ELSEVIER

Environmental Pollution 102, S1 (1998) 427–431

ENVIRONMENTAL POLLUTION

Soil acidification along an ammonium deposition gradient in a Corsican Pine stand in northern Belgium

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Received 27 March 1998; accepted 10 August 1998

Abstract

In a homogeneous Corsican pine (*Pinus nigra* ssp *laricio*) stand, situated in a region of intensive livestock breeding, effects of different NH_x doses on soil acidification were studied. Throughfall collectors were placed every 25 m on a transect of 1.4 km, oriented according to the dominant wind direction. The throughfall water was analysed on NH_4^+. A permanent monitoring plot is situated in the middle of the transect where quantity and chemical composition of different water fractions are monitored fortnightly. Along the transect, soil samples of the upper mineral soil (0–10 cm) were taken and analysed on pH–H_2O and pH–KCl. The measured deposition of NH_4^+–N was very high, especially in the forest edge at the prevailing wind direction (55 kg ha^{-1} $year^{-1}$), where up to twice as much NH_4^+–N was found as in the monitoring plot. A forest edge zone of 180 m with significantly higher NH_4^+ deposition could clearly be delineated. Serious indications were found that all NH_4^+ was nitrified but that this process was slowed down. The variation in NH_4^+ depositions was clearly reflected in the state of soil acidification: pH–H_2O and pH–KCl values varied between 3.1 (edge) and 3.8 (centre), and 2.4 (edge) and 2.8 (centre) respectively.

Keywords: Soil acidification; ammonium deposition; nitrification; Corsican pine stand

Introduction

Over 60% of the Flemish (Northern part of Belgium) forest area is located on poor sandy soils, which are mainly afforested with Scots pine (*Pinus sylvestris* L.) and Corsican pine (*Pinus nigra* ARNOLD ssp. Laricio MAIRE). Because of the low fertility of these aeolian soils, characterised by low buffering capacity and low levels of available nitrogen under natural conditions, the main agricultural practice in these regions is semi-industrial livestock breeding. This livestock production is the dominant source of atmospheric NH_x and its considerable rise during recent decades has caused a significant increase in NH_x-depositions (Dams et al., 1996).

The deposition of NH_x in pine forests is far higher than the national average. The proximity of important sources of NH_x as well as the high filtering capacity of coniferous tree canopies are assumed to be responsible (Frank, 1994). In particular forest edges are exposed to high doses of nitrogen depositions. Forest edges disturb the vertical wind profile and so cause higher air turbulence (Draaijers et al., 1988). Dry deposition near forest edges is substantially increased and consequently trees in forest edges catch more air pollutants than trees in the middle of the forest. The enhancement of dry depositions in forest edges strongly depends on wind velocity and wind direction.

Part of the ammonium deposited on forest soils is consumed by tree roots and another part is nitrified by bacterial activity (van Breemen et al., 1982). Since both processes result in proton release, strong acidification may occur, especially in soils with low buffering capacity. Subsequently high amounts of NO_3^- can leach and poll-

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ute the ground water. Processes like soil acidification, eutrophication and leaching of nitrate can be more intense in forest edges (Draaijers et al., 1988).

This research aimed to provide an answer to three questions: (1) does the forest edge of homogenous pine stands catch more ammonium than the centre of the forest, how far does this effect reach and how strong are the total and relative differences? (2) do we find nitrification in forest soils with a very low pH? and (3) can a doses–effect relation be observed between soil pH and ammonium depositions? To study these research items an experiment was started in 1996 in a homogeneous Corsican pine forest situated in a region of intensive livestock.

Study area

The experiment was set up in the state forest of Ravels in the Northern part of Belgium (51°22′N, 5°2′OL). The forest covers about 800 hectares and is mainly composed of pine stands (*Pinus sylvestris* and *Pinus nigra* ssp. *laricio*) established on former heathland in the beginning of this century. The forest is partly located on the Campine plateau and ranges in elevation from 30 to 35 meters. The Campine plateau originates from a mixture of tertiary sands and gravel-rich sands deposited by the river Meuse. During the Pleistocene these sands were covered by aeolian sand deposits. The coarse sandy soil has a massive, compacted and cemented spodic B horizon and is classified as a Haplic Podzol (FAO, 1988).

