
Effects of Acidic Deposition on Forest Soil and Vegetation [and Discussion]

G. Abrahamsen and H. G. Miller

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Effects of acidic deposition on forest soil and vegetation

BY G. ABRAHAMSEN

The Norwegian Forest Research Institute, 1432 Ås-NLH, Norway

The paper concerns the potential effects of acidic deposition on the nutrient status of soil and forest and on the possible toxic effect of increased Al solubility.

The nutrient status of trees may be influenced by pollutants interacting with the foliage and also by changing availability of nutrients in the soil.

N compounds are often absorbed by the canopy whereas base cations are lost to the soil by foliar leaching. Cation leaching increases with increased acidity of precipitation. Throughfall acidity varies with tree species, season and distance from the emission areas. The impact of increased foliar leaching of base cations is not well known.

In soil, acid deposition may have three effects: (i) a fertilizer effect caused by the deposition of N, and possibly, under specific conditions, also of S; (ii) an acidification effect caused by increased leaching of base cations; and (iii) an Al toxicity effect in cases where soil acidity is increased.

Results of fertilizer experiments indicate that the atmospheric deposition of N is likely to increase forest growth especially in the northern parts of North America and Europe. At more southerly latitudes, nutrients in addition to N are often deficient. Therefore the N deposition is less likely to stimulate forest growth.

Sulphur deposition is not likely to increase forest growth in most areas of the temperate zone. On the contrary, S deposition will mostly increase leaching of base cations such as Mg^{2+} and Ca^{2+} , and possibly K. Experiments with artificial acidification together with observations of increased Mg-deficiency in central Europe, indicate that Mg-deficiency might become a problem on sensitive soils exposed to acid deposition.

The possibility of Al toxicity caused by increased soil acidity is discussed on the basis of experiments with seedlings of Norway spruce. It is concluded that Al toxicity appears to be unlikely unless the Al concentrations in the soil solution increase to about 20 mg l^{-1} .

INTRODUCTION

This paper is about the effects of acidic deposition on forest soil and vegetation. Owing to limitations of space, the paper is restricted to effects on the growth of forest. This does not mean that other vegetation effects are not of interest.

In the paper the term acidic deposition covers all air pollutants linked to the deposition of H^+ ions as well as those having the potential to produce acid in the soil immediately or later. This means that H^+ , SO_4^{2-} , NO_3^- as well as SO_2 , NO_x and NH_4^+ are all included.

It is important to recognize that there is a large variation in the potential effects of acidic deposition on forest. This is owing to geographical variation in soil and vegetation properties and in the amounts of pollutants deposited. Table 1 gives information on the variation in deposition of air pollutants in Europe along a gradient from Germany to the northern part of south Norway.

The deposition of the air pollutants mentioned can have two types of effects on terrestrial

TABLE 1. VARIATION IN SO_2 CONCENTRATION AND ANNUAL AMOUNTS OF AIR POLLUTANTS DEPOSITED ALONG A SOUTH-NORTH GRADIENT

	Solling F.R.G. 51° 45' N	Birkenes Norway 58° 20' N	Langtjern Norway 60° 20' N	Kårvatn Norway 62° 50' N
H^+ /(kg ha ⁻¹ a ⁻¹)	3.0	1.0	0.45	0.23
SO_2 /($\mu\text{g m}^{-3}$ a ⁻¹)	10-25	2.4	1.6	0.9
S/(kg ha ⁻¹ a ⁻¹)	83	25	11	3.9
N/(kg ha ⁻¹ a ⁻¹)	34	25	10	3.1

Data from Ulrich *et al.* 1979; Joranger *et al.* 1980; Overrein *et al.* 1980 and O.E.C.D. 1979.

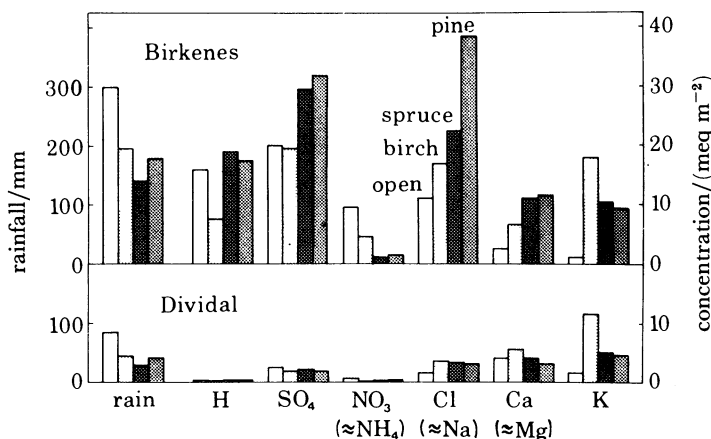


FIG. 1. Chemical content of incident rain and throughfall at Birkenes, southern Norway, and Dividal, northern Norway. Data are weekly sums for the period 1 August to 13 October 1977 (after Horntvedt *et al.* 1980).

ecosystems: (i) vegetation may be injured directly and (ii) vegetation may be affected indirectly by a changed supply of plant nutrients or by production of toxic compounds in the soil. The direct effects are beyond the scope of this paper and will not be further considered.

