

Response of a Scots pine (*Pinus sylvestris*) stand to application of phosphorus, potassium, magnesium and lime.

1. Soil data

G. ARNOLD & A. VAN DIEST

Department of Soil Science & Plant Nutrition, Wageningen Agricultural University, P.O. Box 8005, NL 6700 EC Wageningen, Netherlands

Received 8 April 1993; accepted 8 June 1993

Abstract

In 1985-1988, a 25-y-old Scots pine forest was limed and fertilized with P, K and Mg in a 2^4 factorial design and in an experiment with 5 liming levels, in order to alleviate potential nutrient deficiencies as a result of high N depositions (ca. $40 \text{ kg ha}^{-1} \text{ y}^{-1}$). In this paper, the first of three, the effects of fertilization and liming on nutrients in the forest floor and mineral soil are discussed to serve as a basis for the explanation of foliar nutrient concentrations and tree performance. Of all treatments, liming showed the widest array of effects, especially in the forest floor. It raised the pH in the forest floor and after 4 y that in 0-50 cm mineral soil, and it lowered extractable Al in the forest floor and in 0-50 cm mineral soil in 1989. These effects, except for that on forest floor pH, were stronger with increasing lime dosages. Liming showed transient effects on the amounts of soil inorganic N (N_i). Until 1989, N_i in the forest floor was lowered and that in the mineral soil was raised by liming. This could be attributed to the formation of NO_3^- , which is more mobile than NH_4^+ . Plots limed with 3 Mg (tonnes) lime ha^{-1} appeared to have higher N_i concentrations in the whole sampled profile than those limed with $> 3 \text{ Mg ha}^{-1}$ or the unlimed plots, the reason of which is unclear. Liming removed extractable K and Mg from the forest floor probably by exchange against Ca. The residence time of added P and possibly Mg in the forest floor was increased by liming, probably by a reduced solubility of the added fertilizers. Added K was poorly retained in the forest floor and probably quickly leached to soil layers deeper than 50 cm.

Keywords: fertilizer recommendations, forest fertilization, liming, nitrogen, *Pinus sylvestris*

Introduction

Forest fertilization was first applied and scientifically examined in the 19th century (Baule & Fricker, 1967), as was liming (Trümper, 1936). Both were common practice in the Netherlands, especially in reforestation programmes of heathlands around the beginning of this century. Around 1950, foresters lost interest in it, until the 1980s when it was suggested as a tool to revitalise declined forests (Van den Burg, 1989, 1991). However, in each specific case of forest decline it should be carefully

evaluated whether forest fertilization is appropriate. In Germany, a number of 'damage types' could be distinguished, which demonstrated that forest decline can not always be attributed to one distinct cause, but that locally different complexes of causes were involved. It was shown that in some areas decline corresponded with a nutrient deficiency, although the mechanisms inducing the deficiency were not always clear (Blank, 1988). Although the causes of forest decline are very diverse and speculative (Foster, 1989), there are cases where nutrient deficiencies are definitely involved and amelioration is to be expected after application of those nutrients (e.g. Hüttel, 1990; Zöttl et al., 1989). However, even when a nutrient deficiency is involved, it should be examined whether or not the trees are able to utilize an increased supply of nutrients. When also drought and/or root damage are involved the effect of fertilization may be nullified.

In areas with intensive livestock breeding, large quantities of NH_x (NH_4^+ and NH_3) are emitted. This occurs in several areas in the Netherlands, but also e.g. in Germany (Kaupenjohann, 1989; Uebel, 1991). Forest canopies are exposed to dry deposition of NH_x , causing higher ammonium concentrations in throughfall than in bulk precipitation (e.g. McLeod et al., 1990; Velthorst & Van Breemen, 1989). Thus, on forest soils in the Netherlands an average of 40 kg N (NH_x and NO_x) $\text{ha}^{-1} \text{ year}^{-1}$ is deposited in throughfall precipitation, but quantities locally exceeding 160 kg N $\text{ha}^{-1} \text{ year}^{-1}$ have been reported (Ivens et al., 1988). Bredemeier (1988) reported ammonium-enriched throughfall in an area in Germany with intensive livestock farming.

As forests in the Netherlands are mainly planted on sandy soils low in mineral nutrients (Van den Burg, 1991) N deposition may result in an overabundant N availability causing induced deficiencies of other nutrients. This effect may be aggravated when on the exchange complex NH_4^+ replaces other cations, that are subsequently leached with SO_4^{2-} or NO_3^- as counterions. Weathering of silicates, even when stimulated by a lower pH, proceeds too slowly to replenish such losses of cations (Van Grinsven, 1989). An initial effect of excessive N may be an induced growth push, possibly causing internal nutrient dilution, and thus aggravating the relative deficiency of other nutrients. Several workers have reported an increased tree growth during the past two decades, possibly due to an increased atmospheric N inputs, (Rehfuess et al., 1991; Sauter, 1991). Research in De Peel, the Netherlands, showed forest decline as a consequence of excessive N deposition (Van den Burg et al., 1987).

In the present research a mature Scots pine plantation was amended with P, K, Mg and lime, in order to alleviate potential nutrient deficiencies. Scots pine is the major forest tree species in the Netherlands and in large parts of Scandinavia, Germany, Poland and Russia. Especially in Sweden many fertilization experiments were carried out with Scots pine (e.g. Tamm and Hallbäcken, 1988). Recently, forest fertilization recommendations were presented in the Netherlands (Anon., 1990). The present research partly evaluates these guidelines.

Materials and methods

Pine forest fertilization experiment

The experimental area is situated near Harderwijk, the Netherlands (52°20'N; 5°35'E). The soil is a coarse sandy fluvioglacial deposit covered by a fine drift sand layer of varying depth (10–40 cm) with a weak podzolic soil formation and a forest floor that is distinct from the underlying mineral soil. The water table is at ca. 9 m. The site was planted with Scots pine (*Pinus sylvestris* L.) in 1960.

In 1985 the stand was thinned (Arnold & van Diest, 1993) after which the research started. Initial soil data are presented in Table 1. P, K, Mg and lime were applied in a 2⁴ factorial complete randomized block design (CRBD, 3 replicates). These treatments are denoted as P, K, Mg and Ca, respectively.

In a separate experiment the effect of different lime rates was investigated. Five amounts of lime (0, 3, 6, 9 and 18 Mg ha⁻¹, denoted as 0tL, 3tL, etc.) were applied, also as a CRBD with 3 replicates, accompanied by applications of P, K and Mg as in the factorial experiment. The PKMg treatment of the factorial experiment served as the 0tL treatment. The PKMg additions in the liming experiment served to bring out the effects of liming, since other nutrients would not be limiting. The applied fertilizers, rates and application dates of the factorial experiment and the 3tL level of the liming experiment are presented in Table 2. In autumn 1985, all lime treatments received 3 Mg lime ha⁻¹. Three, 6 and 9 Mg ha⁻¹ were applied to the 6tL, 9tL and 18tL treatments, respectively, in autumn 1986. Finally, 6 Mg ha⁻¹ was applied to the 18tL treatment in spring 1987. The 1986 lime applications were carried out after soil sampling, so in 1986 the liming experiment actually had only one lime level (3tL).

