

# Impact of Air Pollution on Scots Pine Stands Growing in Poland on the Basis of Dendrochronological Analysis <sup>†</sup>

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**Abstract:** Air pollution and climate change are two key factors comprising the global change threat to forest health and sustainability. The intensive development of industry in the second half of the 20th century brought significant changes in the level of pollutants emitted into the atmosphere in Poland. Dry and wet deposition of toxic pollutants (mainly SO<sub>2</sub>, NO<sub>x</sub>, and NH<sub>3</sub>), continuing over more than 40 years, has caused serious damage to forest stands. One of the ways for describing the effect of industrial emissions on forests is tree-rings (dendrochronological) analysis, which has been used in our research. We present a brief description of the studies on the impact of air pollution on the growth of forests growing in the most polluted areas of Poland. The main aim is to evaluate Scots pine stand degradation caused by the pollutants emitted from one of biggest polluters of the environment in Poland for over 25 years (1966–1990). We found that pollutant emission caused disturbances of incremental dynamics and long-term strong reduction of growth. Scots pine growing in the vicinity of the nitrogen fertilizer factory showed a dramatic growth reduction after the beginning of the pollution period. Significant decrease in growth was observed for the majority of investigated trees (75%) to the end of the 1990s. The zone of destruction extends primarily in easterly and southern directions, from the pollution source, associated with the prevailing winds of the region. At the end of the 1990s, the decreasing trend stopped and the wider tree-rings could be observed. This situation was related to a radical reduction in ammonia emissions and an improvement in environmental conditions. However, the growth of damaged trees due to the weakened health condition is lower than the growth of Scots pine on the reference plot and trees are more sensitive to stressful climatic conditions, especially to drought.

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## 1. Introduction

Air pollution and climate change are considered as two key factors comprising the global change threat to forest health and sustainability [1,2]. The impact of these two factors is synergic and results in cumulative effects on the metabolism and physiological process of trees [3]. High concentrations of air pollution (mainly SO<sub>2</sub> and NO<sub>2</sub>) can damage trees directly through the foliage, and indirectly through the soil [1,3]. Typical symptoms are disorders of photosynthesis, stomatal conductance, shift in carbon allocation, water use efficiency, and leaves lost. Global warming results in the increasing of extreme weather events, especially severe droughts compounded by unusually warm temperatures [4,5]. Increasingly, trees are exposed to water stress can cause physiological damage. In addition, trees can be attacked at some point in time by pathogens. Multiple interactions of those factors induce a reduction in tree vigor and growth, and in the end, the death of trees, decline of certain tree species, and changes in ecosystems. A mechanism of the influence of sulfur dioxide and nitrogen oxide on trees is reported in many studies [1–

3]. The impact of air pollution on forests is mainly seen as direct damage: decreasing biomass growth, lost leaves, and acute damage or even death of a tree. However, much more important are indirect damages to the forest, which at first are not visible and which can lead to major changes in ecosystems.

Intensive development of industry in the second half of the 20th century in many regions of the world caused a significant increase in the level of pollutants emitted into the atmosphere and degradation of increasingly large areas of forests [2]. Since the 1990s, the emission of pollutants was reduced in a majority of European countries, but air pollution continues to affect the structure and functioning of forest ecosystems. In Poland, over 40 years of toxic pollutants were emitted into the atmosphere which caused serious damage to the environment (Figure 1). Most forest areas exposed to pollution are characterized by a gradual general deterioration of tree vitality, sometimes ending in the death of trees. The exception was the forests in Puławy, where air pollution induced the rapid death of trees on many hectares. This problem is the main topic of our work. The forest degradation caused by this factory is described in many publications [6,7]. However, the ecological interaction between air pollution and forest resistance to abiotic stress related to climate change, especially drought, was not examined. The role of other environmental factors that could affect such a large degradation of the forest has also not been studied so far.