Methodology

The methodology was based on three principles: (1) depositions of NH_x are highest in regions with intensive livestock, (2) pine forests are effective filters for air pollutants and (3) strong air turbulence develops at forest edges.

A transect of 1.4 km was established from the south-western to the north-eastern part of the forest. Along this transect, soil (Haplic Podzol) and stand characteristics (*Pinus nigra ssp. laricio*; 70 years) are quite similar. Ammonium depositions along this transect were studied by collecting throughfall water. Along the transect every 25 meter throughfall water was collected monthly between May and November 1996. On each point 4 two-litre recipients fitted with funnels (dia. 15 cm) were placed below ground level to avoid growth of algae and to keep the samples cool. A nylon wire mesh was placed in the funnel to prevent contamination by large particles. Throughfall water was collected solely under tree canopies, not in open spots. Stemflow water was not collected because of its low contribution to nutrient fluxes in pine stands. To obtain a representative sample for throughfall for each point, the collected water of the four recipients was mixed. The samples were analysed on NH_4^+ with a specific NH_4^+-electrode (ORION). Because of the prevailing westerly and south-westerly wind directions in Flanders, high NH_x-concentrations were expected near the south-western border of the forest.

On the same locations, 8 soil samples of the upper mineral soil (0–10 cm) were taken, mixed and analysed on pH-H_2O and pH-KCl with a specific electrode (ORION).

In the middle of the transect, a permanent plot of 25 ares for the intensive monitoring of forest ecosystems is situated, where the quality and quantity of different water fractions is permanently (fortnightly) monitored in the framework of the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests. Throughfall water is sampled using 10 randomly distributed bulk collectors. The funnels (dia. 15 cm) of these collectors are placed at 1 meter height in order to avoid the influence of herbs and dust and the polyethylene recipients are placed below ground level. Soil solution is sampled by 3 sets of suction porous cup lysimeters at 10, 35 and 75 cm depth. Bulk deposition is collected using 4 bulk collectors in a meadow outside the forest. The collectors are sampled every fortnight and replaced by distilled water rinsed collectors. Water samples are analysed on pH, acidity, K, Ca, Mg, Na, Al, Fe, NH_4, NO_3, SO_4, Cl, total nitrogen and organic matter.

Results

Table 1 represents data of the nutrient content in bulk precipitation and throughfall water for 1996 in the permanent plot in Ravels, which is situated in the middle of the transect. Large amounts of most elements were added to the precipitation during its passage through the canopy. The concentrations of most elements in throughfall water by far exceed those in rainwater. The throughfall of anorganic nitrogen is mainly composed of ammonium (28.3 kg ha^{-1} $year^{-1}$). Throughfall deposition of nitrate–N reaches 7 kg ha^{-1} year.

The measured concentrations of NH_4^+ and SO_4^{2-} in throughfall water were strongly correlated (r = 0.93) indicating that ammonium is mainly deposited as ammonium sulphate which is probably formed by interaction of ammonia with sulphur dioxide (from fossil fuels). Due to the synergistic effects of NH_3 on the dry deposition of SO_2 (co-deposition) (Van Breemen et al., 1982), high amounts of SO_4^{2-} are determined in throughfall water.

The chemical behaviour of ammonium sulphate during migration through the soil is illustrated by the ionic composition of the soil solution on different depths. Figure 1 shows concentrations of ammonium–N and nitrate–N in the sampled water fractions. It is clear that the concentrations of NH_x in the soil solution at 35 cm

Table 1

Annual values of open field deposition and canopy throughfall for the permanent plot in Ravels in 1996 (in kg ha^{-1} $year^{-1}$, except for H^+ in g ha^{-1} $year^{-1}$ and HCO_3^- in keq ha^{-1} $year^{-1}$)

	NH_4^+-N	NO_3^--N	SO_4^{2-}-S	Cl^-	K^+	Ca^{2+}	Mg^{2+}	Na^+	HCO_3^-	H^+
Open field deposition	19.6	2.9	12.5	19.8	2.3	9.1	1.5	11.6	0.35	12.0
Canopy throughfall	28.3	6.9	24.2	25.9	14.6	7.8	1.9	14.6	0.68	4.8