Table 1. Initial element concentrations in the forest floor, and in the 0–25 and 25–50 cm mineral soil segments.

Element	Soil layer		
	Forest floor (g kg ⁻¹)	0–25 cm (mg kg ⁻¹)	25–50 cm (mg kg ⁻¹)
EON ^a	—	4.6	2.3
NO ₃	—	0.0	0.0
NH ₄	—	4.0	1.1
K	—	5.8	2.1
Mg	—	1.7	0.6
pH	—	4.24	4.56
N-total	15.7	454	263
P-total	0.62	102	142
K-total	0.80	632	728
Ca-total	1.20	69	74
Mg-total	0.33	29	38
Zn-total	—	8	10

^a Extractable organic nitrogen.

Table 2. Amounts and compositions of fertilizers and lime applied in the factorial experiment and at the 3tL level of the liming experiment.

Nutrient	Amount (kg ha ⁻¹)	Fertilizer	Date of first application
P	25	Rock phosphate	autumn 1985
	25	Triple superphosphate	autumn 1985
K	100 ^a	Potassium sulphate	spring 1986
Mg	100 ^a	Kieserite	spring 1986
Ca	1200	Calcium carbonate ^b (powder, 3000 kg)	autumn 1985

^aK and Mg applications were split, with additional applications made in the springs of 1987 and 1988, to a total of 100 kg ha⁻¹ each. ^bContained 3.6% MgCO₃ (1% Mg).

The individual plot size was 22 × 25 m. Within these plots, 5-m-wide boundary zones were observed from which no soil and litter samples were taken.

Sampling and analyses

From 1986 to 1989, in autumn forest floor and mineral soil samples were collected. The forest floor was sampled by quickly forcing a 5 cm bulk density core into the soil and removing the mineral soil collected in the core. At the same point the 0-25 cm and 25-50 cm mineral soil layers were sampled with a gouge. Per plot 20 samples were collected following a grid, and pooled. Until 1989 no treatment had perceptibly influenced the forest floor mass (data not shown).

The forest floor samples were dried at 70°C in a forced-draft oven and ground; soil samples were air-dried and sieved through a 2-mm sieve. To obtain a measure of the available fractions of nutrients 3.00 g dry material was extracted with 30 mL 0.01 M CaCl₂ solution (Houba et al., 1990). This extraction procedure is of common use in agriculture in the Netherlands, but less common in forestry. In forestry in the Netherlands it is common to assess P_{total} (Anon., 1990). However, to obtain additional information on the fate of each applied compound the total contents of all major nutrients were assessed. Portions of 0.400-g (litter: 0.300-g) were digested in an H₂SO₄, salicylic acid, H₂O₂ medium, catalyzed by selenium. This digestion was devised for plant samples; the soil particles were not completely dissolved by the reagents, so for soil the term 'total analysis' cannot be applied. However, probably all N and large fractions of P were digested, because these elements are only or mainly found in organic matter.

In the extracts NH₄, NO₃, P, K, Mg and total extracted N were measured in an automated continuous-flow system: the N species colorimetrically, i.e. NH₄ by indophenol blue colouring; total dissolved N after digesting the extract with K₂S₂O₈, and oxidizing all native and produced NH₄ to NO₃; NO₃ after reduction to nitrite, followed by conversion to a red-coloured diazo compound; P colorimetrically after formation of a blue phosphomolybdenum complex. Extractable organic N was calculated as total extracted N - (NO₃+NH₄). The pH(CaCl₂) was measured with a glass electrode. P in the soil extracts was below the detection limit. In the digests N (as

NH₄) and P were measured as mentioned. In the extracts and the digests K and Ca were measured by atomic emission and Mg by atomic absorption spectrometry. In the 1989 extracts Al was measured colorimetrically.

Data analysis

For statistical tests SAS software (SAS Institute Inc., 1989) was used. The significance levels were differently chosen for the two experiments. In a 2⁴ factorial design a maximum of 15 effects are tested simultaneously. Thus, the probability of obtaining at least one P value $< \alpha$ due to coincidence is conservatively estimated as $1 - (1 - \alpha)^{15}$. At $\alpha = 0.01$ this probability (≤ 0.14) was considered acceptable. At more liberal P values too many effects would be mistaken as significant.

In the liming experiment effects with $P < 5\%$ were considered significant. For the 1986 data all liming levels were equal. For the data acquired in 1987-1989 curve-fitting was carried out, as is appropriate for describing responses to quantitative factors (Mize & Schultz, 1985). Polynomial and exponential models were tested. Polynomial models with significant linear and/or quadratic and insignificant lack-of-fit contrasts were selected. Exponential curve-fitting was carried out with Genstat's Fitcurve directive (Rothamsted Experimental Station, 1990). For each parameter and year separately, polynomial and exponential curve-fitting was carried out. The fitted polynomial model was $Y = A + Bx + Cx^2 + Dx^3$. The fitted exponential model was $Y = A + B \cdot r^x$, where r is the rate parameter, determining the shape of the curve, which, in this case, expresses the measure to which the effectiveness of further increasing lime applications declines. A and B are not given, but they roughly equal the value at the 18tL level and the difference between the control and 18tL level (in that order), respectively, as listed in the tables. Exponential models were favoured above polynomial models if the former had higher R^2 values. Thus, polynomial models with cubic contrasts were always rejected. Note the large interval between 9 and 18 Mg lime ha⁻¹, that adds uncertainty to the correct shape of fitted curves.

Three- or 4-year averages were tested by repeated measures analysis of variance (RMAOV) (Moser et al., 1990). Significant treatment effects according to RMAOV are only listed if the effects in separate years were unidirectional. RMAOV results were only deemed relevant if the test on sphericity of the covariance matrix had a P value < 0.10 .

Results and discussion

The Tables 3-11 present relevant soil analysis results of the factorial and the liming experiments. When significant main effects occurred, the data of the factorial experiment are grouped accordingly. Thus, for instance, '-P' denotes the average of the 24 plots that did not receive P. Important interactions between treatments are mentioned in the text. For all applied nutrients it should be noted that possible increases in the forest floor or mineral soil may have been caused directly, or indirectly through increased returns in root and leaf litter.

Factorial experiment

P- and lime effects. Of the four elements applied, Ca induced the widest array of effects, especially in the forest floor (Tables 3, 4). In 1986 liming had increased the

Table 3. Concentrations of CaCl_2 -extractable elements in the forest floor of the factorial experiment (mg kg^{-1} DM).

