The Recovery of Damaged Pine Forests in an Area Formerly Polluted by Nitrogen

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An area in Lithuania containing coniferous stands of Scots pine and Norway spruce that were dead or damaged due to nitrogen pollution by a nitrogen fertilizer plant (JV Achema) was found to have expanded between 1974 and 1989 to a distance of 20 to 25 km northeast of the plant in the direction of prevailing winds. Over the last 10 years, when nitrogen pollution by the plant had decreased, a clear process of recovery of the damaged ecosystems could be observed. The following features of this process as it occurred in damaged Scots pine stands are discussed: (1) refoliation (or decreased defoliation) of damaged trees, where a clear positive trend could be observed; (2) changes in the species composition and in the covering by ground vegetation, where small changes and indication of less-nitrophilous species coverage could be detected; and (3) chemical and acidity changes in Luvisols and Arenosols, where a significant decrease could be seen especially concerning nitrate concentrations.

KEY WORDS: reduced nitrogen pollution, Scots pine stands, refoliation, ground vegetation, Luvisols, Arenosols, acidity, nitrate, chemical composition

DOMAINS: plant science, soil systems, ecosystems and communities, environmental sciences, environmental monitoring

INTRODUCTION

At the beginning of the 1970s, large plants for producing nitrogen fertilizers for agricultural development were built in the European part of the former Soviet Union, specifically in Russia (Novgorod and Dzerzhinsk), the Ukraine (Rovno and Severodonetsk), Lithuania (Jonava), and Belorussia (Grodno). The impact that pollutants from these nitrogen fertilizer plants had on forests of highly developed West European countries such as Sweden has been rather insignificant (partly due to its being episodic)[1]. In the vicinity of the huge nitrogen fertilizer plants in the former Soviet Union, however, the decline or mortality of forests at distances of up to 20 to 25 km in the direction of prevailing winds could be observed[2]. At lesser distances, changes in soil chemical properties and subsequent soil acidification were ascertained[2,3].

The present article summarizes the condition of forest ecosystems in the vicinity of a nitrogen fertilizer plant (JV Achema) in Lithuania that was put into operation in 1965. The plant was surrounded by forests, and society viewed their resulting decline in quite negative terms. This led to a variety of studies on the degradation of the forest ecosystem[2,3,4,5,6,7,8]. An obvious recovery of the damaged forest ecosystems has been observed during the reduction in air pollution that has occurred during the past 10 years. The following features of this process in the Scots pine stands will be discussed: (1) recovery of vitality by the trees; (2) changes in plant species composition and in ground vegetation; and (3) changes in forest litter and in soil-chemical parameters.

EXPERIMENTAL METHODS AND PROCEDURES

Investigations were conducted at different distances of up to 22 km to the northeast of the JV Achema plant, in the direction of prevailing winds. This plant is situated in central Lithuania (55°05’ north, 24°20’ east). In the forests surrounding it there is a prevalence of Scots pine (Pinus sylvestris L.), 39%; birch (Betula pendula Roth.), 22%; and Norway spruce (Picea abies [L.] Karst.), 20%. These stands have an average age of 50 years[9].
The forest coverage is 39%, and the sandy forest soils are classified mainly as Arenosols or Luvisols.

During the period from 1974 to 1989, when forests (mostly Scots pine and Norway spruce stands) were declining[10] in an area ranging from 20 to 25 km in the direction of prevailing winds from the JV Achema plant, annual emissions from the plant amounted to some 15,000 to 40,000 tonnes (Fig. 1). The greatest part of these pollutants consisted of dust from mineral fertilizers (38%) and of CO (27%), as well as SO₂ (13%), NOₓ (10%), and NH₃ (10%) gases[11]. From 1990 to 1992, the process of forest decline halted when the annual emission amounts decreased to a level of 11,000 to 12,000 tonnes. Later, in the period from 1993 to 2000, the amount of pollutants decreased still further to only about 5,000 to 7,000 tonnes annually. Closing of the most environmentally polluting shops and the use of natural gas instead of oil has led to a changed composition of pollutants such that CO (67%), NOₓ (9 to11%), and NH₃ (7 to 11%) gases prevail.