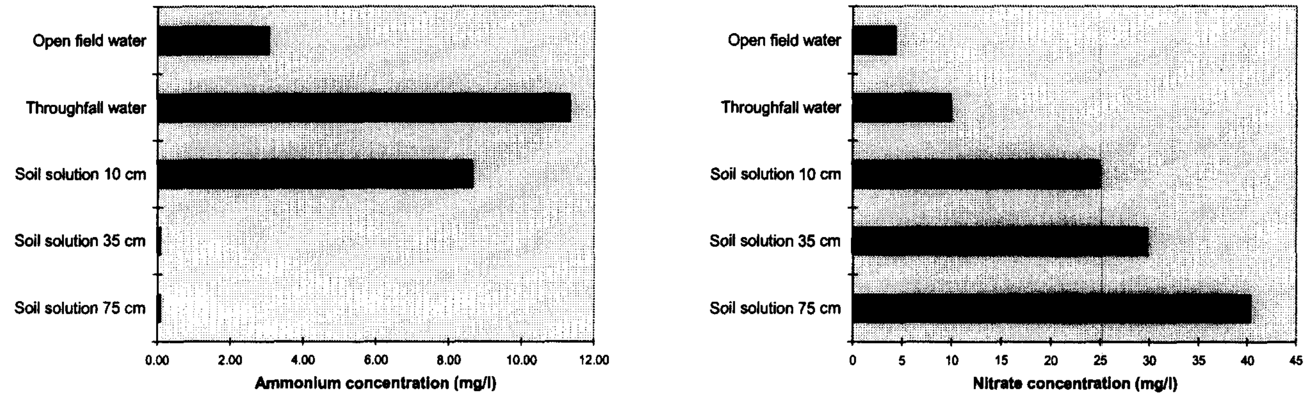

Fig. 1. Evolution of NHx^+ and NO_3^--concentrations (in mg/l) in the different water fractions measured in 1996.

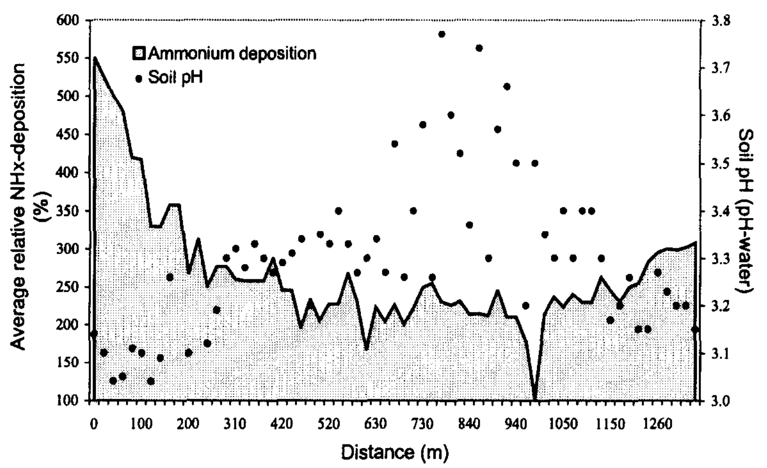

Fig. 2. Throughfall depositions of ammonium-N and pH–H_2O of the upper 10 cm of the mineral soil along the transect.

and 75 cm are negligible (< 0.01 ppm) in comparison to the concentrations of nitrate. NO_3^--concentrations clearly increase with depth: 25 ppm at 10 cm, 30 ppm at 35 cm and 40 ppm at 75 cm. Obviously, at 10 cm depth ammonium is not completely nitrified.

Figure 2 shows the average relative NH_x-depositions and the soil pH of the upper 10 cm of the mineral soil along the transect. The width of the zone with increased throughfall depositions can be defined as the zone in which the relative increase of depositions is larger than the internal variability (Draaijers et al., 1988). In a forest edge of 180 m, NH_x concentrations were found to be significantly higher than in the centre of the forest. The south-western edge of the forest catches 55 kg ha^{-1} $year^{-1}$, which is on average twice as much NH_x as the centre of the forest. In the north-eastern border, smaller differences in NH_x-depositions were found. Climatological data showed south-western winds to be dominant during the sampling period (May–November 1996).