The general objective of the study is to determine the impact of air pollution and climate change on Scots pine growing in the vicinity of the nitrogen factory in Puławy. We decided to find answers to the following questions:

- (1) what are the direct and indirect effects of air pollution?
- (2) what is the spatiotemporal distribution of forest degradation?
- (3) what factors, besides air pollution, contributed to such a large forest degradation?

Scots pine is a dominant species in Poland, and it is species very sensitive to air pollution [8]. Exposure of needles to pollution may lead to the decline of trees.

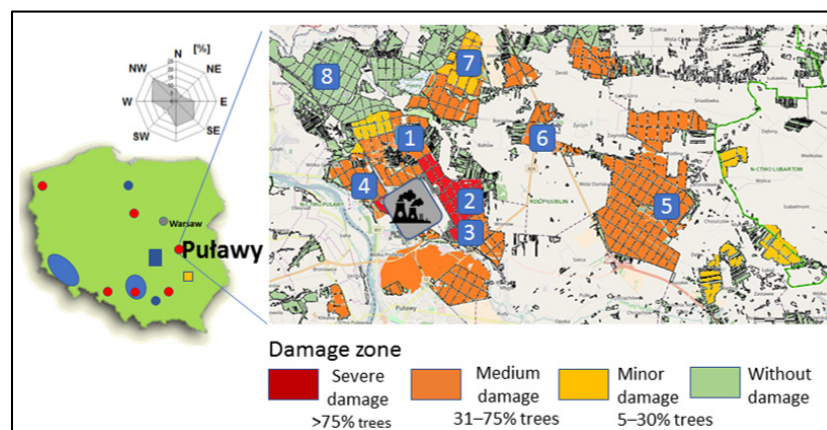
## 2. Study Site, Materials, and Methods

The nitrogen fertilizer factory in Puławy was one of the biggest polluters of the environment in Poland for over 25 years (1966–1990). This factory was built on the western edge of a large forest complex in a region with prevailing westerly winds. The factory was opened in the autumn of 1966 and the first damage were observed in the early spring of 1967 [7]. In the next three years, on the eastern side of the plant, in an area of 500 hectares, the forests were completely degraded and there formed a “biological death zone”. Since 1970, the damaged area has expanded outwards. Currently, forests with high destruction (>75% of trees) cover 1200 ha, and forests with moderate (31–75% trees) and low (5–30% trees) damage, are approximately 500 and 7000 ha, respectively.

Trees that have survived to this day were exposed to long-term stress, which reduced their vitality and affected their growth. One of the best methods to determine the effect of pollution on tree growth is by dendrochronological analysis [7–10]. It is a retrospective analysis of the variation in tree-ring widths, which allows for the estimation of the direct and indirect effects of pollution. Decreasing vitality and growth reduction are noted in the tree-ring width (TRW), therefore, they can be used as an indicator for forest health in polluted regions. This method has been used in our research.

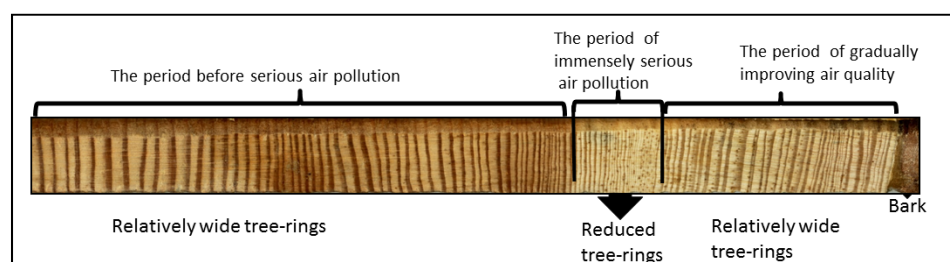
For this study, eight Scots pine sites were selected: seven plots were located in different damage zones in addition to a reference plot in the stand without damage (Figure 1). All the investigated stands represented a fresh mixed coniferous forest habitat and were about 100–120 years old. At each study site, 20 samples were taken with the Pressler's increment borer at breast height, one core per tree. In total, we collected cores from 160 Scots pines growing at different distances from the factory and in different geographical directions. The TRW analyses were carried using standard dendrochronological techniques [9]. The measurements of the annual TRW were made with the CooRecorder software [11], visual and statistical cross-dating TRW, and quality checking with CDendro