From 1997 to 2000, air pollution by NO₂ and SO₂ gases was monitored by use of passive diffusion samplers[12]. These were placed in 10 to 15 study locations 2 m above the ground two to three times during the vegetation period, for periods of 30 to 40 days each. The diffusion samplers were prepared by and analysed at the Institute of Physics in Vilnius.

The condition of the 50- to 100-year-old Scots pine stands was studied from 1995 to 2000 at seven permanent observation plots (POPs) established at distances of 10 to 22 km from the plant. In each POP assessment were made of the defoliation and discoloration of 170 to 280 examples of predominant, dominant, and codominant trees (rated according to the Kraft system)[13].

Ground-vegetation studies of 60- to 80-year-old Vaccinio-myrtillusum Scots pine stands in 16 POPs at distances of 10 to 12 km and 20 to 22 km from the plant were carried out during June of 1988 and 1999. In each POP, the floristic composition and the covering of individual plant species in eight vegetation-sample squares was assessed.

Assessment of phytocenotic changes was based on the mean weighted value of a corresponding ecological factor (Eᵢ = light, Eₙ = amount of nitrogen in the soil, and Eₛ = soil acidity):

\[ Eᵢ = \sum \frac{Nᵢ \cdot pᵢ}{P} \]

where Eᵢ is the ecological factor, Nᵢ the indicator value of the ecological factor for the species[14], pᵢ is covering by the ith species, and P the overall covering by all the layer species. The data obtained were compared with ground vegetation data for Scots pine stands of corresponding age in nonindustrial areas of Lithuania[15].

In 1979, forest soils were studied in the cutting area of dead Scots pine stands (Luvisols, 0.2 km from JV Achema) and in stands of pine that survived (Arenosols, located at distances of 2 and 22 km from the plant). According to data from earlier years, chemical parameters of the Luvisols 0.2 km from the plant and of Arenosols 2 km from the plant were subjected to changes due to air pollution, whereas Arenosols that were located 22 km from the plant could be regarded as relatively unpolluted[2]. The samples of forest litter and of mineral horizons (from layers 0–5, 5–10, 10–20, 25–35, and 45–55 cm deep) were collected in September in either five or ten replicates. The forest litter mass was determined in the field. The following measures for the forest soil samples were analysed: pH in a 1 M KCl suspension, NO₂-N by ionometer; NH₄-N (in a 1% K₂SO₄ suspension), mobile phosphorus (P₂O₅) (in a 0.2 M HCl suspension), and mobile S (in a 1 M KCl suspension). Except pH all were analysed by colorimetric methods. Al³⁺ was analysed in a 1 M KCl suspension via the titration method[16].

The statistical significance of the differences obtained was assessed by use of Student’s t-test.

RESULTS AND DISCUSSION

Reduction of Air Pollution

During the vegetation periods of 1997 to 2000, the mean NO₂ concentrations up to a point 22 km northeast of JV Achema varied from 1.94 to 11.48 μg m⁻³, and those of SO₂ from 2.49 to 8.45 μg m⁻³ (Table 1). The maximal concentrations of NO₂ in the air was 17.16 μg m⁻³ and of SO₂ 16.28 μg m⁻³. The annual levels of emissions from JV Achema during the period from 1993 to 1996 failed to exceed the levels found there during 1997 to 2000 (Fig. 1). It can thus be stated that since 1993 the concentrations of pollutants studied in the zone in which tree stands were dam-

**FIGURE 1.** Changes in emissions from the JV Achema plant during the period from 1981 to 2000.
aged did not exceed the critical annual mean levels found for forest trees in general[17].

**Condition of Scots Pine Stands**

In Fig. 2, three stages in the changes in condition of the 50- to 100-year-old Scots pine stands near JV Achema can be distinguished: (1) a worsening until 1992; (2) a stabilization from 1992 to 1995; and (3) an improvement from 1995 to 2000. These stages can be related to air pollution as follows.