The elements that must be considered are H^+ , S- and N-compounds. S and N are both essential nutrient elements. Deposition of these elements may therefore produce a fertilizer effect. The other effect of this deposition is increased leaching of other essential plant nutrients such as Mg, K and Ca. Increased leaching from soils of these elements may reduce their availability to plants and increase soil acidity and potentially toxic Al ions in soil solution. The aim of this paper is to discuss our present knowledge of these indirect effects of acid deposition on soil and forest.

INTERACTION BETWEEN PRECIPITATION AND FOREST VEGETATION

It has long been known that the chemical composition of rainwater is changed when it passes through a vegetation canopy. An example is shown in figure 1, which gives the chemical content of incident rain and throughfall below birch, spruce and pine at Birkenes, south Norway, and Dividal, north Norway. Birkenes is more heavily exposed to long range transported air pollutants than Dividal, which is in a more or less unpolluted area. In Birkenes, throughfall below all tree species is enriched in K^+ , Ca^{2+} , Mg^{2+} , Cl^- and Na^+ . It is also enriched in SO_4^{2-}

and H^+ below spruce and pine but not below birch. NO_3^- and NH_4^+ are taken up by the canopy. In Dividal a similar pattern is found for K^+ , Cl^- and Na^+ , but there is little difference between incident rain and throughfall for Ca^{2+} , Mg^{2+} , NO_3^- , NH_4^+ , SO_4^{2-} and H^+ . The explanation for the differences between the areas is probably that in Birkenes dry deposited SO_4^{2-} , Cl^- and Na^+ are washed off the canopy. The higher enrichment of Ca^{2+} and Mg^{2+} is probably owing to leaching from the canopy.

The leaching of Ca^{2+} and Mg^{2+} is likely to increase as a result of increasing acidity of rain. Wood & Bormann (1975) showed a sharp increase in the leaching of K^+ , Ca^{2+} and Mg^{2+} when the pH of the 'rain' dropped below pH 4. Similar results were published by Abrahamsen *et al.* (1976a) and Horntvedt *et al.* (1980).

The results presented in figure 1 indicate that throughfall below conifers is more acidic than incident rain, whereas the opposite is true for birch. Nihlgård (1970) also observed increased acidity of throughfall compared to incident rain below spruce and reduced acidity below birch. In Solling (F.R.G.), increased acidity of throughfall was observed under both spruce and beech, but more so under spruce (Ulrich *et al.* 1979). In Scotland, acidity of throughfall below conifers has been shown to vary during the season. During late winter months throughfall was more acidic than incident rain but during mid- to late-summer throughfall was less acid (Miller & Miller 1983). On average for a whole year, throughfall was less acidic than incident rain. These results appear to be different from Norwegian results also in that throughfall in Scotland was enriched in NH_4^+ .

The conclusions that may be drawn from these studies are:

- (i) acidity of throughfall water varies with tree species and season. Conifers appear often to have more acidic throughfall than deciduous tree species.
- (ii) acidity of throughfall and SO_4^{2-} concentrations increase when distance to emission centres decreases.
- (iii) leaching of base cations from the canopy increases with increased acidity of rain.
- (iv) N compounds are often absorbed in the canopy.

These factors may influence the nutrient status of trees. However, it has not been shown that increased foliar leaching is reflected in reduced nutrient content of foliage. The increased leaching may be compensated by increased nutrient uptake from the soil (Abrahamsen & Dollard 1979; Horntvedt *et al.* 1980).

INTERACTION BETWEEN ACIDIC DEPOSITION AND SOIL

Potentially, acid deposition can have a number of different effects in soil that are of significance for plant growth. In my mind the most important effects can be classified into two: (i) the fertilizer effect of the deposition of N and S, and (ii) the acidification effect of increased leaching of SO_4^{2-} and sometimes NO_3^- together with base cations such as Mg^{2+} , Ca^{2+} and possibly K^+ .

Potential consequences of increased soil acidity are shortages of essential plant nutrients like Mg, and possibly Ca and K, increased mobility of Al and Mn possibly giving rise to toxic concentrations, changes in biological processes in soil, and many others.

Fertilizer effect of S and N deposition

Both N and S are essential nutrient elements but as the requirement for N is usually much higher than for S, the effect of N is of greatest significance.

S-deficiency is quite common in agricultural areas but very rare in forests (Leaf 1968; Humphreys *et al.* 1975; Lambert & Turner 1980). In forests it appears to be mainly limited to areas in the tropics or to unglaciated areas in the temperate zone. Reports of S-deficiency come from eastern Australia and western U.S.A. S-deficiency may, however, be induced by the use of N-fertilizer. Such inducement, which has been reported from northwestern U.S.A. (Turner *et al.* 1977), is owing to inadequate protein synthesis caused by lack of the S-containing amino acids cysteine, cystine and methionine. In spite of this possible growth-stimulating effect of S, it is reasonable to expect that the deposition of S in forest ecosystems will only rarely stimulate growth.