and COFECHA software [11,12], and chronologies construction and basic statistics using the ARSTAN program [13]. The determination of the period and degree of reductions in tree-ring widths was based on the Schweingruber method [10], in which the reduction rate  $R$ , expressed as a percentage, is calculated from the ratio of the sum of the reduced widths of increments to the sum of the tree-rings widths from the period preceding these reduction. The reduction values were divided into three ranges: low  $30\%R < 50\%$ , high  $50\% < R < 70\%$ , very high  $> 70\%$ .



**Figure 1.** The location of study plots. In addition, also marked on the map are the locations of Polish industrial plants emitting toxic pollution causing damage to forests in Poland (red circles—nitrogen plants, blue symbols—other plants or industrial region).

Climate–tree growth relationships were investigated by calculating bootstrapped multivariate response functions between growth and climate variables. Analyses were made for the period spanning from June in the year preceding ring formation to September in the year of the current increment (16 months in total) using DendroClim2002 software [14]. Climate data came from the meteorological station in Puławy. Analyses were carried out for three periods: 1936–1966 (period of 30 years before the start of the factory); 1967–1995 (the period of 30 years of extremely high air pollution); 1996–2015 (since 1995 there has been a decrease in emissions of ammonia and gradually decreasing air pollution (Figure 2)).



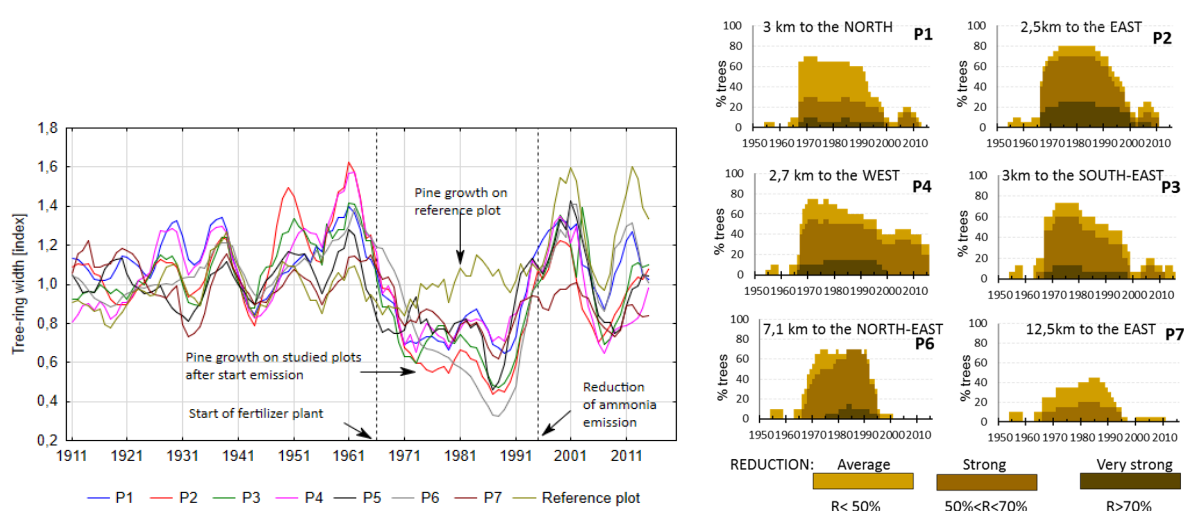
**Figure 2.** Illustration of a zone with reduced radial growth (sample taken from a pine growing on the 1st plot).