- Until 1998, when JV Achema was emitting more than 20,000 tonnes of pollutants annually, tree defoliation in the Scots pine stands nearby increased. When annual emissions fell markedly (to 11,000 to 12,000 tonnes), defoliation continued to increase for another 3 to 4 years. This tendency was shown not by any clear increase in the percentage of mean defoliation (there were no significant differences), but by a significant decrease in the dispersion of the index.
- During a period of 3 to 4 years (from 1992 to 1995) when the air pollution was lower than it had been, defoliation remained stable.
- After 6 to 7 years of reduced air pollution, refoliation (or a decrease in defoliation) began.

Figure 2 also shows changes since 1989 in the condition of Scots pine stands of analogous age in nonindustrial areas of Lithuania. The mean defoliation of the stands near JV Achema during the period from 1989 to 1999 was higher by some 4 to 12% than in nonindustrial areas. This difference fell markedly (to 2.7%) in the year 2000. It can also be seen that since 1996 an improvement in the condition of the Scots pine stands not only near JV Achema but also in Lithuania as a whole has occurred. It thus appears that the present condition of stands near JV Achema is influenced not only by local air pollution but also by background pollution and by meteorological factors.

**Changes in Ground Vegetation**

The deposition of nitrogen compounds can have a double effect on ground vegetation, both that of nutrient enrichment and of acidification. Ground vegetation (grasses, bryophytes, lichens, etc.) is often more sensitive to such effects than are forest trees[18]. In stands in Germany and in the Czech Republic that have been severely damaged by anthropogenic pollution, the observed invasion of nitrophilous plants and grain herbs has been attributed not only to the eutrophication of the environment caused by increased nitrogen deposition[19,20], but also to a reduction in competition due to thinning of the crowns (defoliation), and to weakening of the trees[21]. In the Baltic states anthropogenic phytocenosis is characterized by three interrelated synanthropic processes: ruderalization, graminification, and frutification[22]. Floristic changes most frequently take place due to an abundance of plant species that are not typical of a forest environment. Ellenberg’s scale is the indicator most widely employed in Western Europe for describing ecological changes in forest ecosystems that are due to a heightened anthropogenic impact[14,23,24].

According to data obtained in 1999 at a distance of 20 to 22 km from JV Achema, the species composition of the vegetation and the covering of dominant species were then close to those found in such communities in nonindustrial sections of the country[15]. At a reasonably short distance from the plant (10 to 12 km from it) a reduction in the covering of the grass-brush species (Vaccinium myrtillus, V. vitis-idaea) typical for Vaccinio-myrtillosum Scots pine stands, and an increase in the covering of

| TABLE 1 Mean Monthly NO₂ and SO₂ Concentrations (µg m⁻³) in Damaged Forests Near the JV Achema Plant |
|---------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Distance from the Plant | NO₂ | | | | SO₂ | | | |
| Northeast from the Plant | 1997 | 1998 | 1999 | 2000 | 1997 | 1998 | 1999 | 2000 |
| 0–6 km | 11.48 | 5.50 | 7.83 | 2.71 | 8.45 | 2.62 | 3.48 | 6.39 |
| | (6.90–17.16) | (0.83–9.74) | (1.33–17.52) | (1.40–4.90) | (3.53–16.28) | (0.00–5.40) | (1.75–6.36) | (0.00–17.20) |
| 8–22 km | 9.38 | 2.68 | 5.46 | 1.94 | 5.59 | 2.49 | 4.54 | 3.86 |
| | (7.10–13.04) | (0.83–3.92) | (3.29–7.38) | (1.10–3.20) | (2.09–9.14) | (0.68–2.74) | (1.75–12.74) | (0.00–8.05) |
| Critical annual mean levels for forest trees[17] | 30 | | | | 20 | | |

* Minimum and maximum concentrations shown in parentheses.
nitrophilous plants (*Rubus idaeus*) could be observed (Table 2). The abundance of mosses characteristic for *Vaccinium-myrtillus* Scots pine stands also increased as the distance from the plant increased.

