Dendrochronologia 31 (2013) 179–186

Contents lists available at ScienceDirect

Dendrochronologia

journal homepage: www.elsevier.com/locate/dendro

Original article

Dendrochronological research of Scots pine (*Pinus sylvestris* L.) radial growth in vicinity of industrial pollution

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ARTICLE INFO

Article history:
Received 20 July 2012
Accepted 11 April 2013

Keywords:
Scots pine
Tree-ring
Air pollution
Growth promotion
Growth inhibition
Forest recovery

ABSTRACT

The aim of this research is to investigate changes in the annual radial increment of Scots pine (*Pinus sylvestris* L.) in the vicinity of intensive (3–10 km) and moderate (11–20 km) industrial pollution during different growth periods (growth promotion, inhibition, and recovery). Low level of emission was beneficial for tree growth during the growth promotion period, and the annual radial increment in the zones of intensive and moderate pollution increased by approximately 15–25% and 10%, respectively. Severe loss was reported to forests during the growth inhibition period when nitrogen and sulphur dioxide emissions were 37–40 thousand (thou.) tons per year. About 40–45% tree radial increment loss was observed in the stands closest to the pollution source, and 15–20% loss was observed for the most distant stands. The stabilization of radial growth decrease and the beginning of recovery of damaged stands began in 1988–1992, when the annual amount of industrial emissions and environmental pollution were considerably reduced. The stabilization of radial growth and the initiation of recovery after pollution reduction were high for the most damaged stands. Their radial increment was stable and close to that of the control stands in 2000–2011. Stands with less damage growing further from the pollution source were recovered earlier, and their radial increment stabilized near the control increment in 1995–1999. The results of linear regression analysis demonstrated that the impact of pollution is different for stands growing at different distances from the plant, and the impact decreases with distance ($R^2 = 0.78$ and $R^2 = 0.75$, respectively; $p < 0.05$).

Introduction

Air pollutants, including sulphur, nitrogen, and ozone, have significant cumulative effects on forests (Tkacz et al., 2007; Malik et al., 2012), and their oxidation products are considered as the main factors regulating the process of acidification of biological systems (Schulze, 1989; Manion and Lachance, 1992; Mylona, 1996; Juknys et al., 2003). High concentrations of SO_2 and NO_2 can damage trees directly through the foliage, and indirectly, through the soil (De Vries et al., 2000). Direct impacts include disorders of photosynthesis, shift in carbon allocation leading to a weakened root system, accelerated foliar leaching affecting the nutrient status (Innes, 1993; Schweingruber, 1996). Indirect impacts include loss of base cations from soil causing deficiency of these nutrients (notably Mg), the release of toxic aluminum affecting fine root growth. Inhibiting the uptake of base cations and a decrease in pH may also affect mineralization processes and thereby nutrient availability (Schweingruber, 1996; De Vries et al., 2000). Presence of acidifying compounds in the environment can lead to crown defoliation and foliage discoloration (Klap et al., 2000; Ozolinčius and Stakėnas, 2001). The lower part of stem may not form full annual rings (Banks, 1991) that can change the ratio of the early and late wood in the annual tree rings (Schweingruber, 1996).

In addition to air pollution, other factors could also influence tree growth (Manion and Lachance, 1992). Changes in long-term climate and short-term meteorological events will strengthen the impact of pollutants. Unfavorable climatic conditions (Innes, 1994, 1998; Laubhann et al., 2009) and invasions of forest pests, insects, and various diseases (Kandler, 1992; Chakraborty et al., 2008; Hemery, 2008; Pitman et al., 2010; Ostry et al., 2011) are often mentioned together with pollutants. Industrial emissions can affect the radial growth of Scots pine (*Pinus sylvestris* L.) in combination with other environmental factors. Climatic conditions also could have a large impact on the health and vitality of forest ecosystems (Bytnerowicz et al., 2007; Paoletti et al., 2007; Serengil et al., 2011; Matyssek et al., 2012).

