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# Impact of air pollution on Scots pine stands growing in Poland on the basis of dendrochronological analysis

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**Abstract:** Air pollution and climate change are two key factors comprising the global change threat to forest health and sustainability. 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 $SO_2$, NOx, & $NH_3$), continuing over more than 40 years, has caused serious damage to forest stands. One of the ways describing the effect of industrial emissions on forests is the tree-rings (dendrochronological) analysis, it has been used in our research. We present a brief description of the studies on impact of air pollution on growth of forest growing in the most polluted areas of Poland. The main aim is to evaluate of Scots pine stand degradation caused by the pollutants emitted from the 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. Scott 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 1990s decreasing trend stopped and the wider tree-rings could be observed. This situation was related with a radical reduction of ammonia emissions and an improvement of environmental conditions. However, 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.

**Keywords:** Scots pine; tree-ring; air pollution; growth reduction; climate change; Poland

## 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 metabolism and physiological process of trees [3]. Hight concentrations of air pollution (mainly $SO^2$ and $NO^2$) can damages trees directly through the foliage, and indirectly, through the soil [1, 3]. Typical symptom are disorders of photosynthesis, stomatal conductance, shift in carbon allocation, water use efficiency and leaves lost. Global warming results in 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 pathogen. Multiple interaction of those factors induce reduction of trees vigour and growth, and in the end, the death of tree, decline of certain tree species and change of ecosystem. A mechanism of the influence of sulphur dioxide & nitrogen oxide on trees is reported in many studies [e.g. 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 is 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 world caused significant increase of 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 Europe' 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 environment (Figure 1). Most forest areas exposed to pollution are characterized by gradual general deterioration of the tree's vitality, sometimes ending in death of trees. The exception was the forests in Puławy, where air pollution induced rapid death of trees on many hectares. This problem is the main topic of our work. In our study we decided to evaluate of Scots pine stands degradation caused by the pollutants emitted from the nitrogen fertilizer plant in Puławy. The forest degradation caused by this factory were described in many publication [e.g. 6, 7]. However, the ecological interaction between air pollution and forest resistance to abiotic stress related to climate change, especially drought, 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 the air pollution and climate change on Scots pine growing in the vicinity 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 dominant species in Poland, and it is species very sensitive to air pollution [8]. Exposure of needles on direct contact with pollution may lead to the decline of trees

## 2. Study site, material & methods

The nitrogen fertilizer factory in Puławy was the one of 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 region with prevailing westerly winds. The factory was started in the autumn of 1966 and the first damage were observed in early spring in 1967 [7]. In the next three years, on the eastern side of the plant, on an area of 500 hectares, the forests were completely degraded and there formed a "biological death zone". Since 1970 the damaged area expanded outwards. Currently, forests with high destruction (> 75% of trees) cover 1,200 ha, and forests with moderate (31-75% trees) and less (5-30% trees) damages, approximately 500 ha and 7,000 ha, respectively.

Trees that have survived to this day were exposed to a long-term stress, which reduced their vitality and affected their growth. The one of the best methods to determine the effect of pollution on tree growth is the dendrochronological analysis [7-10]. It is a retrospective analysis of the variation of 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 use 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, located in different damage zones and reference plot in the stand without damage (Figure 1). The all investigated stands represented a fresh mixed coniferous forest habitat and were about 100-120 years old. In each study sites, 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 in 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 crossdating TRW and quality checking with CDendro and COFECHA software [11, 12,], chronologies construction and basic statistic using the ARSTAN program [13]. The reductions of tree-ring widths (for each measured TRW series) were made according [10] into three ranges: low 30%R<50%, high 50%<R<70%, very high >70%.

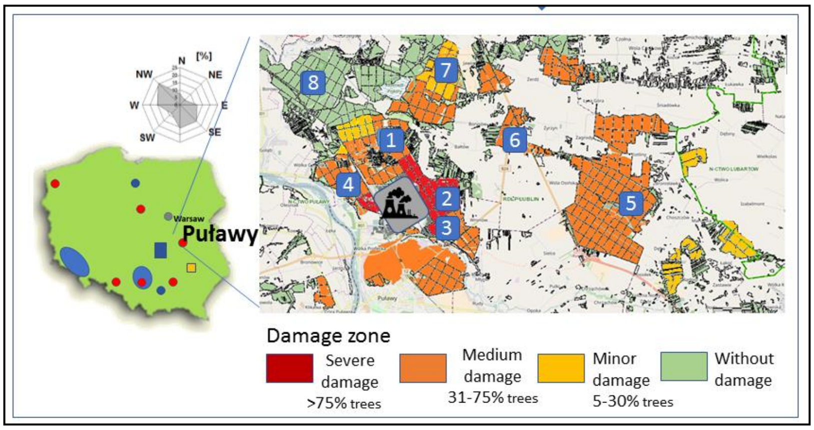


**Figure 1.** The location of study plots. In addition, marked on the map locations of Polish industrial plants emitting toxic pollution causing damage of forests in Poland (red circles – nitrogen plants, blue sign- other plants or the industrial region).