The species composition of the vegetation communities and the weighted acid tolerance values (\(E_a\)) showed that under conditions of reduced air pollution, forest ecosystems closer to the plant (10 to 12 km) remained anthropogenically degraded (Fig. 3). On the other hand, a distinct process of ground vegetation recovery could be observed in terms of an abundance of species typical to *Vaccinium-myrtillus* Scots pine stands and a reduction in nitrophilous vegetation (Table 2), as well as changes in environ-

**TABLE 2**

Mean Coverage by the Main Species of *Vaccinium-myrtillus* of the Forest Type in Scots Pine Stands Near the JV Achema Plant

| Species                          | 10–12 km  | 20–22 km |
|---------------------------------|-----------|----------|
|                                 | 1988      | 1999     | 1988     | 1999     |
| *Chamerion angustifolium* (L.) Holub. | 0.3 ± 0.1*| 0.0      | 0.0      | 0.0      |
| *Festuca ovina* L.             | 4.7 ± 2.5 | 7.6 ± 1.9| 1.2 ± 0.7| 5.5 ± 2.8|
| *Melampyrum pratense* L.       | 1.8 ± 0.5 | 3.0 ± 0.7| 0.7 ± 0.3| 1.2 ± 0.3|
| *Rubus idaeus* L.              | 24.7 ± 4.0*| 2.9 ± 1.5*| 4.1 ± 1.7*| 0.5 ± 0.2*|
| *Vaccinium myrtillus* L.       | 5.6 ± 2.2 | 8.8 ± 3.1| 7.8 ± 1.7*| 23.1 ± 5.0*|
| *V. vitis-idaea* L.            | 1.1 ± 0.4 | 1.5 ± 0.7 | 1.3 ± 0.3 | 3.0 ± 0.9 |
| *Dicranum polysetum* Sw.       | 2.7 ± 0.7 | 5.6 ± 1.3 | 9.1 ± 2.4 | 12.2 ± 2.9|
| *Hylocomium splendens* (Hedw.) Schimp. | 1.6 ± 1.0*| 12.2 ± 3.6*| 11.6 ± 2.6| 14.4 ± 3.0|
| *Pleurozium schreberi* (Brid.) Mitt. | 25.9 ± 3.8*| 42.8 ± 5.1*| 21.4 ± 3.7*| 38.6 ± 6.1*|
| *Ptilium crista-castrensis* (Hedw.) De Not. | 2.0 ± 1.1*| 13.7 ± 4.1*| 1.4 ± 1.0 | 2.3 ± 1.3 |

Number of sample squares (\(n\)) 36 40 46 32

* Statistically significant (\(p = 0.05\)) changes between 1988 and 1999.
ment conditions, as shown by weighted Ellenberg’s light \( (E_L) \) and nitrogen-demand \( (E_N) \) indicator values (Fig. 3).

**Chemical Changes in Forest Soils**

Under conditions of reduced air pollution, changes in the chemical parameters of the mineral horizons for forest soils near JV Achema were found to be influenced by the migration of pollutants from the forest litter, as indicated by studies in clear-cut areas of dead stands in which there was an ongoing mineralization of the forest litter and in Scots pine stands in which changes in the mass of the forest litter were very slight.

In the 20-year period since 1979 the forest litter mass of Luvisols in clear-cut areas of dead Scots pine stands was found to have decreased by a factor of almost 8 (from 67.9 to 8.7 tonnes ha\(^{-1}\)). Comparison with earlier years showed that in 1996 the accumulation of \( \text{NH}_4 \)-N in forest litter had decreased on average by a factor of 56 (as compared with 1989) and that the accumulation of mobile S and \( \text{NO}_3 \)-N had decreased by a factor of more than 20. In contrast, the mean changes in the amounts of these chemical compounds in the upper 60 cm of mineral soil were not statistically significant.