The sensitivity of trees and bushes to pollutants is unique each species (Vaičys and Armolaitis, 1986). The species that are more

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http://dx.doi.org/10.1016/j.dendro.2013.04.001

resistant to SO_2 and NO_2 are *Robinia pseudoacacia* L., *Acer platanoides* L., *Ulmus minor* Mill., *Euonymus europaeus* L., *Prunus padus* L. Species, such as *Alnus glutinosa* (L.) Gaerfn., *Alnus incana* (L.) Moench, *Qercus robur* L., *Larix decidua* Mill., *Corylus avellana* L., are moderately resistant. Low resistant species are *Betula pendula* Roth, *Populus tremula* L. Conifers (*Pinus sylvestris* L., *Picea abies* (L.) H. Karst. and *Juniperus communis* L.) are very sensitive tree species (Vaičys and Armolaitis, 1986). Other studies explored that Silver fir (*Abies alba* Mill.) is more sensitive to environmental pollution than Scots pine or Norway spruce (Filipiak and Ufnalski, 2004; Wilson and Elling, 2004).

Tree-rings are repositories of information on environmental phenomena (Eckstein, 1990) and serve as natural monitors (Schweingruber, 1996). Therefore, the use of tree rings as an indicator of environmental conditions is important for the evaluation of long-term impacts in forest health in the polluted areas. Many studies show the tree-rings as indicator of forest health in polluted environment (Hirano and Morimato, 1999; Krąpiec and Szychowska-Krąpiec, 2001; Juknys et al., 2002, 2003; Filipiak and Ufnalski, 2004; Wilson and Elling, 2004; Wilczyńki and Feliksik, 2005; Wilczyńki, 2006; Danek, 2007; Kask et al., 2008; Stravinskienė and Erlickytė-Marčiukaitienė, 2009; Malik et al., 2012; Rydval and Wilson, 2012).

The main goal of this research is to estimate the long-term impact of industrial pollution on the radial increment of Scots pine (*Pinus sylvestris* L.).

History of the Achema plant

J/S Achema (formerly Azotas) is the largest nitrogen fertilizer producer in the Baltic countries. It is situated in the central part of Lithuania, the Jonava district (55°05′ N; 24°20′ E) at the confluence of the Neris and Sventoji rivers (Armolaitis, 1998; Juknys et al., 2003). The first production – ammonium was produced in the beginning of 1965 (Armolaitis and Stakenas, 2001). Later, with the rapid expansion of the plant, the company started producing methanol (in 1968), urea (in 1969), polyvinyl acetate dispersion, urea formaldehyde resins (in 1972), ammonium nitrate (in 1973), and nitrophoska (in 1975). Since 1975, under increased production capacity and the launch of combined (nitrogen, phosphorus, and potassium) fertilizers, the first signs of forest damage were observed in the vicinity of the plant dried up 1.5 ha of forest, and later, the area of dead stands increased and in 1976 comprised 6 ha (Armolaitis, 1998).

CO, SO_2, NO_2, NH_3, and mineral dust are the major components of the emissions from the Achema mineral fertiliser plant. Since 1971, the amount and concentration of emitted pollutants gradually increased. The largest compound stream of annual emissions was in 1979–1981: every year 34–40 thou. tons of pollutants emitted into the atmosphere. These were mostly CO (9874 tons per year), SO_2 (4630 tons), NO_x (3862 tons), NH_3 (3734 tons), methanol (923 tons) as well as the dust of mineral fertilizers (13860 tons per year) (Armolaitis et al., 1999). Sulphates amounted to 100 kg/ha in the intensive pollution zone and 87 kg/ha in the moderate pollution zone, which exceeded background concentrations by 2.5 and 2.2 times, respectively. The emission of nitrate exceeded the background by 5.9 times in the intensive pollution zone and by 4.8 times in the moderate pollution zone (Armolaitis, 1998; Juknys et al., 2002, 2003). As observed from Fig. 1, emission began to decrease in 1982, and until 1999 emission levels were reduced by more than 10 times.