Treatment	Year			
	1986	1987	1988	1989
<i>NH₄</i>				
Control	237	189	174	193
-Ca	205	190	202	184 000 ^a
+Ca	141 ***	124 ***	107 ***	114 ***
<i>NO₃</i>				
Control	4	6	29	81
-Ca	4	8	42	36 000
+Ca	34 ***	27 ***	51	103 ***
<i>P</i>				
Control	—	129	78	75
-P	—	102	98	87 000
+P	—	141 ***	117 **	107 ***
-Ca	—	133	107	89
+Ca	—	110 *	108	105 **
<i>K</i>				
Control	—	340	209	303
-K	—	253	166	317 000
+K	—	301 *	213 ***	362
-Ca	—	316	206	364 000
+Ca	—	238 ***	173 *	315 *
<i>Mg</i>				
Control	—	177	247	238
-P	—	279	418	368 00
+P	—	264	381	340
-Ca	—	293	434	390 000
+Ca	—	250 **	365 ***	318 ***
-Mg	—	170	206	231 000
+Mg	—	373 ***	593 ***	477 ***
<i>pH</i>				
Control	4.00	3.26	3.10	3.17
-Ca	4.12	3.47	3.19	3.29 000
+Ca	6.05***	5.60***	5.27***	5.14***
<i>Al</i>				
Control	—	—	—	20
-Ca	—	—	—	17
+Ca	—	—	—	5 ***

^a Symbols following a pair of figures: ***, 000 = $P < 0.0001$, **, 00 = $P < 0.001$, *, 0 = $P < 0.01$, for ANOVA (*) and Repeated Measures Analysis of Variance (o), respectively.

RESPONSE OF A SCOTS PINE STAND TO FERTILIZATION. 1.

Table 4. Concentrations of CaCl_2 -extractable elements in 0-25 and 25-50 cm mineral soil of the factorial experiment (mg kg^{-1} air-dry soil).

Treatment	Year			
	1986	1987	1988	1989
0-25 cm				
NO_3				
Control	1.1	0.5	1.2	1.9
-Ca	1.0	0.4	1.0	1.3 ^{ooo}
+Ca	2.3 ^{***}	0.7 ^{***}	1.9 ^{***}	1.6
NH_4				
Average	3.7	1.6	1.7	1.4
K				
Control	6.6	4.6	3.2	4.6
-K	6.9	5.0	3.8	5.0 ^{ooo}
+K	10.4 [*]	8.8 [*]	6.2 ^{***}	8.8 ^{***}
Mg				
Control	2.6	1.1	1.8	1.5
-Ca	3.7	2.6	4.1	3.0 ^{oo}
+Ca	4.1	3.0	5.3 [*]	3.6
-Mg	2.6	1.7	2.4	1.9 ^{ooo}
+Mg	5.3 ^{***}	3.8 ^{***}	7.0 ^{***}	4.7 ^{***}
pH				
Control	4.15	4.34	4.24	4.27
-Ca	4.12	4.28	4.20	4.21
+Ca	4.12	4.29	4.23	4.27 ^{**}
Al				
Control	—	—	—	28.8
-Ca	—	—	—	33.0
+Ca	—	—	—	26.0 [*]
25-50 cm				
NO_3				
Control	1.1	0.3	0.8	1.9
-Ca	1.1	0.3	0.9	1.6 ^{ooo}
+Ca	2.4 ^{***}	0.7 ^{**}	1.9 ^{***}	2.0
NH_4				
Average	1.1	0.8	1.1	0.5
K				
Control	3.7	3.6	1.4	1.8
-K	3.4	2.9	1.4	2.5
+K	3.2	3.7	3.1 [*]	4.9 ^{***}
Mg				
Control	1.2	—	0.9	1.2
-Mg	2.7	—	1.0	1.2
+Mg	2.8	—	3.6 ^{***}	2.4 ^{***}
pH				
Control	4.70	4.62	4.57	4.51
-Ca	4.64	4.57	4.48	4.46
+Ca	4.63	4.56	4.50	4.51 [*]
Al				
Control	—	—	—	15.4
-Ca	—	—	—	17.9
+Ca	—	—	—	14.4 ^{***}

^a For an explanation of symbols see Table 3.

forest floor pH by ca. 2 units. In all treatments the pH of the forest floor declined in the period 1986-1988 (Table 3). The pH decline of the unlimed forest floor may indicate that soil acidification by nitrification of deposited NH_x proceeds in spite of a low pH. More likely, the 1985 thinning may have enhanced nitrification by disturbing the ecosystem (Vitousek et al., 1979). Later disturbances (windfelling and subsequent thinning in 1990) were followed by increased NO_3 concentrations in the soil solution (Arnold et al., 1993b). In autumn 1991 the forest floor pH in the Ca plots was 4.15 and that in the control plots had remained stable at 3.15 (Arnold et al., 1993a). Liming started to raise the pH of both mineral soil layers in 1988. In 1989 the increases were small, but significant (Table 4). Also in 1991 a small, but significant difference in pH (0-22 cm mineral soil) was found between the control- and Ca plots (Arnold et al., 1993a). It may be assumed that a pH gradient had developed in the 0-25 cm layer, with considerable pH increases in the top cm. Marschner and Wilczynski (1991) found a pH increase from 3.3 to 4.1 in the top 10 cm mineral soil 3 y after liming an Arenosol under Scots pine. It is frequently observed that surface application of lime does not ameliorate subsoil acidity (e.g. Kreutzer et al., 1991; McCray & Sumner, 1990), but the present sandy soil with a low buffer capacity and high permeability evidently permitted discernable pH changes below a 25-cm depth to take place after liming. It can be questioned, however, whether pH changes of this magnitude are of any biological significance. Moreover, in this pH range Scots pine would probably not respond to a small pH increase. The pH optimum for Scots pine growth has been examined by a number of authors, reviewed by Van den Burg (1981). The reported optima vary between $\text{pH}(\text{H}_2\text{O})$ 3.5 and 6.5, and the tolerated pH values between 3 and 7.8, showing that Scots pine is highly tolerant of low pH values.

The annual variations in N concentrations in the forest floor and mineral soil were considerable, especially for NO_3 (Table 3). The reason for this may be the variable circumstances, especially temperature and soil moisture content, before and during the samplings, influencing mineralization and immobilization rates. From the start of the experiment liming altered the N transformations and N distribution of the soil profile. NO_3 was significantly increased due to liming in both soil strata in 1986-1988 (Table 4) and in the forest floor in each year, except 1988 (Table 3). NH_4 was lowered by liming in the forest floor (1986-1989) and unaffected by any treatment in the mineral soil. Extractable organic N was remarkably inert to fertilization and liming in the whole profile: only in 1988, it showed a weakly significant increase in the forest floor due to liming (data not shown). It amounted to 193, 3 and 1 mg kg^{-1} in the forest floor and both mineral soil strata, respectively. The amount of inorganic N, N_i ($\text{NO}_3 + \text{NH}_4$), on an area basis (g N m^{-2}) was calculated for each soil compartment, using soil and litter dry matter data. The forest floor mass of the experimental area is about 70 Mg DM ha^{-1} and the mineral soil bulk density is ca. 1500 kg m^{-3} (Arnold et al., 1993a). In 1986-1988 the N_i pool of the forest floor was significantly lowered by liming, while in the mineral soil the reverse was true (Table 5). This can be attributed to the greater mobility of NO_3 compared to NH_4 . Only in 1986 liming increased the N_i content of the whole soil profile. In 1987 and 1988 the total amount of N_i in the profile was not affected by liming. In 1989 all effects of liming on N_i

RESPONSE OF A SCOTS PINE STAND TO FERTILIZATION. 1.