Due to the leaching of chemical compounds and to other factors (such as the presence of unexpected pollutants or of unusual meteorological conditions) changes in the acidity of the forest litter, although frequently of considerable weight, are often controversial in terms of how they should be interpreted. As can be seen in Table 3, from 1985 to 1988, when sulphur and nitrogen depositions 0.2 km from the plant \((150 \text{ kg S ha}^{-1} \text{ and } 120 \text{ kg N ha}^{-1} \text{ annually})\) exceeded the background level in Lithuania by a factor of at least 9 to 12\(^{[5]}\), the mineral horizons of the Luvisols had acidified markedly. During a brief 3-year period, the exchange in acidity in the upper 35 cm of the deep mineral soil layer had increased on average by 0.34 to 0.67 pH\(_{EC}\)
When air pollution decreased, the reaction of forest litter became more alkaline, although the acidity of the mineral horizons remained unchanged, only beginning to decrease after 1998 (Fig. 4).

In terms of the data presented, it appears that changes in forest soil acidity proceed rather slowly during a reduction in air pollution. One can thus suggest that forest soil should be monitored at least every 10 years[13]. During a similar 10- to 12-year period (1988 to 1999) in almost all cases at locations near to JV Achema, Luvisols were found to become 0.23 to 0.70 pHKCl more alkaline (Table 3). This process is now even more intensive. During a period of only one year (1999 to 2000), the acidity of the upper 55-cm layer of Luvisols was found to decrease by 0.28 to 0.36 pHKCl.

In comparing Figs. 3 and 4, one can note that when air pollution was reduced the recovery reaction (the decrease in acidity) of the studied Luvisols was more gradual and started 3 to 4 years later than the reflation of the Scots pine stands.

The changes in the chemical parameters of the Arenosols in the Scots pine stands that survived when air pollution was reduced were significant as well (Fig. 5). Although their reaction did not change, from between 1987 and 1989 to 1999, over 10 to 12 years, mobile S leached (amounts were less than the analysis precision limit) from forest litter of polluted Arenosols; in addition, quantities of NO3-N decreased on average 5.5 times, P2O5 and Al3+ about 2 times, and NH4-N 1.7 times.

In the forest litter of the unpolluted Arenosols (controls), there was a marked decrease in the amounts of mobile S by a

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### TABLE 3
Mean pHKCl Changes in Luvisols at a 0.2-km Distance from the JV Achema Plant

| Depth  | Years     | 0 (Forest Litter) | 0–5 cm | 5–10 cm | 10–20 cm | 25–35 cm | 45–55 cm |
|--------|-----------|-------------------|--------|---------|----------|----------|----------|
|        |           | O                 |        |         |          |          |          |
| 1985   |           | 4.26 ± 0.27       | 3.50 ± 0.16 | 3.64 ± 0.17 | 4.30 ± 0.14 | 4.19 ± 0.10 | 3.97 ± 0.07 |
| 1987   |           | 4.68 ± 0.37       | 3.27 ± 0.07 | 3.48 ± 0.09 | 3.79 ± 0.19 | 4.10 ± 0.11 | 4.19 ± 0.06 |
| 1988   |           | 4.14 ± 0.48       | 3.01 ± 0.25 | 3.30 ± 0.11 | 3.63 ± 0.12 | 3.85 ± 0.21 | 3.89 ± 0.10 |
| 1989   |           | 4.83 ± 0.31       | 3.38 ± 0.05 | 3.48 ± 0.08 | 3.85 ± 0.16 | 4.03 ± 0.09 | 4.04 ± 0.19 |
| 1992   |           | 5.04 ± 0.32       | 3.36 ± 0.03 | 3.38 ± 0.03 | 3.44 ± 0.33 | 4.08 ± 0.05 | 3.96 ± 0.09 |
| 1998   |           | 5.63 ± 0.27       | 3.47 ± 0.09 | 3.40 ± 0.04 | 3.55 ± 0.09 | 4.03 ± 0.19 | 4.05 ± 0.06 |
| 1999   |           | 4.84 ± 0.14       | 3.54 ± 0.11 | 3.60 ± 0.06 | 3.86 ± 0.06 | 4.13 ± 0.07 | 4.15 ± 0.09 |
| 2000   |           | 5.22 ± 0.40       | 3.82 ± 0.12 | 3.96 ± 0.10 | 4.19 ± 0.10 | 4.45 ± 0.08 | 4.46 ± 0.07 |