N-deficiency, in contrast to S-deficiency, is common and widespread throughout the world. Fertilization with N is therefore a widely used method for increasing forest production. For example, in Scandinavia 150–200 kg N ha⁻¹, mostly in the form of NH₄NO₃ is often applied five to ten years before the final cutting. A large number of fertilizer experiments carried out in Sweden have shown that 150 kg (NH₄NO₃)-N ha⁻¹, on average, may increase forest growth by 2.1 m³ ha⁻¹ a⁻¹ over a five year period (Rosvall 1979). Similar Norwegian experiments have given an increment increase of 1.3 m³ ha⁻¹ a⁻¹ over a five year period. (B. Tveite, personal communication). The fertilizer experiments in the Nordic countries have shown that N generally is the only nutrient element in short supply on mineral soils. Shortage of other elements like K, P, and micronutrients like B, is rarely observed on mineral soils, but commonly on peat soils. In the northern part of North America N also appears to be the only element in short supply (Bengtson 1979). However, at more southerly latitudes both in Europe and North America, shortages of P, K and Mg together with N-deficiency are commonly reported (Mayhead 1976; Bengtson 1979; Baule 1980; Heinsdorf 1981; Hippeli *et al.* 1981; Leube *et al.* 1981; Miller 1981; Rehfues 1981).

The experience from the fertilizer experiments implies that the N-deposition occurring in Scandinavia and in the northern parts of the U.S.A. and in Canada is probably increasing forest production. The N-deposition comes in the same chemical form as in fertilizer and in many places it comes in the same amounts over a five to ten year period as used in practical forest fertilization.

We do not have any clear evidence for increased forest growth in Norway owing to atmospheric N-deposition. On the other hand, the tree-ring analyses that have been carried out do not contradict the hypothesis of increased growth. The areas with the highest deposition often have had better growth during the last 20–30 years than areas with lesser deposition (Abrahamsen *et al.* 1976a; Strand 1980).

As fertilizer studies in countries south of Scandinavia mostly have shown shortages in nutrients in addition to N, the deposition of N in these countries is likely to influence growth less than in the northern areas. The Swedish fertilizer studies have also shown that the response to N-fertilization is less in southernmost Sweden than further north (Rosvall 1979). Ulrich (1980) mentions that in the F.R.G. N-fertilization experiments established immediately after World War II led to substantial growth increase. As a result, numerous fertilizer experiments were established in the 1960s, but almost none of these showed the expected growth increase.

During the last decade Mg-deficiency has increased in extent in the F.R.G. and also in Poland (Rehfuess 1981; Baule 1980).

Leaching of base cations

Soil acidity is determined by the activity of H^+ in the soil solution (soil pH) and the exchangeable acidity. There is an equilibrium between the pH of the soil solution and the exchangeable acidity. Therefore if the H -ion concentration in the soil solution increases, H^+ may exchange with base cations adsorbed to the negatively charged soil particles. This means that both the exchangeable acidity and the concentration of base cations in the soil solution may increase. The leaching of base cations will then take place when there is a surplus of water and if there are equivalent amounts of mobile anions in this water. In most soils anions are much more mobile than cations owing to shortage in positively charged adsorption sites.

The deposition of acidic air pollutants is likely to increase the leaching of base cations from soils as it means increased ion exchange between H^+ in the soil solution and base cations adsorbed to the soil particles. In addition the concentration of the anions SO_4^{2-} and NO_3^- in the soil solution may increase. To what extent the concentration of these anions will increase depends on the total deposition of N and S and also on the degree to which the anions are adsorbed to the soil particles or immobilized by plant or soil organisms.

According to what has been previously mentioned, the net biological immobilization of S is probably small in most forest ecosystems in the temperate zone. SO_4^{2-} might be retained in the soil by sorption to amorphous oxides and hydroxides of Al and Fe. However, various studies on the leaching of S from forest watersheds or from lysimeters with temperate forest soils, have shown that the leaching of S corresponds approximately to or is slightly smaller than the total deposition of S (Abrahamsen 1980). This means that S deposition is a very important factor for increased leaching of base cations from forest soils.

NO_3^- is to an even lesser degree adsorbed by soil particles. However NO_3^- as well as NH_4^+ are readily immobilized in soils owing to the great demand for N by plants and microorganisms. When the available information on inputs and outputs of N is assembled, as previously done for S, it appears that on the average only 30% of the amount of N deposited was leached (Abrahamsen 1980). In that compilation also the input and output figures from the Solling site (F.R.G.) were included (Heinrichs & Mayer 1977). Compared to input, the leaching of N below the root zone was 27% in the beech forest and 66% in the spruce forest. The leaching of N from the spruce forest was therefore much higher than what is normally found in coniferous forests. For example in the watersheds studied by Gjessing *et al.* (1976) only 4–25% of the amount of N deposited was leached. It is to be expected that when N is not in short supply increased leaching will take place. The relatively high leaching in the Solling site might therefore be a sign of N saturation of the system.