### 3. Results and Discussion

Emissions of pollution from the factory in Puławy caused long-lasting, strong growth reduction of pines living in the region, which is a sign of a long-term chronic decline in vitality (Figure 3). Growth reductions appeared in the majority of the examined trees and they were spatially and temporally varied. We found a significant decline in pine vitality on all research plots. The fastest and strongest response to pollution and greatest growth reductions (decline in tree vitality) occurred in stands growing nearest to factory (the zone up to 3 km) and was not directly connected with prevailing wind directions. The growth

reductions were long-term, lasting over 30 years (Figures 2 and 3). In the stands growing a little further away (3–10 km), growth reduction occurred a little later (in the early 1970s) and lasted about 20 years. In the stands growing further away (over 10 km), the decline in growth lasted for an even shorter time and was weaker. The duration and level of growth reduction in stands growing further from the plant (>3 km) depended on the wind direction.

In forests growing in the zone up to 3 km from an emitter, almost all trees (80%) had long-term, strong, and very strong growth reductions (above 50%). In forests growing further away from the emitter, generally, the degree of damage to trees decreased with increasing distance from the emitter. However, trees growing in sites situated in prevailing wind directions suffered more than trees growing at a similar distance from the factory but in a northerly direction. The distribution of reductions in research plots indicates a clear relationship between the amount of reductions and distance from the emitter and the prevailing wind direction (Figure 3, right).



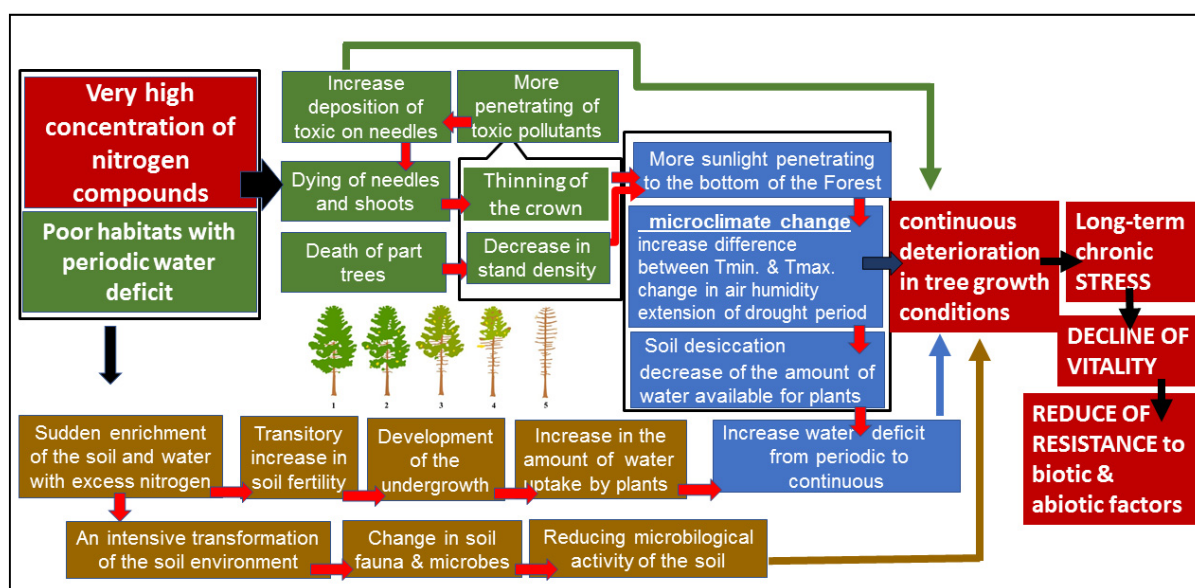
**Figure 3.** Left: Tree-ring chronologies of Scots pine growing in the vicinity of the factory; right: graph showing growth reductions at Scots pines from plots.