From 1979 to 1989, the level of emission reduced from 40 thou. tons to nearly 22 thou. tons (see Fig. 1). However, the forests (mostly Scots pine and Norway spruce stands) were declining in an area

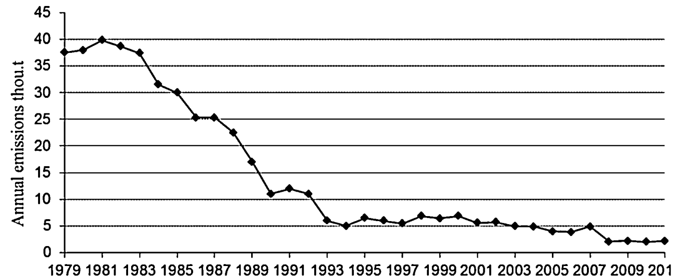

Fig. 1. Annual emissions from Achema factory during 1979–2011. *Source*: Department of environmental protection of Achema.

ranging to 20 km in the direction of prevailing winds from the Achema plant. Due to the accumulation of nitrogen compounds, not only trees were drying out, but also the species composition of vegetation communities has changed (nitrophilous plants started spreading: *Rubus idaeus* L., *Epilobium angustifolium* (L.) Holub, *Urtica dioica* L. etc.). Forest soil acidification (increase of Al^{3+} ions and leaching of Ca^{2+}, and Mg^{2+} ions) and microbiota changes (increased the amount of amino bacteria, the decomposition processes of organic matter were disrupted) were recorded (Armolaitis and Stakenas, 2001).

Emissions from Achema were reduced after a serious accident in the Nitrophoska department and its subsequent closure in 1989. In the beginning of 1990s, due to the industrial decline and technological modernization, emissions decreased significantly. Essential reductions of air pollution emissions started in 1993 (Armolaitis, 1998).

In 1997, the total amount of emissions comprised of 5.5 thou. tons. Despite the overall decrease in emissions, low level increase in total annual emissions was registered in 1998 (7.5 thou. tons), 2004 (6 thou. tons), and 2007 (4.9 thou. tons). In recent years (2008–2011), annual emissions comprised of 2.1–2.4 thou. tons, i.e., several times lower than in 1980–1982 (see Fig. 1). According to the data of Achema Environmental protection department in 2011, the structure of pollutants has also changed, and at present, mostly NO_x (766 tons per year), CO (713 tons per year) and NH_3 (432 tons per year) gases are emitted.

Materials and methods

Investigations were conducted in ten damaged semi-mature (80–90 years old) Scots pine (*Pinus sylvestris* L.) stands (Table 1). The sample plots were established along a 20 km transect running to the north–east direction from the plant in Jonava district (Fig. 2). For this research, two different distances were chosen (3–10 km and 11–20 km), away from pollution source. The forest type of these stands is *Pinetum vaccinio–myrtillosum*, according to international classification of soils – *Arenosols* (FAO/UN, 2006). Site conditions and the main stand characteristics of the monitored stands were similar. Four control stands were selected in the relatively clean environment in Dubrava experimental forest enterprise (Kaunas district, 15 km south–east from Kaunas city; 54°84′ N; 24°12′ E) and Aukštaitija National Park (Utena district, 30 km east from Utena city; 55°46′ N; 24°23′ E), which by age and biometric parameters were similar to the stands nearby Achema plant (see Table 1).

Using the international monitoring methodology (UN/ECE, 1994), Scots pine trees of 1 (dominant) and 2 (codominant) classes according to Kraft's classification were selected as samples. 300 sampled trees from damaged stands and 120 sampled trees from relatively healthy (control) stands were chosen. Wood samples (cores) were taken by Pressler's borer at 1.3 m height from a root