The reduced response to N-fertilization in forests in southern Sweden and the reports of increased NO_3^- in groundwater in that area (Thoms & Joelsson 1982), might be a sign of N saturation. Similar observations have, however, not been made in Norway. Based on mathematical modelling of tree growth and nutrient demand, Ågren (1983) has estimated the time it will take for forests to become saturated with N. His most important assumptions are that 20% of the deposited N is used by trees and that saturation of the system is obtained when the foliage has a N content of 2%. This exercise indicates that saturation is more quickly attained on good sites than on poor sites and obviously more quickly the higher the deposition

rate. Given the assumptions made by Ågren (1983) saturation of medium and poor spruce and pine forest sites is likely to take place within the periods given in table 2.

If the deposition of N reduces the deficiency of N in forest ecosystems and even saturates the system with N, NO_3^- leaching is likely to be a consequence. In most countries exposed to long distance transport of air pollutants this is not the case today, but there are signs of such conditions in areas closer to the great emission centres. In that case the leaching from soils will increase.

TABLE 2. APPROXIMATE NUMBER OF YEARS BEFORE MEDIUM AND POOR PINE AND SPRUCE FOREST MIGHT BECOME SATURATED WITH N

site		deposition of N		
		kg ha ⁻¹ a ⁻¹		
	5	10	20	30
medium	150	80	40	25
poor	—	> 170	100	65

After Ågren 1983.

Increased leaching of base cations does not necessarily mean that soil acidity has to increase. This is because the exchanged cations may be compensated by increased mobilization of base cations by weathering processes. However, as pointed out in a recent review paper (Abrahamsen & Stuanes 1983) there are indications that the weathering rate in many forest ecosystems is adapted to the natural internal H^+ production in the forest ecosystem. This means that the weathering may neutralize the H^+ naturally produced in the system, but any additional H^+ supply may not be neutralized. This conclusion is supported by results of studies of soil in relation to distance from large SO_2 emitters, by experiments with artificial acidification and also by reanalysis of soils for acid-base properties (Abrahamsen & Stuanes 1983). Increased acidity means also reduced availability of Mg, Ca and possibly K. This may in the long term have a negative influence on the growth of trees.

There are experimental results that may be used to evaluate the theories mentioned above. (For a review see Abrahamsen & Tveite (1983)). In Norway five field plot experiments with application of artificial acidic rain were established during the period 1972–1975 (Abrahamsen *et al.* 1976*b*). In these experiments 50 mm of groundwater acidified to certain pH levels (most often pH 6, 4, 3, 2.5 and even 2) were applied monthly during the frost-free period. The acidity of the artificial rain was adjusted only by means of sulphuric acid – not by nitric acid. In only one of these experiments clear effects on tree growth were found. The experiment was carried out in a young pine forest. It was started in 1974 and watering continued until September 1981. Altogether 1900 mm of artificial rain was applied. Figure 2 shows height growth in the different treatments as percentages of the height growth in the pH 6 treatment (control). During the years 1976 and 1977 increased growth of trees at the plots receiving water at pH 3, 2.5 and 2 was found. After 1979, however, significant reduction in the growth was observed at the plots supplied water of pH 2.5 and 2.0.

Foliar analyses from this experiment indicate that the increased growth during 1976 and 1977 was caused by increased availability of N in the soil (figure 3). Abrahamsen *et al.* (1983) postulated that this effect was caused by increased N-mineralization owing to the relatively concentrated acid applied. The growth reduction observed in the two most acidic treatments

during the years 1979–1982 cannot be explained by any difference between the treatments in the supply of N. As shown by Tveite (1980) the only nutrients reduced in foliar content by the acid application were Ca, Mg and Mn. Mn is a micronutrient and the content is probably well above deficiency levels. Of the other two nutrients only the Mg content was close to deficiency level (figure 3).

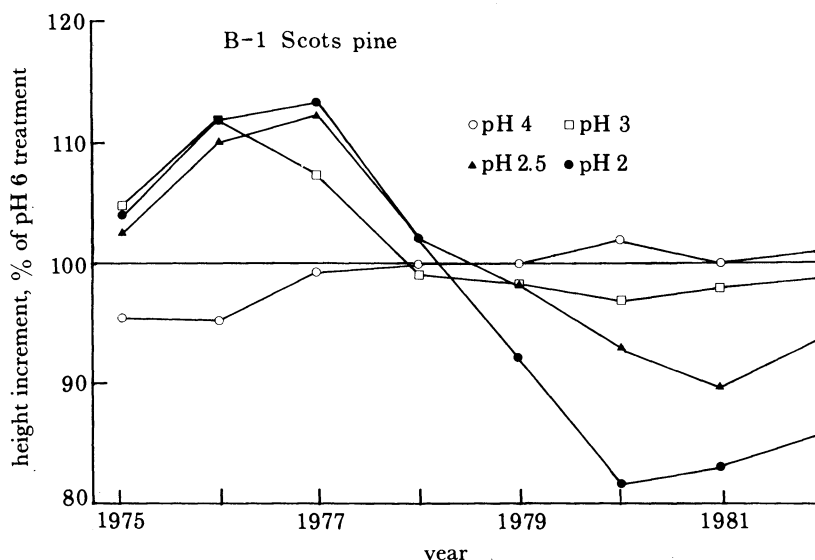


FIGURE 2. Height growth of Scots pine (*ca.* 15 years old in 1982) exposed to artificial rain of various pH levels (experiment B1). From Abrahamsen *et al.* (1983) with the addition of unpublished data for the years 1981 and 1982. Further information in text.