Table 5. Amounts of CaCl_2 -extractable inorganic N in the forest floor and mineral soil of the factorial experiment.

Year	Treatment	Inorganic N (g m^{-2}) per soil layer				
		forest floor	0-25 cm	25-50 cm	0-50 cm	total
1986	-Ca	1.43	1.68	0.77	2.45	3.88
	+Ca	1.20 ***	2.28 ***	1.32 ***	3.60 ***	4.80 ***
1987	-Ca	1.36	0.72	0.41	1.12	2.48
	+Ca	1.03 ***	0.87 *	0.55 *	1.42 **	2.45
1988	-Ca	1.68	1.04	0.77	1.80	3.48
	+Ca	1.09 ***	1.33 ***	1.09 ***	2.42 ***	3.51
1989	-Ca	1.51	1.05	0.84	1.89	3.40
	+Ca	1.49	1.05	0.91	1.97	3.45

*** = $P < 0.0001$, ** = $P < 0.001$, * = $P < 0.01$.

had vanished. N_i was not affected by the other treatments. It should be noted that the N_i data presented here regard *states*. In a separate experiment N mineralization *rates* were determined (Arnold et al., 1993a).

Extractable K and Mg in the forest floor were reduced by liming (Table 3). The decrease in extractable Mg by liming occurred in spite of an increased Mg_{total} concentration in the forest floor after liming (Table 6). Most likely adsorbed K and Mg were exchanged against Ca and subsequently leached, while Mg contained in the lime was not retained in the overabundant presence of Ca. Ca is known to quickly replace other cations on the exchange complex (Mochoge & Beese, 1986). Nitrate, released by nitrification in the forest floor after liming, may have promoted leaching of cations by serving as an accompanying anion. Liming, therefore, may have enhanced K- and Mg leaching from the forest floor. However, it did not markedly influence extractable K- and Mg concentrations in the mineral soil. Extractable Mg (0-25 cm) did tend to be increased by liming, but only in 1988 this effect was significant (Table 4). RMAOV indicates a significant liming effect on extractable Mg for the whole measurement period. $\text{Ca} \times \text{Mg}$ interactions for Mg_{total} and extractable Mg in the forest floor (consistent throughout the years, but significant with RMAOV only) show that the Mg-effected increase in Mg_{total} was higher when both Mg and lime were applied than when only Mg was applied, while for extractable Mg the reverse was true, indicating that kieserite dissolved at a slower rate when applied after liming. This interaction, however, did not influence Mg concentrations in the mineral soil.

The average values for P_{total} in the forest floor (Table 6) are somewhat misleading. P_{total} in the forest floor was higher only when lime and P were applied together ($\text{P} \times \text{Ca}$ interaction in 1986-1988, $P < 0.0001$). Without P application, liming had no influence on P_{total} . In 1987 extractable P in the forest floor was significantly reduced by liming, but in 1989 this effect was reversed (Table 3). The latter liming effects did not interact with P application, which may indicate that the effect of liming on extractable P mainly involved native P. It can be speculated that lime first fixed native P by precipitation and that in 1989 the decreased pH had caused this fixed P to dis-

Table 6. 'Total' concentrations of elements in the forest floor of the factorial experiment (g kg^{-1} DM).

Treatment	Year		
	1986	1987	1988
<i>N_{total}</i>			
Control	13.4	17.1	15.6
-Ca	12.3	16.7	15.9 000 ^a
+Ca	11.7	15.8 ***	14.3 ***
<i>P_{total}</i>			
Control	0.53	0.74	0.59
-P	0.47	0.66	0.59 000
+P	0.98 ***	1.07 ***	0.90 ***
-Ca	0.64	0.75	0.65 000
+Ca	0.81 ***	0.98 ***	0.84 ***
<i>K_{total}</i>			
Average	0.77	0.79	0.65
<i>Ca_{total}</i>			
Control	1.15	2.31	1.09
-Ca	1.48	2.23	1.42 000
+Ca	20.42 ***	21.88 ***	21.99 ***
<i>Mg_{total}</i>			
Control	0.35	0.31	0.31
-Ca	0.46	0.57	0.60 000
+Ca	0.77 ***	0.88 ***	0.86 ***
-Mg	0.47	0.43	0.42 000
+Mg	0.75 ***	1.02 ***	1.03 ***

^a For an explanation of symbols see Table 3.

solve again. If so, the effects of liming on extractable P apparently were too small to affect P_{total} (see below).

The implications of liming effects on P_{total} are illustrated by calculating the 1986 amounts of P_{total} in the forest floor per P and Ca combination and plotting these amounts against pH (Fig. 1). This shows that the amount of P_{total} was highest at the +P+Ca plots. The +P+Ca treatments had average additional amounts of 47, 45 and 35 kg P ha^{-1} in 1986, 1987 and 1988, respectively, relative to the -P-Ca treatments, while these amounts were only 20, 8 and 5 kg ha^{-1} for the +P-Ca treatments. Thus, adding lime and P together prevented P leaching from the forest floor. This is most likely due to a reduced dissolution, and subsequent down-wash, of the applied P fertilizers at a higher pH. A confirmation of this is the fairly good correlation of P_{total} with pH at the +P+Ca objects in 1986 (Fig. 1).

P_{total} in the mineral soil was not affected by P application or liming (Table 7), probably because the total amount of P in the mineral soil (ca. 400 kg ha^{-1}) was too large to be noticeably affected by any infiltrated amounts.

P lowered extractable Mg in the forest floor (Table 3). This was probably due to Mg exchanging against Ca contained in the P fertilizers.