ΔpH1985-1988
-0.12
-0.49a
-0.34a
-0.67a
-0.34a
-0.08

ΔpH1988-1989
+0.70a
+0.53a
+0.30a
+0.23a
+0.28
+0.25a

ΔpH1999-2000
+0.38
+0.28a
+0.36a
+0.33a
+0.32a
+0.31a

*Note: Means ± s.e. (n = 10) are shown.

* Statistically significant (p = 0.05) changes.

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![Figure 4](image-url) Mean pHKCl changes in Luvisols at a distance of 0.2 km from the JV Achema plant during the period from 1985 to 2000.
factor of 16 on average, and of NO₃⁻-N by a factor of 2.8. This can be attributed to the reduction in background pollution both in Europe in general and in Lithuania[25].

Summarizing the data in Fig. 5, one can state that in 1999, when the air pollution had been reduced, the contamination of the forest litter of the Arenosols had diminished markedly as well. The amounts of mobile N forms, of P₂O₅, and of Al³⁺ became statistically similar to those of the controls, the amounts of mobile S in them being even less. However, the forest litter of polluted Arenosols was on the average 0.81 pHₑₒ₂₇ more acidic.

As Fig. 6 indicates, the amounts of NO₃⁻-N and mobile S underwent the greatest changes in the mineral horizons of the polluted Arenosols over a 10- to 12-year period. In the entire profile studied, the amounts of NO₃⁻-N decreased on average at a depth of 0 to 20 cm by as much as 20 to 34 times, and at a depth of 25 to 55 cm by 4 to 5 times. This should be interpreted as a decrease in the nitrification (formation of nitric acid) that was stimulated earlier by the high ammonia deposition that contributed to an increase in pH of the organic layer (Fig. 4). When mobile S in the upper 10-cm deep layer was leached out, its amount in deeper layers remained statistically unchanged. Changes in the amounts of NH₄-N and P₂O₅ were in almost all cases not statistically significant (at a p = 0.05 level). The chemical parameters (pHₑₒ₂₇ and the amount of Al³⁺) that reflected acidification of the mineral horizons of the polluted Arenosols did not change significantly over a period of 10 to 12 years (Fig. 7). This is similar to the results seen from European roof trials to exclude acid deposition[26].

In the control Arenosols, in contrast to the polluted ones, all the mineral soil chemical parameters that were studied it was only the amounts of NO₃⁻-N, that changed significantly over a 10- to 12-year period (Figs. 6 and 7). These parameters decreased in most cases by a factor of 2 to 4.

**CONCLUSIONS**

During the reduction in air pollution by NOₓ, NH₃, SO₂, and mineral dust over the last 10 years, an obvious recovery of the damaged forest ecosystems near the nitrogen fertilizer plant JV Achema was observed. After the air pollution had decreased, defoliation of the 50- to 100-year-old Scots pine stands was found to have stabilized or to still be in progress. Refoliation of the damaged Scots pine stands began some 6 to 7 years later. But even when air pollution had decreased, ground vegetation in the Scots pine stands remained anthropogenically degraded. Although a distinct recovery process could be observed, an enrichment of typical *Vaccinium-myrtillus* forest-type species and a reduction in the number of nitrophilous plants was evident. Changes in the
chemical parameters of the mineral horizons of polluted forest soils were influenced by pollutant migration from the forest litter. In clear-cut areas of dead stands in which there was ongoing mineralization of the forest litter and nitrification of deposited ammonia/ammonium a decrease in the acidity of Luvisols, as compared with the refoliation of the Scots pine stands, started 3 to 4 years later. In the Scots pine stands, contamination of the forest litter by mobile S, N, and P was significantly reduced, with no change in mass. And although the amounts of NO$_3$-N and of mobile S diminished in the mineral horizons of the polluted Arenosols, their acidity had not decreased.
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