Soil analyses from the same experiment show that the saturation had been severely reduced in the upper two soil layers by the acid application (table 3). In the B horizon the effects are considerably smaller. The main reason for the decrease in base saturation is the reduced content of exchangeable Ca and Mg in the soil. The Ca and Mg content in the O layer at the 'pH 2 plots' is only about 10% of the mean of the control plots. In the E layer the corresponding value is about 20%. As shown in the table the K content has been only slightly reduced by the acid application. This agrees with the foliar analysis where no effect on the K content of the needles could be found (Tveite 1980).

The results of this experiment do not indicate that short term negative effects of the acidic deposition are occurring in Norway, but in the long term negative effects on the supply of Mg may be indicated. However, it is important to realize that the short term effect of a strong acid (pH 2.5 or 2) cannot be compared to the long term effect of the acid deposition occurring, for example, in Norway and elsewhere. Strong acid is likely to give larger effects than equivalent amounts of more dilute acid. This is partly because strong acid kills part of the ground vegetation and in this way influences the nutrient cycling. But it is also owing to larger changes in the equilibrium conditions between the water phase, the 'adsorbed phase' and the mineral phase in the soil. Similar large changes will not be caused by more dilute acid. Nevertheless, I believe that the results may indicate that the long term consequences of acid deposition will be nutrient deficiency in sensitive soils. The nutrient most likely to become deficient appears to be Mg. The widespread deficiency of Mg now reported from many central European countries appears to support this hypothesis.

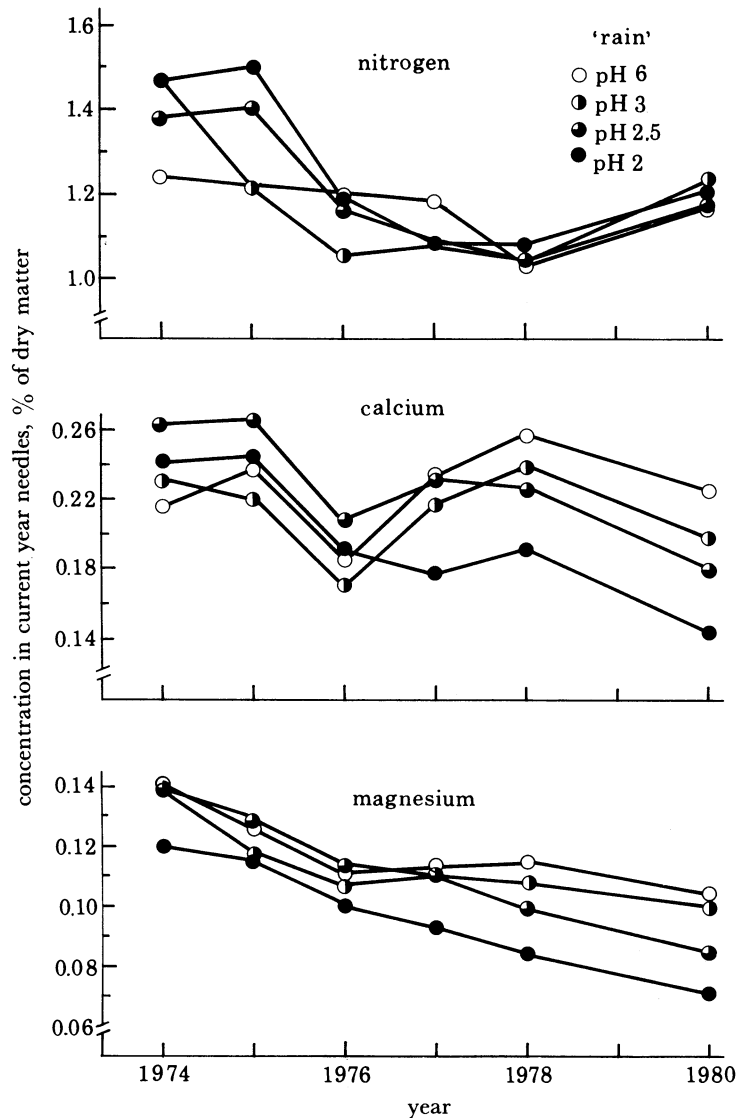


FIGURE 3. Foliar content of N, Ca and Mg in current year needles of Scots pine exposed to artificial rain of various pH levels. See figure 2 legend for further explanation.

Al toxicity

Increased soil acidity generally increases the solubility of elements like Al, Mn and others. These ions are, in certain concentrations, toxic to plants. As the acid deposition is likely to increase the acidity of certain soils these ions might become available in increasing amounts.