Extractable Al was significantly reduced by liming in the whole sampled profile

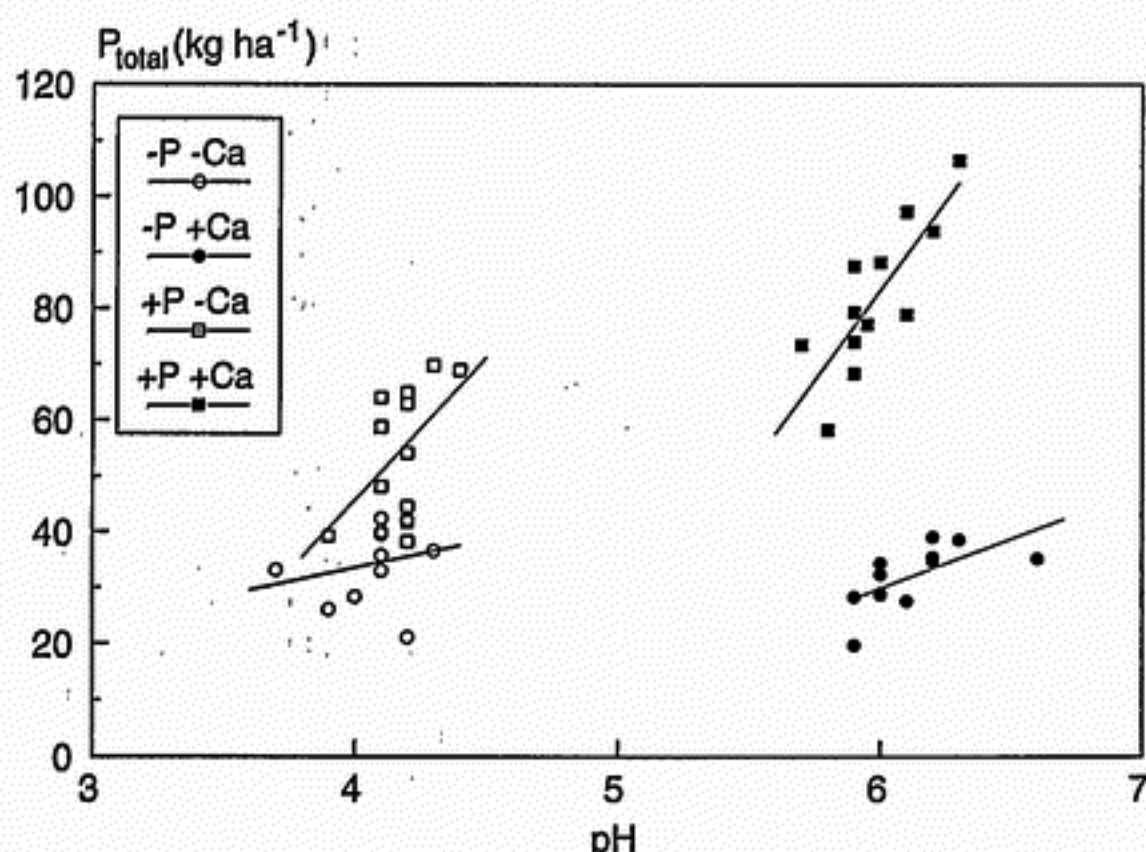


Fig. 1. The effect of P application and liming on P_{total} in the forest floor in 1986 in relation to forest floor pH.

in 1989 (Table 3). Al and pH were negatively correlated. However, in the forest floor there are no linear relationships between pH and Al at the +Ca and -Ca objects separately. In 0-25 cm and 25-50 cm mineral soil, the R^2 values for Al versus pH are 0.25 ($P < 0.002$) and 0.12 ($P < 0.05$), respectively. This may indicate that the processes influencing the amount of CaCl_2 -extractable Al change with depth. At a greater depth pH changes by liming are smaller and the amount of CaCl_2 -extractable Al is probably mainly decreased by exchange against Ca.

Effects of K- and Mg application. In the forest floor, K application initially increased extractable K, but this effect turned insignificant in 1989 (Table 3). However, any in-

Table 7. 'Total' concentrations of elements in the 0-25 and 25-50 cm mineral soil layers of the factorial experiment (g kg^{-1} air-dry soil).

Layer	Year	N_{total}	P_{total}	K_{total}	Ca_{total}
0-25	1986	0.45	0.11	0.57	0.11
	1987	0.52	0.12	0.56	0.15
	1988	0.34	0.11	0.35	0.20
25-50	1986	0.25	0.14	0.88	0.11
	1987	0.43	0.13	0.71	0.15
	1988	0.33	0.13	0.48	0.18

crease in K_{total} in the forest floor by K application was never significant (Table 6). In 1986-1988, K and Mg were applied about 6 months before sampling (Table 2). The subsequent small and insignificant increases in K_{total} in the forest floor indicate that the solubility of K_2SO_4 is too high and K^+ adsorption too low to effect a durably improved K availability in the forest floor. However, by tree uptake K was incorporated in the system's K cycle and so it remained more available than in the -K plots (Arnold et al., 1993b; Arnold & van Diest, 1993). $CaCl_2$ -extractable Mg and Mg_{total} in the forest floor remained at significantly increased levels after Mg application (Tables 3, 6), although kieserite is also highly soluble.

Unexpectedly, the amounts of K and Mg in the mineral soil were similar. In the 0-25 cm mineral soil layer extractable K and Mg were readily and persistently raised by fertilization from 1986 on (Table 4), the increases corresponding with ca. 12 kg ha^{-1} for each element, each year. In the 25-50 cm layer K and Mg were increased in 1988 and 1989 (Table 4) with ca. 8 kg ha^{-1} in both years. These amounts were rather constant in time because of the split applications until 1988 (Table 2). The lack of increase in K_{total} by K fertilization in the forest floor and the observed extractable amounts of K and Mg suggest that relatively less K than Mg was recovered by the extractions, or that K was quickly transported to deeper soil layers.

Liming experiment

The results of the liming experiment partly duplicate those of the factorial experiment. Therefore, only additional results will be discussed. The significant liming effects that were found in the factorial experiment were not always confirmed by the results of the liming experiment. This may partly be due to the statistically less efficient design of the latter.

The forest floor pH of the limed plots remained at an essentially constant elevated level over the four-year period. Only the 3tL treatment, that received lime in 1985 only, showed a gradual decrease (Table 8), as in the factorial experiment. In each year after 1986, the relationship between forest floor pH and lime rate could be described by an exponential curve. For the 1987 and 1988 data, these curves level off at ca. 6 Mg lime ha^{-1} . This indicates that at higher applications than 6 Mg ha^{-1} the lime particles reached an equilibrium with the forest floor soil solution. In 1989, the pH reached a plateau at ca. 12 Mg lime ha^{-1} . This shift of the maximum pH to higher lime applications indicates that the amount of lime determines when the forest floor pH starts to decline again. Probably a new acidification front starts from above (Kreutzer et al., 1991) and a reduced overall forest floor pH may result from lime dissolution in the top forest floor layer. It is not possible to infer lime dissolution rates from the data. Ca was probably retained by adsorption in the forest floor and, thus, may still be present in large quantities when all lime is dissolved (Kreutzer et al., 1991). The proper parameter for assessing lime dissolution, i.e. bicarbonate content, was not determined.

In 1987 and 1989 the pH of the topsoil was significantly raised by liming (Table 8). In 1987, about 6 months after completion of the highest lime application, the effect matched a sharply increasing exponential curve, but in 1989 the pH increased

RESPONSE OF A SCOTS PINE STAND TO FERTILIZATION. 1.