It can be seen from Fig. 2 that extremely low soil-pH values were measured in both forest edges, especially in the south-western edge, where pH–H_2O-values vary between 3.05 and 3.15 and pH–KCl values range between 2.35 and 2.55. In the centre of the forest pH–H_2O and pH–KCl reach values of respectively 3.80 and 2.80. In the forest edge zone of 250 m from the south-western border, pH-values were found to be significantly lower than in the centre of the forest. For the north-eastern border no zone with significant lower pH-values was found.

Discussion and conclusions

The ammonium–N depositions in this forest are very high: between 28 and 55 kg ha^{-1} $year^{-1}$, whereas a "natural" value of total N-depositions of 1–9 kg per ha^{-1} $year^{-1}$ can be expected (Denneman, 1989). The deposition of ammonium–N in 1996 in the present study is even lower than the depositions registered in years with higher precipitation.

Between the measured concentrations of NH_4^+ and SO_4^{2-} a strong correlation was found, indicating that ammonium is mainly deposited as ammonium sulphate. This confirms the hypothesis of Van Breemen et al. (1982), who found that dry deposition of SO_2 could be stimulated by synergistic effects of NH_3.

Considering the migration of nitrogen through the soil, we found that ammonium concentrations are important until 10 cm depth. At 35 cm depth, ammonium concentrations are negligible. The inverse behaviour is found for NO_3^-: the concentration of this ion clearly increases with depth. The deposited ammonium is probably partly taken up by plant roots and partly nitrified yielding NO_3^-. According to Van der Maas (1985), nitrification is inhibited under conditions of particularly high NH_x deposition and very poor soil conditions. Also Persson and Wiren (1995) stated that strong acidification of the soil leads to an inhibition of bacterial conversion of ammonium to nitrate. The fact that the ammonium concentration is still important at 10 cm depth (of the mineral soil), whereas this is restricted to the upper few centimetres in less acidified forests (De Schrijver, 1997), can be an indication that the process of nitrification is slowed down.

At the forest edge in the prevailing wind direction (south-west) the double amount of ammonium–N (55 kg ha^{-1} $year^{-1}$) was found in comparison to the centre of the forest (28 kg ha^{-1} $year^{-1}$). This zone was found to be 180 m wide. In the north-eastern border only small differences in NH_x-depositions were measured. This is in accordance with the conclusions of Draaijers et al. (1988) who found that increase of depositions in forest edges depends on the direction of the wind during the dry period preceding a rainstorm. In forest edges of other wind directions, higher depositions are restricted to the first few meters of the forest edge due to some small turbulent currents which develop at the leeside. It is expected that the deposition gradient strongly depends on the characteristics of forest borders. Tree species, leaf area index, aerodynamic roughness and distance between the trees probably play an important role.

The variation in ammonium depositions (and probably also sulphate and nitrate) is clearly reflected by the state of soil acidification. The pH–H_2O and pH–KCl values are extremely low in the entire forest, but especially in the zone with the highest depositions of acidifying components. In a forest edge zone of 250 m from the south-western border, pH–H_2O values vary between 3.05 and 3.15 and were found to be significantly lower than in the centre of the forest. For the north-eastern border no zone with significant lower pH-values was found.

It is obvious that ammonium plays an important role as acidifying component not only because of the high depositions but also because of its stimulus to the deposition of sulphate. The contribution of ammonium, sulphate and nitrate to acid deposition in the Corsican pine stand in Ravels is calculated as 50%, 35% and 15%, respectively (De Keersmaeker, 1997).

As a consequence, leaching of cations such as potassium, calcium, magnesium, leading to nutrient imbalances for plant growth, and release of potential toxic metals such as Al and Fe may occur (Van Dijk et al., 1989; Tomlinson, 1991). A combination of these effects can be expected to have serious consequences for the vitality of the forest.

The leaching of high amounts of nitrate to the ground water (Van Breemen, 1988) can endanger the use of forests as sources of drinking water supply. These high amounts of nitrate leaching to the ground water — as well as direct nitrate inputs from fertilisers and liquid manure on the surrounding arable land — can reach aquifers underlying the forests on Pleistocene sandy areas, which are traditionally important for collection of high-quality drinking water.

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