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 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 start of factory); 1967-1995 (the period of 30 years of extremely high air pollution) and 1996-2015 (since 1995 decrease emission of ammonia, gradually decrease air pollutions (Figure 2).

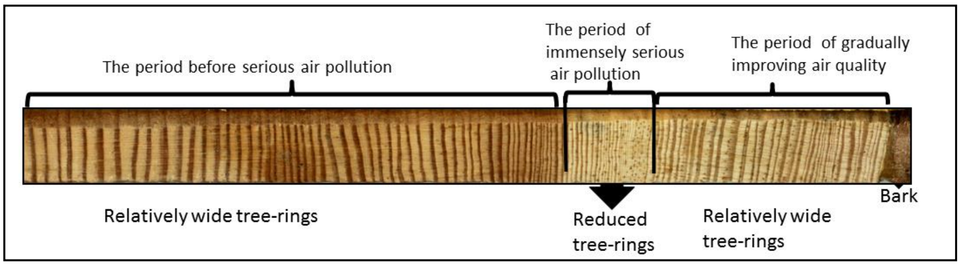


**Figure 2.** Illustration of a zone with reduced radial growth (sample taken from a pine growing on the 1st plots).

## 3. Results & 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 of vitality (Figure 3). Growth reductions appeared in the majority of the examined trees and they were spatial and temporal varied. We found a significant decline of pine vitality on all research plots. The fastest and the strongest response to pollution and greatest growth reductions (decline of tree vitality) occurred in zone to 3km and was not directly connected with prevailing wind directions. The growth reductions were long-term, over 30 years long (Figure 2, 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 (over 10km) decline of growth lasted even shorter and was weaker. The duration and level of growth reduction in stands growing further from the plant (>3km) depended on the wind direction.

In forests growing in the zone up to 3 km from emitter almost all trees (80%) had long-term, strong and very strong growth reductions (above 50%). Pines growing in the northern part of this zone had lower reduction/less damage. 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 direction suffered more than trees growing at similar distance from the factory but in northerly direction. The distribution of reductions in research plots indicates a clear relationship between the amount of reductions and distance from emitter and the prevailing wind direction (Figure 3 right).

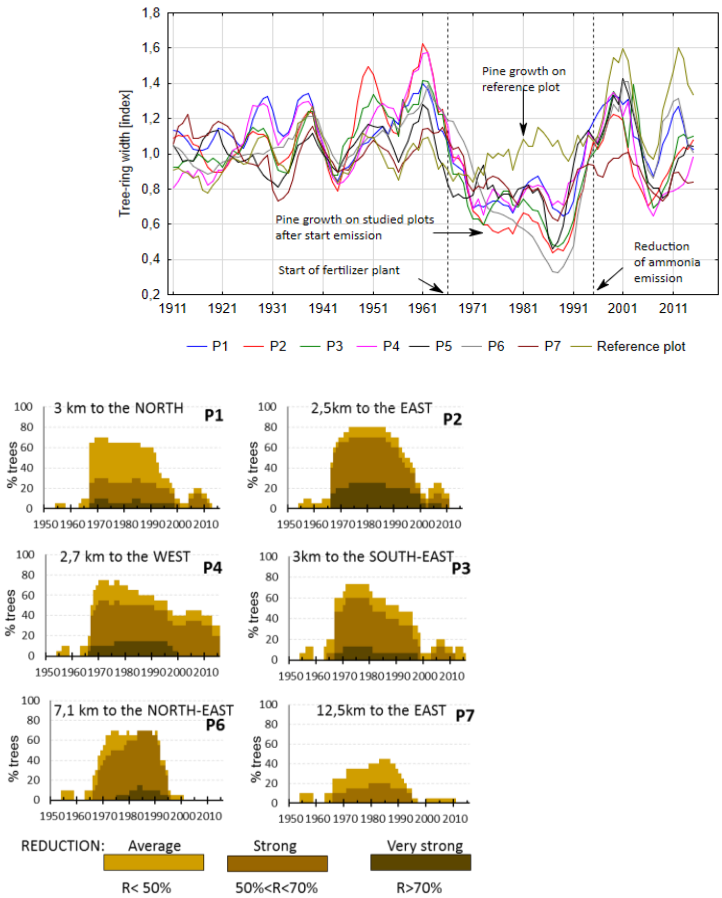


**Figure 3.** Left: Tree-ring chronologies of Scots pine growing vicinity of the factory; Right: Graph showing growth reductions at Scots pines from plots.