Among these elements, attention has especially been given to Al. Al toxicity is an important growth-limiting factor for agricultural crops in many acidic soils. In general, such Al toxicity does not occur in soils with pH above 5.5, but is common at lower pH values – particularly below pH 5 where the solubility of Al increases sharply.

High Al concentrations appear to be harmful to plants for two reasons. First, cell division in the roots is inhibited and the roots also appear to lose their plasticity. Second, Al has a number of effects on plant nutrition among which the inhibitory effect on P uptake is well known.

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In some recent papers it has been suggested that acid precipitation mobilizes soil Al to the extent that forest trees are damaged (Ulrich *et al.* 1979, 1980; Matzner & Ulrich 1981). Ulrich *et al.* (1980) observed that the Al concentration in the equilibrium soil solution increased from 0.3–0.95 mg l⁻¹ in April to values between 1.1 and 1.8 mg l⁻¹ in November of 1969. Simultaneously the biomass of fine roots decreased from 2500 kg ha⁻¹ in May to 200 kg in

TABLE 3. BASE SATURATION AND EXCHANGEABLE Ca, Mg, AND K (1 M CH₃COONH₄ pH 7) OF THE SOIL OF EXPERIMENT B1

layer	soil depth cm	not	pH of artificial rain				
		watered	6	4	3	2.5	2
		equivalent amount of precipitation (1000/mm) with pH = 4.2 and (Ca ²⁺ + Mg ²⁺) = 7 μM					
		7	4.8	6.9	25	69	210
base saturation, %							
O	0–4	12.0	11.5	11.2	7.8	4.0	1.6
E	4–6	5.3	4.4	5.6	3.6	2.6	1.5
Bs1	9–14	1.4	1.3	1.5	1.6	1.2	1.0
Bs2	24–29	1.2	1.3	1.5	1.5	1.3	1.1
Ca/(mmol kg ⁻¹)							
O	0–4	48.5	45.7	47.9	35.2	16.5	5.3
E	4–6	1.40	1.10	1.61	0.93	0.75	0.27
Bs1	9–14	0.19	0.18	0.24	0.22	0.13	0.12
Bs2	24–29	0.09	0.11	0.13	0.13	0.10	0.09
Mg/(mmol kg ⁻¹)							
O	0–4	13.3	13.0	12.3	6.66	3.00	1.38
E	4–6	0.61	0.47	0.56	0.32	0.25	0.13
Bs1	9–14	0.12	0.12	0.15	0.11	0.09	0.11
Bs2	24–29	0.05	0.05	0.05	0.06	0.04	0.05
K/(mmol kg ⁻¹)							
O	0–4	6.52	7.09	6.57	6.35	5.54	4.70
E	4–6	0.59	0.59	0.61	0.64	0.68	0.51
Bs1	9–14	0.31	0.34	0.35	0.31	0.36	0.43
Bs2	24–29	0.17	0.16	0.20	0.20	0.20	0.26

Experiment started in 1974; acid application ended in 1981. The soil analyses are from 1981.

August. On this basis they concluded that 'aluminium concentrations of 1–2 mg Al l⁻¹, as now existing continuously, should therefore seriously damage root systems of the trees especially in periods (seasons; years) where nitrification is favoured'. They also conclude that 'in central Europe – central parts of West and East Germany, Czechoslovakia and Poland; see O.E.C.D. 1977 – the forests on most soils are highly endangered by increasing soil acidification due to acid rain, if the site is subject to substantial dry deposition of SO₂'. In a later paper Matzner & Ulrich (1981) showed that the Al concentration in the seepage water under beech during the years 1969–1979 has varied from almost nil to about 6 mg l⁻¹. Under spruce the variation has been from about 1 mg l⁻¹ in 1972 to about 15 mg l⁻¹ in 1976–79.

Ulrich and colleagues also emphasize the importance of the interaction between Al and Ca in soil (Ulrich 1983). They assume that Al injury is likely when the molecular ratio of Ca/Al in the equilibrium soil solution or in the fine roots is one or less.

These postulates must be evaluated on the basis of what is known about Al toxicity in trees. Different studies have been carried out with the purpose of examining effects of Al on trees (for a review see Abrahamson & Tveite (1983)). These studies showed in general that Al concentrations had to be rather high (80–160 mg Al l⁻¹) before any damage could be observed. However, the studies were all carried out with high concentrations of Ca in the growth solution. Therefore the studies are probably not fitted for illuminating the effects of Al on nutrient-poor and acidic soils. For this reason a study was carried out on seedlings of Norway spruce in nutrient solution (Vagstad 1983).

