: drought, nun moth *Lymantria monacha* outbreak and pollutant emissions from the chemical plant. Nun moth outbreak was controlled by means of biological and chemical treatments, which considerably reduced Scots pine defoliation (personal communication). A greater problem was soil drought, which occurred in the studied region at the end of the 1970s and in the 1980s that resulted in a dramatic decrease in the level of the water table in Lake Głębokie located nearby (2 m below the average, personal communication). At that time, water from the underground water intake in Pilchów was pumped to Głębokie Lake to solve the problem, and this caused further decline in the groundwater level in the vicinity of the intake (about 1.5 km away from the study plot). Nonetheless, the most significant reduction of Scots pine tree-ring width was due to the activities of the nearby chemical plant, which produced loads of fertilisers at that point in time by means of environment-unfriendly technologies and emitted sulphur dioxide, fluorine compounds, ammonia, sulphuric acid mist as well as particulate matter to the atmosphere. Under north-west winds or windless conditions, these pollutants were either carried away or settled near the plant. In the years 1992–1999, a rapid increase in the width of observed tree rings is observed, which can be explained by the systemic changes in Poland's economy that resulted in fertiliser production drop off, followed by technology improvement and reduction of pollutant emissions. Recent years in the chronology (after 2000) show a decrease in the width of tree rings. Even with gradually more favourable climatic conditions observed in the 21st century, that is, progressively warmer winters and sooner spring starts as well as increased CO_2 concentration in the air, no increase in width of tree rings has been observed. This issue, described by many authors, has been referred to as the divergence and widely discussed. Contemporary climate changes, and in particular a rapid increase in winter temperatures and greater than before incidence of extreme weather events, do not positively affect the tree-ring width in the studied Scots pine stand. There is a need for further monitoring of tree response under unknown effects of measures taken under climate policies in the coming decades. Above all, this old Scots pine stand should be subject to permanent monitoring, as it has been exposed to the hazards of harmful emissions of pollutants from the nearby chemical plant and adverse changes to the recreational function.

Similar analyses as regards to Scots pine exposed to high air pollution were conducted by Szychowska-Krąpiec and Wiśniowski (1996) in the Wkrzańska Forest as well as Borowiec et al. (2005a, b). In the 1980s, nearby the chemical plant 'Police', more than ever, there were recorded dead tops of trees, necrosis of needles, considerable reductions in tree-ring increment and missing rings. An extent of growth reduction and the number of missing rings depended on the distance from the pollutant emitter and the age of the trees (Szychowska-Krąpiec, Wiśniowski 1996, Borowiec et al. 2005a, b). In the area of Olkusz, the relationship between the number, size and duration of growth reduction and the distance from the emitter was demonstrated by Danek (2008). The author stressed the negative effect of site drainage on Scots pine trees under industrial pollution pressure.

Havas and Huttunen (1972) reported negative effects of particulate matter released because of production of fertiliser on the increment in diameter of the Scots pine. Growth responses are shifted in time and revealed in trees of different age (50-year and 100-year olds). A study carried out by De Ridder et al. (2007) in Belgium showed a strong correlation between tree-ring width and pollutant emissions (heavy metals, especially zinc). Along with the reduction of heavy metal emissions, a noticeable increase in the width of tree rings was observed; however, the problem was also the lack of long series of measurement of pollutant emissions. Reductions in the diameter increment are also associated with emissions of copper compounds (Thompson 1981). Established chronologies were strongly correlated with the beginning of production and the distance from the emitter. The possibility of reconstruction of the amount of pollutants emitted (heavy metal content in the rings and a change in the width of tree rings) was also indicated by Lepp (1970). However, the interpretation of the results should take into account the processes related to uptake, transport and accumulation of heavy metals in trees. Cook (1987) pointed out the difficulties in research on relationships between tree-ring width and environmental contamination. This author presented a series of statistical analyses to help identify a signal from the contaminated environment in tree growth patterns and pointed out the importance of further research with regard to severe environmental pollution that brings about tree health deterioration and sometimes decline in entire stands.

7. Conclusion

Scots pine growing on intensively used recreational areas in the Urban Forests in Szczecin shows the 'growth–climate' relation, typical of this part of Europe. The main factor modelling the width of tree rings are the thermal conditions in the period between winter and spring, along with the pluvial conditions in the summer. At the same time, because of the proximity of the largest industrial pollution emitter in the region, a definite relationship was found between the width of tree ring and emission size as well as the stress period.

Conflict of interest

The authors declare no potential conflicts.

Acknowledgment and source of funding

The research was financed under the statutory subsidy of the Climatology and Meteorology Laboratory as well as the Department of Geology and Paleogeography of the Faculty of Earth Sciences at the University of Szczecin.

We would like to thank the first-year geology students at the Faculty of Earth Sciences, University of Szczecin (2016/2017), for their help in field and laboratory works. We would also like to thank Mr. Wojciech Tomczak, a retired manager of the Urban Forests, for providing information on the forest under the study.

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Authors' contribution

A.C. – field and laboratory work, desk studies, manuscript writing, preparation of graphics; B.C. – laboratory work, desk studies, manuscript writing, preparation of graphics.

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