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 for pines growing in Silesia - the most polluted region in Poland where the impact of air pollution was longer, and amount of pollution was the larger. We decided to try to find an answer what other factors could cause so 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 concentration of different pollution near the factory. Because the emission of toxic nitrogen compounds occurred from relatively low chimneys, excessive fallout and high concentration of these compounds took place near the factory. Sulphur dioxide was emitted from a chimney 160 tall, which resulted in lower levels of this pollution in the vicinity of the factory.

We think the toxic nitrogen compounds, especially ammonia, were main factors of damage of forests growing within a radius of 3km. The impact of sulphur dioxide on forest degradation probably was greater in stand located further from emitter. this was confirmed by the correlation between chronologies and the amount of ammonia and sulfur dioxide emitted pollution.

Our concept of the direct and indirect impact of air pollution on the growth of the studied pine stand is shown on Figure 4. Generally, very high concentration on nitrogen compounds caused death of part trees which resulted in decrease in stand density. Dying of pine needles and shoots resulted in thinning of the crown. These resulted on the one hand in bigger penetration of toxic pollutants and increase deposition of toxic on needles. This process was ongoing. On the other hand, decrease in stand density and thinning of the crown resulted in more sunlight penetrating to the bottom of the forest and microclimate change. Very high concentration of nitrogen compounds resulted in sudden enrichment of the soil with excess nitrogen, which in consequence resulted in an increase in water deficit.

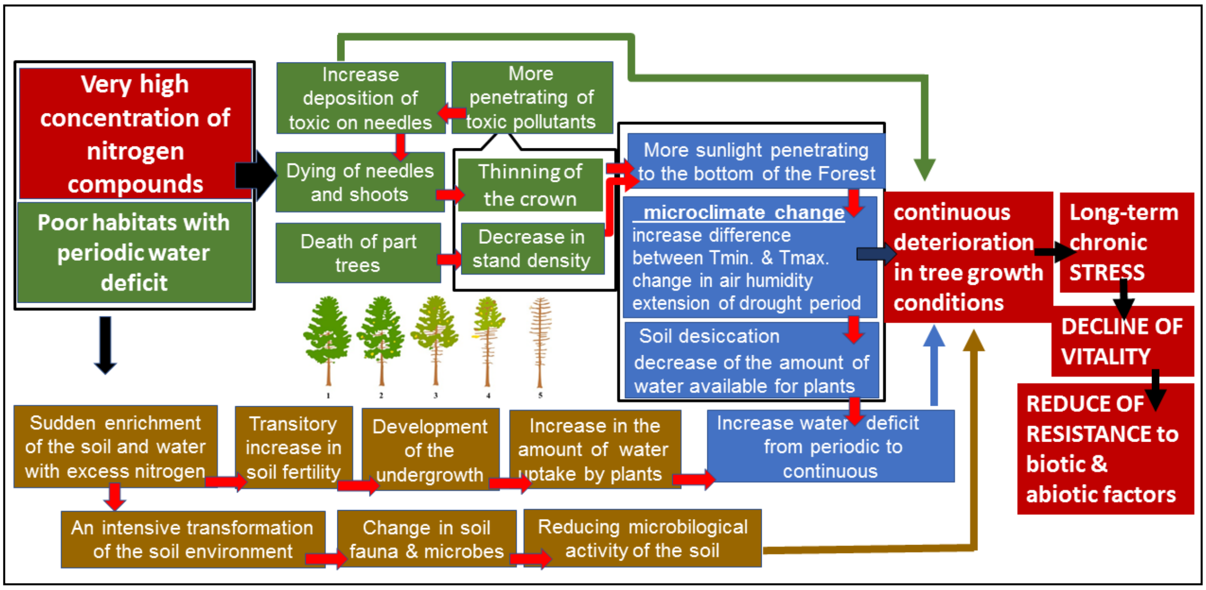


**Figure 4.** Concept of the direct and indirect impact of air pollution on the growth of the studied Scots pine stands,.

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

What about climate? Are damaged trees really more sensitive to climatic conditions? We found main determinants of the growth of examined pines were the thermal conditions in winter and summer precipitation. Frosty winter and summer drought have the strong negative impact on growth. The effect of climate conditions on pine growth was similar in direction on all plots, but since late 1960s it was different in strength of relationships. Pines exposed to toxic pollutions were more sensitive to cold winters and prolonged summer drought. Reduction of industrial emissions and improvement of 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, are more sensitive to adverse weather conditions, especially drought.

## 4. Conclusion

The level and spatial extent of forest ecosystem degradation in Puławy region was caused by both the amount and type of pollutions, and local factors, especially anemometric and habitat conditions and high of chimneys. A high frequency of lull combined with low chimneys emitting toxic pollutants multiplied the negative effects of pollutant emissions. The radical reduction of 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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