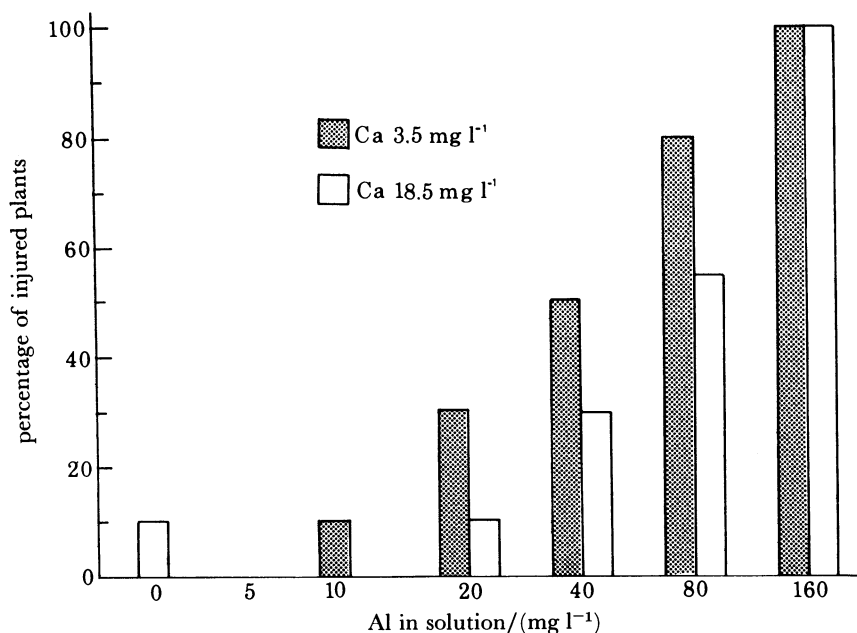


FIGURE 4. Frequency distribution, %, of severely damaged or dead seedlings of Norway spruce grown in nutrient solutions with various concentrations of Al and Ca. Al added as Al₂(SO₄)₃, Ca as a mixture of CaSO₄ and Ca(NO₃)₂. Experimental period six weeks (after Vagstad 1983).

The seedlings were grown in a greenhouse using nutrient solutions prepared by the method of Andersson *et al.* (1974). Two experiments were carried out. In the first, Al was present in concentrations of 0–160 mg l⁻¹ and Ca 3.5 and 18.5 mg l⁻¹. In the second, Al varied from 0 to 40 mg l⁻¹ and Ca concentrations were 1 and 3.5 mg l⁻¹. Al was added as Al₂(SO₄)₃ and Ca as a mixture of Ca(NO₃)₂ and CaSO₄. Thus the experiments covered a large range of Al concentrations combined with low Ca/Al molar ratios. pH of the solutions varied between 4.4 and 3.5, but mostly from 3.8 to 3.5.

Figure 4 gives results of experiment 1. It appears that the number of severely damaged or dead plants is not increased compared to the control unless Al increases to 20 mg l⁻¹ or above. The same picture is obtained for the total biomass of the plants (figure 5). Both figures show a positive effect of the higher Ca concentration. Similar results were obtained in the second experiment. Reduced growth was observed when Al concentrations increased above 20–25 mg l⁻¹ and a positive effect of Ca was also found. Chemical analyses of the new roots that were developed in the solution showed that Al concentrations in the roots increased to more or less a constant concentration when the Al in the solution increased to 10 mg l⁻¹ or more. At the same time Ca and Mg concentration in the roots decreased significantly to more or less constant values (figure 6).

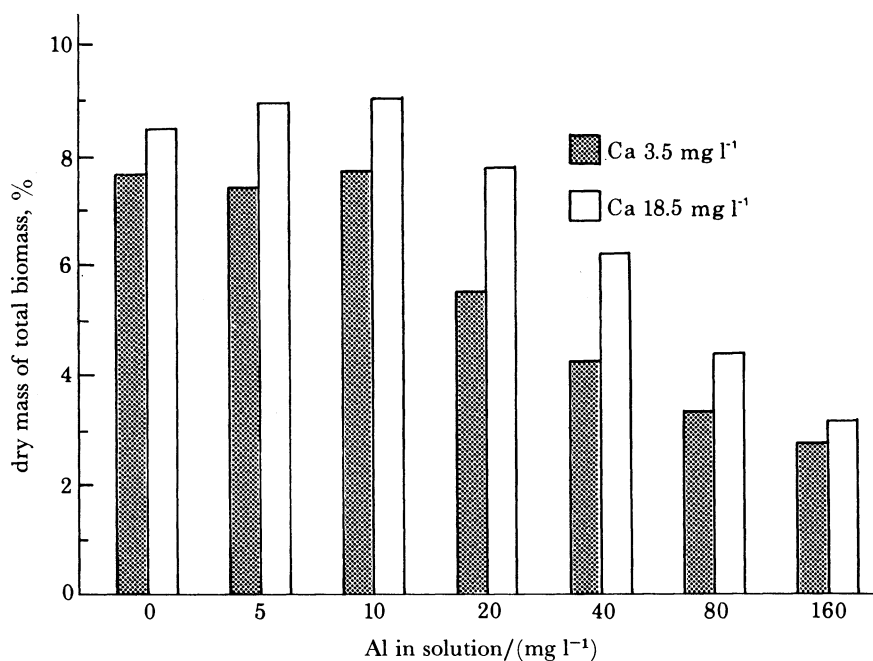


FIGURE 5. Biomass of Norway spruce seedlings grown in nutrient solutions with various concentrations of Al and Ca. Experimental period six weeks. See figure 4 legend for further explanation (after Vagstad 1983).