In comparison to other forest complexes around nitrogen factories in Poland, the damage to trees in Puławy was much greater. A lower degree of damage is characteristic of pines growing in Silesia—the most polluted region in Poland where the impact of air pollution was longer, and the amount of pollution was larger. We decided to try to find an answer to what other factors could cause large growth reductions and their spatiotemporal distribution. We think that these factors could have been anemometric conditions in the region, relatively low chimneys emitting nitrogen compounds, and poor habitats. Emissions from low chimneys in conditions of low wind speed and lull caused large deposition of pollution around the plant and very high concentrations of different pollution near the factory. As the emission of toxic nitrogen compounds occurred from relatively low chimneys, excessive fallout and a high concentration of these compounds took place near the factory.

We think the toxic nitrogen compounds, especially ammonia, were the main factors of damage to forests growing within a radius of 3 km. The impact of sulfur dioxide on forest degradation probably was greater in stands located further from an emitter. This was confirmed by the correlation between chronologies and the amount of ammonia and sulfur dioxide emitted pollution. In the case of the sulfur dioxide, the emission occurred from relatively high emitter (chimney 160 m tall). This resulted in lower SO<sub>2</sub> levels in the vicinity of the factory itself, but it transported the pollutants over distances as much as 100–120 km.

Our concept of the direct and indirect impact of air pollution on the growth of the studied pine stand is shown in Figure 4. Generally, very high concentrations of nitrogen

compounds caused the death of part trees, which resulted in a decrease in stand density. The death of pine needles and shoots resulted in the thinning of the crown. These resulted, on the one hand, in the greater penetration of toxic pollutants and increased deposition of toxins on needles. This process was ongoing. On the other hand, a decrease in stand density and the thinning of the crown resulted in more sunlight penetrating to the bottom of the forest and microclimate change. Very high concentrations of nitrogen compounds resulted in the sudden enrichment of the soil with excess nitrogen, which in consequence resulted in an increase in water deficit.



**Figure 4.** Concept of the direct and indirect impact of air pollution on the growth of the studied Scots pine stands.

Changes in the stand, microclimate, and soil environment resulted in a continuous deterioration of tree growth conditions, long-term chronic stress, decline of vitality, and a reduction in the resistance to biotic and abiotic factors. We decided to check the impact of the climate and pests. The impact of pest could not be investigated because since the 1970s, threats to research stands from pests were relatively low.

What about the climate? Are damaged trees really more sensitive to climatic conditions? We found the main determinants of the growth of examined pines were the thermal conditions in winter and summer precipitation. A frosty winter and summer drought have a strong negative impact on growth. The effect of climate conditions on pine growth was similar in direction on all plots, but since the late 1960s it was different in the strength of relationships. Pines exposed to toxic pollutions were more sensitive to cold winters and prolonged summer drought. A reduction in industrial emissions and an improvement in environmental conditions in the last decade of the twentieth century resulted in the formation of wider rings. However, these trees are still weakened, have reduced resistance to climatic stress, and are more sensitive to adverse weather conditions, especially drought.

#### 4. Conclusions

The level and spatial extent of forest ecosystem degradation in the Puławy region was caused by both the amount and type of pollutions, and local factors, especially anemometric and habitat conditions and height of chimneys. A high frequency of lull combined with low chimneys emitting toxic pollutants multiplied the negative effects of pollutant emissions. The radical reduction in pollutant emissions improved the environmental conditions, and the trees began to grow, however, long-term strong anthropopressure caused a long-lasting reduction in the resistance of trees to abiotic factors. Our research



indicates that in areas where there has been a high concentration of pollution for a long time, the adverse impact of pollution on forests persists for a very long time, even 20 years after a radical reduction in emissions. These forests have reduced resistance to abiotic stress related to climate change, especially drought. Therefore, a greater impact of climate change, especially extreme events, on the process of dying trees growing in areas with strong anthropopressure can be expected.

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