Table 8. Concentrations of CaCl₂-extractable elements in the forest floor and mineral soil of the liming experiment (mg kg⁻¹ DM),

	Year				Year			
	1986	1987	1988	1989	1986	1987	1988	1989
Forest floor	NH₄				NO₃			
Control ^a	170	182	181	191	3.0	9.2	54.0	39.0
3tL	119	131	128	126	37.3	14.2	37.4	83.0
6tL		102	100	86		13.3	44.3	75.3
9tL		119	111	106		12.2	48.7	73.3
18tL		77	99	105		10.3	36.0	73.3
	***	*		**	***b			
	P				K			
Control	—	133	123	99	—	336	233	412
3tL	—	133	103	114	—	246	158	311
6tL		91	85	74		226	160	248
9tL		98	95	75		179	148	244
18tL		57	55	58		197	136	219
		*		***		**		**
	Mg							
Control	—	362	610	471				
3tL	—	333	474	372				
6tL		328	491	365				
9tL		322	420	380				
18tL		290	403	264				
		**	**					
	pH				Al			
Control	4.07	3.61	3.33	3.39	—	—	—	11.8
3tL	5.80	5.59	5.37	5.06	—	—	—	4.3
6tL		5.92	5.71	5.99		—	—	5.6
9tL		6.03	5.82	6.11		—	—	2.0
18tL		6.23	6.03	6.40		—	—	4.9
	***	***	***	***				**
0-25 cm	pH				Al			
Control	4.12	4.24	4.22	4.21	—	—	—	29.8
3tL	4.19	4.31	4.25	4.32	—	—	—	27.1
6tL		4.30	4.19	4.34		—	—	17.9
9tL		4.31	4.21	4.30		—	—	25.2
18tL		4.30	4.30	4.43		—	—	14.5
		**		*				*
25-50 cm	pH				Al			
Control	4.62	4.54	4.48	4.46	—	—	—	29.8
3tL	4.63	4.58	4.55	4.52	—	—	—	27.1
6tL		4.55	4.46	4.56		—	—	17.9
9tL		4.60	4.54	4.57		—	—	25.2
18tL		4.58	4.71	4.65		—	—	14.5
		**		*				*

^a PKMg treatment. b*** = $P < 0.001$, ** = $P < 0.01$, * = $P < 0.05$.

linearly with lime rate (Table 11). In 1988 and 1989 the pH of the 25-50 cm layer was linearly related with lime level (Tables 8, 11). This shows that on poorly buffering sandy soils high lime applications may have profound effects on the pH of deeper soil horizons. However, applying lime may have several detrimental effects, i.e. loss of organic matter, increased soil heavy-metal concentrations and NO_3 leaching (Marschner and Wilczynski, 1991; Marschner et al., 1989), and thus should be carried out with caution. Presently, in the Netherlands low lime applications corresponding with $1500 \text{ kg CaCO}_3 \text{ ha}^{-1}$ are advised to prevent these deleterious effects (Anon., 1990).

Extractable NH_4 in the forest floor was significantly decreased by liming (Table 8). This effect was significant in 1986 and linear in 1987 and 1989 (Table 11). NO_3 in the forest floor and 0-25 cm mineral soil was significantly increased by liming in 1986 only. In the mineral soil liming had little influence on both N species. NO_3 in 0-25 cm and 25-50 cm mineral soil tended to be increased by liming, but the effects were not significant and not apparently related with lime level (Table 8). As a consequence, liming had little influence on the areal amounts of N_i (Table 9). In each year the amount of N_i in the forest floor was higher in the control than in the liming treat-

Table 9. Amounts of CaCl_2 -extractable inorganic N (g m^{-2}) in the forest floor and mineral soil of the liming experiment.

Year	Treatment	Forest floor	Mineral soil layer		Total
			0-25 cm	25-50 cm	
1986	Control ^a	1.19	1.50	0.88	3.57
	3tL	1.09	3.44	1.36	5.88
	6tL	0.97	2.60	1.06	4.62
	9tL	1.10	2.78	0.70	4.58
	18tL	1.14	2.66	1.35	5.15
1987	Control	1.32	0.66	0.40	2.37
	3tL	1.00	0.64	0.47	2.11
	6tL	0.79	0.65	0.41	1.84
	9tL	0.90	0.63	0.44	1.97
	18tL	0.60	0.83 * ^c	0.56	1.98
1988	Control	1.61	1.02	0.83	3.46
	3tL	1.14	1.49	1.45	4.07
	6tL	0.99	1.05	0.93	2.96
	9tL	1.09	1.12	1.02	3.23
	18tL	0.93	1.51 *	1.39 *	3.83 *
1989	Control	1.58	0.93	0.63	3.14
	3tL	1.43	1.03	1.08	3.53
	6tL	1.11	0.83	1.03	2.97
	9tL	1.23	1.20	0.88	3.31
	18tL	1.22	1.18	0.96	3.36

^a PKMg treatment; ^b* = $P < 0.05$; ^c = fits an exponential model.

ments. However, only in 1987 the effect of liming was significant with an exponential decrease in N_i with increasing lime rate. In the mineral soil, the N_i pool tended to be increased by liming, but only in 1988 the effect of liming was significant, although it could not be described by polynomial nor by exponential models. Each year, but most distinctly in 1988, the 3tL plots had relatively high amounts of N_i in the mineral soil, thus disturbing an otherwise positive linear relationship with lime rate (Table 9). The reason for this is not clear. Occasional differences in texture and leaching properties per plot, interfering with the liming effect, should also have affected the concentrations of other nutrients and, hence, are not a likely explanation for these high N_i concentrations. Neither is there a reason to assume that the trees absorbed more N at higher lime applications (Arnold & van Diest, 1993). The N_{total} concentrations in the forest floor suggest that N loss (possibly due to N mineralization) increased linearly with lime rate (Table 10, 11), and, hence, do not explain high N_i concentrations in the 3tL treatment.

Extractable P in the forest floor was linearly lowered by liming in 1987 and exponentially in 1989 (Tables 8, 11). However, the R^2 value of the latter relationship is low, so the model is not appropriate. In fact, in 1989 extractable P of the 3tL level was equal to, or even higher than that of the control. This agrees with results from the factorial experiment, where liming first lowered extractable P (at the 3tL level), after which it grew higher than that of the -Ca plots (Table 3). It can thus be concluded that retarded dissolution of applied P, that initially was fixed in the forest floor, only occurred at the lowest liming level, where the pH values gradually decreased (Tables 3, 8). P_{total} in the forest floor showed little differences between the lime treatments (Table 10). The tendency of P_{total} to decrease at the highest liming level may indicate that at that level added P precipitated in forms that were not fully

Table 10. 'Total' concentrations of N and P in the forest floor ($g\ kg^{-1}$ DM) of the liming experiment.

Treatment	Year		
	1986	1987	1988
	N_{total}		
Control ^a	11.1	16.5	16.2
3tL	9.9	15.4	13.6
6tL	15.1	13.6	
9tL	13.7	14.1	
18tL	12.1	11.4	
		***b	**
	P_{total}		
Control	0.67	0.84	0.64
3tL	0.80	1.12	1.04
6tL		1.21	1.00
9tL		1.18	0.92
18tL		0.85	0.86

^a PKMg treatment. ^b*** = $P < 0.001$, ** = $P < 0.01$.

Table 11. All curve-fitting results with R^2 values > 50% of several response parameters vs. liming rate (Mg ha^{-1}) in the liming experiment. Element dimensions are as used in previous tables.