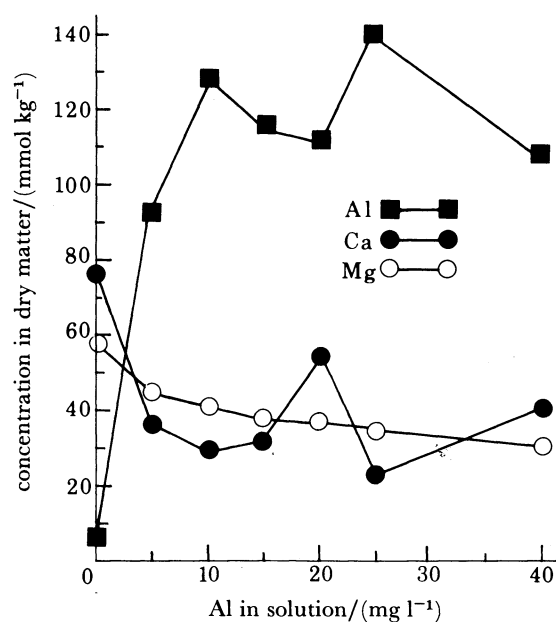


FIGURE 6. Concentrations of Ca, Mg and Al in new roots of Norway spruce grown in nutrient solutions with various concentrations of Al and Ca. Experimental period ten weeks. See figure 4 legend for further explanation (after Vagstad 1983).

These results must be considered as preliminary. The experiments should be repeated under other experimental conditions, for example with plants grown in soil, before final conclusions are drawn. However, similar results have been obtained on sitka spruce by H. G. Miller (personal communication) and on various other North American tree species (T. C. Hutchinson, personal communication).

CONCLUSION

Indirect effects of acidic deposition on forest concern altered nutrient supply and potentially toxic effects of increased Al mobility. The nutrient status of trees may be influenced by pollutants interacting with the foliage and also by changing availability of nutrients in the soil.

N compounds are often absorbed by the canopy whereas 'base cations' are lost to the soil by foliar leaching. Cation leaching increases with increased acidity of precipitation. Throughfall acidity varies with tree species, season and distance from the emission areas. The impact of increased foliar leaching of 'base cations' is not well known.

In soil, acidic deposition may have three effects: (i) a fertilizer effect caused by the deposition of N, and possibly under specific conditions also of S; (ii) an acidification effect caused by increased leaching of 'base cations' and (iii) an Al toxicity effect in cases where soil acidity is considerably increased.

Results of fertilizer experiments indicate that the atmospheric deposition of N is likely to increase forest growth, especially in the northern parts of North America and Europe. At more southerly latitudes, other nutrients than N alone often are deficient. Therefore the N deposition is less likely to stimulate forest growth.

Sulphur deposition is not likely to increase forest growth in most areas of the temperate zone. On the contrary, S deposition will mostly increase leaching of 'base cations' such as Mg^{2+} and Ca^{2+} , and possibly K^+ . Experiments with artificial acidification, together with observations of increased Mg-deficiency in central Europe, indicate that Mg-deficiency might become a problem in sensitive soils exposed to acidic deposition.

The study of Al-toxicity on seedlings of Norway spruce indicates that concentrations above 10–20 mg Al l^{-1} may be toxic when Ca is in low concentrations.

In the equilibrium soil solution of a spruce forest in Solling, F.R.G., the total Al concentration has been reported to vary around 15 mg l^{-1} . In this forest seedlings of Norway spruce may therefore be negatively influenced by the Al concentrations. However, before a more definite conclusion is drawn the experiments should be repeated and more knowledge of the Al chemistry of the soil solution should be obtained.

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Discussion

H. G. MILLER (*Macaulay Institute for Soil Research, Craigiebuckler, Aberdeen, U.K.*) I was interested in Dr Abrahamson's observation that in his experiments with Norway spruce in nutrient solution there has been no root damage at aluminium levels up to $20/10^6$. We at the Macaulay Institute have had similar results with Sitka spruce, indeed when we supply the aluminium and phosphate in alternate weeks no damage has been observed at up to $40/10^6$. Perhaps Dr Abrahamson could tell us how these levels relate to aluminium concentrations found in soil?

G. ABRAHAMSEN. Our experiments indicate a slight increase in injuries to seedlings of Norway spruce and a slight decrease in biomass when aluminium increased from 10 to $20/10^6$ and Ca was at the lowest level. Our results, therefore, indicate damage at lower Al concentrations than you have found for Sitka Spruce.

As to Dr Miller's question, we have only measured Al concentrations (total Al) in the lysimeter experiments where artificial rain of various acidities was applied to an iron podzol on sandy loam. We collected the leachate at a soil depth of 40 cm. Lysimeters supplied with water of pH 4 and higher, never had Al concentrations above $1.5/10^6$. Those supplied with water of pH 3 had up to $7/10^6$ Al.