Element	Year	Soil layer	Exponential models		Linear and polynomial models			
			R^2	r value	R^2	intercept	linear component	square component
Al	89	Ff ^a			90.6	10.8	-1.58	0.070
Al	89	0-25			68.1	28.47	-0.774	
Al	89	25-50			93.8	17.4	-1.41	0.049
C _a _{total}	87	Ff	74.8	0.905	92.9	2.83	6.37	-0.170
C _a _{total}	88	Ff	88.3	0.912	94.8	1.87	6.65	-0.169
EON ^b	87	Ff			70.4	189	-3.22	
EON	88	0-25			76.8	2.53	0.033	
K	87	Ff	74.4	0.739	83.6	330	-25.6	1.01
K	89	Ff	57.6	0.767	83.8	402	-29.7	1.093
Mg	87	Ff			78.9	353	-3.61	
Mg	88	Ff	67.2	0.791	80.9	592	-27.3	0.94
Mg	89	Ff			72.6	440	-9.73	
Mg	89	0-25			66.7	4.21	0.066	
Mg _{total}	87	Ff	91.5	0.953	93.9	0.818	0.103	
Mg _{total}	88	Ff	93.2	1.019	96.4	0.746	0.112	
NH ₄	87	Ff			77.0	158	-4.94	
NH ₄	89	Ff	74.0	0.597	84.6	182	-17.45	0.742
N _{total}	87	Ff	85.3	0.969	89.9	16.3	-0.245	
N _{total}	88	Ff	54.3	0.938	79.2	15.3	-0.216	
P	87	Ff			73.3	134	-4.35	
P	89	Ff	59.3	0.956				
pH	87	Ff	98.3	0.614				
pH	87	0-25	69.1	0.028				
pH	88	Ff	96.9	0.614				
pH	88	25-50			69.7	4.46	0.012	
pH	89	Ff	98.6	0.751				
pH	89	0-25			76.4	4.25	0.0099	
pH	89	25-50			64.6	4.48	0.0099	
P _{total}	87	Ff			64.1	0.868	0.081	-0.005
P _{total}	88	Ff	64.5	0.028				

^a Forest floor, ^b Extractable organic nitrogen.

disclosed by the applied digestion (Materials and methods section).

The concentration of extractable Al in 1989 was markedly affected by lime rate (Table 8). In each soil compartment the Al concentrations decreased linearly with lime level (Tables 8, 11). In the forest floor the correlation between pH and Al was moderate ($R^2 = 0.35$, $P < 0.05$). In 0-25 cm and 25-50 cm mineral soil, Al and pH were clearly negatively correlated ($R^2 = 0.76$, $P < 0.001$ and $R^2 = 0.51$, $P < 0.01$, respectively).

Conclusions

Variable effects of liming an acid forest soil were observed. Most of these effects were linear with lime rate and, thus, more effective with increasing lime applications. In the first place, moderate lime applications (i.e. around 3 Mg ha⁻¹) appeared to stimulate N mineralization, whereas higher applications did not cause further increases, but even tended to reduce the mineralization rate. Second, liming may affect the residence time of added P and possibly other nutrients in the forest floor after surface dressing. It was shown in the present experiment that the pH increase effected by liming may temporarily anchor P fertilizers in the forest floor, followed by a gradual release when the pH declines again. Thus, the simultaneous additions of lime and P created a relatively small, but longer-lasting increase in readily available P, which may be profitable in silviculture. Third, the effects usually expected from liming, i.e. reductions in H⁺ and Al concentrations, were observed in the forest floor. They even occurred in the subsoil, which can be attributed to the high permeability and low buffer capacity of the sandy soil.

The above-mentioned effects of liming may be advantageous. However, liming also has possible disadvantages. First, especially at high lime dosages the increase in forest floor pH is long-lasting, and a durably increased N mineralization may be expected. With such gradual N releases, the ecosystem will probably develop a profoundly modified flora (Van Dobben, 1992) and microflora (Kuyper, 1990). Second, nitrification may be harmful. Since pine trees were shown to more readily absorb NH₄ than NO₃ (Arnold, 1992), liming may be expected to result in an accumulation of soil NO₃, which may enhance NO₃ leaching.

The amount of lime to be applied should be determined by weighing the desired and unwanted effects. In the present experiment, the applied amounts were high, compared with the recommended application of 1.5 Mg lime ha⁻¹ (Anon., 1990). This amount is advised to avoid adverse effects of liming. However, when a low soil pH or high levels of soluble Al in the subsoil hamper tree performance, higher dosages on highly permeable soils may offset the induced negative effects.

Presently there are no soil analysis-based fertilizer recommendations for K and Mg for mature forests in the Netherlands. Recommendations for K and Mg fertilization are based on foliar analysis. For P a soil concentration < 87 mg P_{total} kg⁻¹ is considered deficient for *Pinus* spp. (Anon., 1990). In the present experiment soil P_{total} was higher than this value (Table 7). However, soil testing has not been practised sufficiently to serve as a sound basis for fertilizer recommendations in forestry in the Netherlands. Also in other countries it is reported that foliar analysis and field trials are commonly considered more reliable than soil information (e.g. Jokela et al., 1988). The use of foliar analysis for assessing nutrient requirements is dealt with in a subsequent paper (Arnold & van Diest, 1993).

References

- Anonymous, 1990. Final Report - Commission on Forest Fertilization Recommendations. (In Dutch). Ministry of Agriculture, (former) Department of Forestry and Landscaping, Report no. 1990-11, 63 pp.

- Arnold, G., 1992. Soil acidification as caused by the nitrogen uptake pattern of Scots pine (*Pinus sylvestris*). *Plant and Soil* 142: 41-51.
- Arnold, G., M.L. van Beusichem & A. van Diest, 1993a. Nitrogen mineralization and H^+ transfers in the forest floor and mineral soil of a Scots pine (*Pinus sylvestris* L.) forest, as measured by the ion exchange resin core technique. *Plant and Soil* (Submitted).
- Arnold, G., I.L. Sweers & A. van Diest, 1993b. Response of a Scots pine (*Pinus sylvestris*) stand to application of phosphorus, potassium, magnesium and lime. 2. Soil solution composition. *Netherlands Journal of Agricultural Science* 41: 267-289.
- Arnold, G. & A. van Diest, 1993. Response of a Scots pine (*Pinus sylvestris*) stand to application of phosphorus, potassium, magnesium and lime. 3. Foliar concentrations and stand development. *Netherlands Journal of Agricultural Science* 41: 291-307.
- Baule, H. & C. Fricker, 1967. Die Düngung von Waldbäumen. Bayerischer Landwirtschaftsverlag GmbH, München, 260 pp.
- Blank, L.W., T.M. Roberts & R.A. Skeffington, 1988. New perspectives on forest decline. *Nature* 336 (3 Nov. 1988): 27-30.
- Bredemeier, M., 1988. Forest canopy transformation of atmospheric deposition. *Water, Air and Soil Pollution* 40: 121-138.
- Dighton, J. & A.F. Harrison, 1990. Changes in phosphate status of sitka spruce plantations of increasing age, as determined by root bioassay. *Forest Ecology and Management* 31: 35-44.
- Foster, N.W., 1989. Acid deposition: what is fact, what is speculation, what is needed? *Water, Air and Soil Pollution* 48: 299-306.
- Houba, V.J.G., I. Novozamsky, Th.M. Lexmond & J.J. Van der Lee, 1990. Applicability of 0.01 M $CaCl_2$ as a single extraction solution for the assessment of the nutrient status of soils and other diagnostic purposes. *Communications in Soil Science and Plant Analysis* 21: 2281-2290.
- Hüttl, R.F., 1990. Nutrient supply and fertilizer experiments in view of N saturation. *Plant and Soil* 128: 45-58.
- Ivens, W.P.M.F., G.P.J. Draaijers & W. Bleuten, 1988. Atmospheric nitrogen deposition in a forest next to an intensively used agricultural area. In: P. Mathy (ed.): Air Pollution and Ecosystems, Proceedings International Symposium, Grenoble, France, 1987, p. 536-541. D. Reidel Publishing Company, Dordrecht, the Netherlands.
- Jokela, E.J., B. Harding & J.L. Troth, 1988. Decision-making criteria for forest fertilization in the southeast: an industrial perspective. *Southern Journal of Applied Forestry* 12: 153-160.
- Kaupenjohann, M., H. Döhler & M. Bauer, 1989. Effects of N-immissions on nutrient status and vitality of *Pinus sylvestris* near a hen house. *Plant and Soil* 113: 279-282.
- Kreutzer, K., A. Göttlein & P. Pröbstle, 1991. Dynamik und chemische Auswirkungen der Auflösung von Dolomitskalk unter Fichte (*Picea abies* [L.] Karst.). In: K. Kreutzer & A. Göttlein (eds.), Ökosystemforschung Högwald, p. 186-204. Forstwissenschaftliche Forschungen, Heft 39, 1991.
- Kuyper, Th.W., 1990. Some effects of forest fertilisation on ectomycorrhizal fungi and ectomycorrhizas: implications for tree response and nitrogen pollution. In: H. Persson (ed.), Above and Below-ground Interactions in Forest Trees in Acidified Soils. Air Pollution Research Report 32, p. 66-73.
- Marschner, B., K. Stahr & M. Renger, 1989. Potential hazards of lime applications in a damaged pine forest ecosystem in Berlin, Germany. *Water, Air and Soil Pollution* 48: 45-57.
- Marschner, B. & W. Wilczynski, 1991. The effect of liming on quantity and chemical composition of soil organic matter in a pine forest in Berlin, Germany. *Plant and Soil* 137: 229-236.
- McCray, J.M. & M.E. Sumner, 1990. Assessing and modifying Ca and Al levels in acid subsoils. *Advances in Soil Science* 14: 45-75.
- McLeod, A.R., M.R. Holland, P.J.A. Shaw, P.M. Sutherland, N.M. Darrall & R.A. Skeffington, 1990. Enhancement of nitrogen deposition to forest trees exposed to SO_2 . *Nature* 347: 277-279.
- Mize, C.W. & R.C. Schultz, 1985. Comparing treatment means correctly and appropriately. *Canadian Journal of Forest Research* 15: 1142-1148.
- Mochoge, B.O. & F. Beese, 1986. Leaching of plant nutrients from an acid forest soil after nitrogen fertilizer application. *Plant and Soil* 91: 17-29.
- Moser, E.B., A.M. Saxton & S.R. Pezeshki, 1990. Repeated measures analysis of variance: application to tree research. *Canadian Journal of Forest Research* 20: 524-535.
- Rehfuess, K.E., F. Makeschin & H. Rodenkirchen, 1991. Results and experience from amelioration trials

RESPONSE OF A SCOTS PINE STAND TO FERTILIZATION. 1.

- in Scots pine (*Pinus sylvestris*) forests of Northeastern Bavaria. *Fertilizer Research* 27: 95-105.
- Rothamsted Experimental Station, 1990. Genstat 5, Release 2.1.
- SAS Institute Inc., 1990. SAS/STAT User's Guide, Version 6, Fourth Edition. SAS Institute Inc., Cary NC.
- Sauter, U. 1991. Zeitliche Variationen des Ernährungszustands nordbayerischer Kiefernbestände. *Forstwissenschaftliches Centralblatt* 110: 13-33.
- Tamm, C.O. & L.Hallbäck, 1988. Changes in soil acidity in two forest areas with different acid deposition: 1920s to 1980s. *Ambio* 17: 56-61.
- Trümper, K.H., 1936. Vierzig Jahre Erfolgreiche Kalkanwendung in der Forstwirtschaft: eine Bodenkundliche, Waldbauliche und Wirtschaftliche Studie. Meschede, 80 pp.
- Uebel, E., 1991. Ergebnisse eines 1934 angelegten Forstdüngungsversuches unter dem Einfluß atmosphärischer NH_x -Einträge I. Ergebnisse der Bodenuntersuchung. *Kali-Briefe (Büntehof)* 20: 613-619.
- Van den Burg, J., 1981. pH and Tree Growth - a review. (In Dutch). Research Institute for Forestry and Urban Ecology 'De Dorschkamp', Report no. 282, 596 pp.
- Van den Burg, J., P.W.Evers, G.F.P.Martakis, J.P.M.Relou & D.C.van der Werf 1987. The Condition of Scots Pine (*Pinus sylvestris*) and Corsican Pine (*Pinus nigra* var. *maritima*) Stands and the Mineral Nutritional Status in the 'Peel' and 'Veluwe' Areas, Autumn 1986. (In Dutch). Research Institute for Forestry and Urban Ecology 'De Dorschkamp', Report no. 519, 66 pp.
- Van den Burg, J., 1989. Fertilization in forestry in the Netherlands. (In Dutch). *Meststoffen* 1989: 5-19.
- Van den Burg, J., 1991. Results and experiences from fertilization experiments in The Netherlands. *Fertilizer Research* 27: 107-111.
- Van Dobben, H.F., G.M. Dirkse, C.J.F. ter Braak & C.O.Tamm, 1992. Effects of Acidification, Liming and Fertilization on the Undergrowth of a Pine Forest Stand in Central Sweden. Institute for Forestry and Nature Research, Report no. 92/91, 26 pp.
- Van Grinsven, J.J.M., J.Kros, N.van Breemen, W.H.van Riemsdijk & E.van Eck 1989. Simulated response of an acid forest soil to acid deposition and mitigation measures. *Netherlands Journal of Agricultural Science* 37: 279-299.
- Velthorst, E.J. & N.van Breemen 1989. Changes in the composition of rainwater upon passage through the canopies of trees and of ground vegetation in a Dutch oak-birch forest. *Plant and Soil* 119: 81-85.
- Vitousek, P.M., J.R. Gosz, C.C. Grier, J.M. Melillo, W.A. Reiners & R.L. Todd 1979. Nitrate losses from disturbed ecosystems. *Science* 204: 469-474.
- Zöttl, H.W., 1987. Responses of forests in decline to experimental fertilization. In: T.C. Hutchinson & K.M. Meema (eds.), *Effects of Atmospheric Pollutants on Forests, Wetlands and Agricultural Ecosystems*, p. 255-265. Springer-Verlag, Berlin, Heidelberg.
- Zöttl, H.W., R.F. Hüttl, S. Fink, G.H. Tomlinson & J. Wisniewski, 1989. Nutritional disturbances and histological changes in declining forests. *Water, Air and Soil Pollution* 48: 87-109.