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Phosphorus deficiency induced by nitrogen input in Douglas fir in the Netherlands

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Summary A re-examination of earlier NPK fertilization experiments in Douglas fir stands on sandy soils shows the effects of high nitrogen input by air pollution during the last 10–15 years on plant nutrition at these sites. In 1960, experimental plots showed a positive growth reaction to nitrogen, phosphorus, and potassium fertilization. All suffered from severe phosphorus deficiency in 1984, low phosphorus in the needles was invariably accompanied by a high nitrogen content, with all N/P ratios between 20 and 30. The same conclusion emerges from an independent investigation of nutrient status of a selection of Douglas fir stands. Hence, if stand productivity and a balanced nutrient status of the trees is to be maintained, the increase in atmospheric input of nitrogen calls for supplementary fertilization. Given the current N/P ratios in the needles, a positive growth response to phosphorus fertilization is to be expected.

Introduction

Douglas fir growth on sandy soils of the northwestern European lowlands is, in addition to water shortage, often limited by the availability of macronutrients such as nitrogen and phosphorus. Nitrogen and phosphorus availability is determined mainly by the total rooted soil volume, root density, the concentration of the nutrients in the soil solution, and the rate of release from unstable organic and inorganic pools in the soil. Most of the nitrogen in the rooted soil volume occurs in an organically bound form, and is released by mineralization. In addition to mineralization of organic matter, nitrogen is added to the soil solution as ammonium or nitrate constituents of natural rain, by dry deposition of ammonia, by biological nitrogen fixation, or as a result of industrial fertilizer use. Phosphorus in the root zone can occur in many forms, in both organic and inorganic components, and is slowly released into the soil solution. The amount of nitrogen entering the system can be fairly large as a result of atmospheric deposition and the activity of nitrogen fixing micro-organisms, whereas phosphorus input other than from fertilizer use is generally negligible.

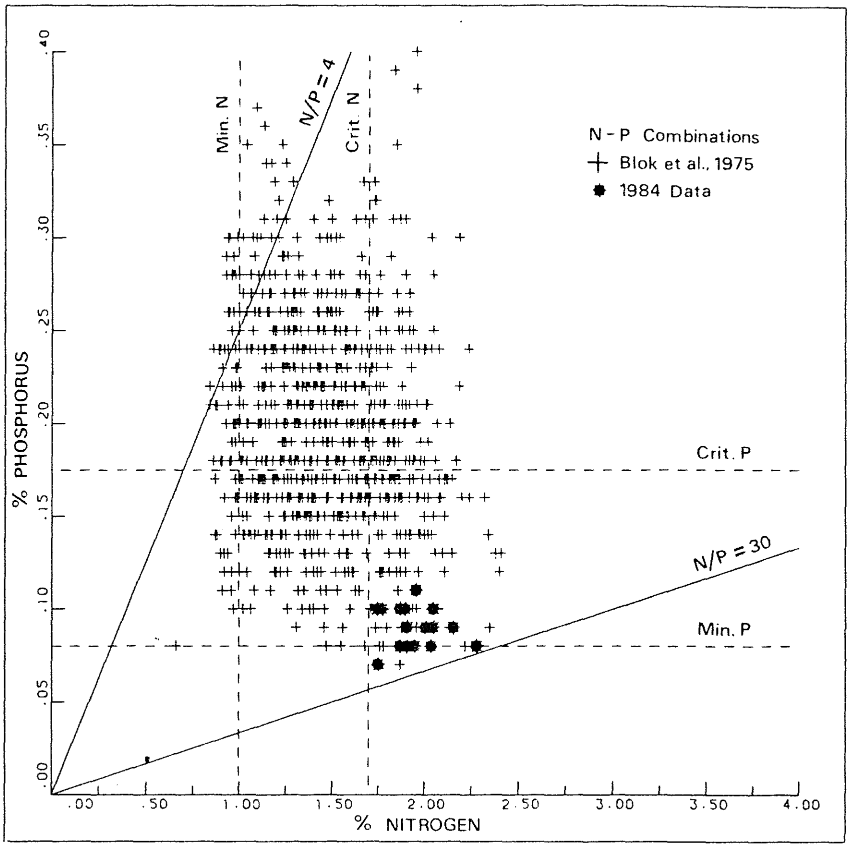

Fig. 1. Phosphorus *versus* nitrogen concentrations in the needles as determined by Blok *et al.*[2] in a large number of factorial fertilization experiments on the main sandy soil types in the Netherlands (+). The nitrogen and phosphorus concentrations in needles from the Kootwijk and Ulvenhout sites in November 1984 are also given (●).

Owing to the functional link between nitrogen and phosphorus within the plant, important interactions occur between the two[1]. Each nutrient determines the possible concentration range of the other, such that their ratio stays within fixed boundaries; *e.g.* the maximum nitrogen concentration in the needles that can occur, is determined by the supply of phosphorus. The N/P ratio of the plant tissue can be used to assess nutritional status by indicating which nutrient is relatively short in supply[4], and gives an indication of the reactions to be expected if fertilizers are applied. The possible range of N/P ratios can be determined from standard fertilization experiments, *e.g.* as reported by Blok *et al.*[2]. From their results (Figure 1) it appears that the N/P ratio in Douglas fir ranges from 4, with a relative deficiency of nitrogen, to 30 in the case of relative phosphorus deficiency. These values do not differ greatly from those for other coniferous species, or for agricultural crops[4,7,8].

Abundance of nitrogen in the soil may lead to a reduction in root growth relative to shoot growth, which can cause a reduction in phosphorus uptake relative to nitrogen uptake. Total root uptake depends strongly on phosphorus availability in the soil. The concentration of phosphorus in the soil solution depends, among others, on soil pH, and a decrease in pH can reduce phosphorus concentration by causing precipitation of Al-phosphate or Fe-phosphates. Recent research by van Breemen *et al.*[14] indicates that nitrification of ammonium and accompanying soil acidification can occur even at a pH of less than 4. Hence, the increased input of ammonium in Dutch forest soils may lead to a pH decrease, which in turn can be accompanied by a reduction of the phosphorus concentration in the soil solution.

Given the considerable increase in atmospheric deposition of nitrogenous compounds in the Netherlands in recent years (from 15–20 kg nitrogen $ha^{-1} yr^{-1}$ to a value of 50 kg nitrogen $ha^{-1} yr^{-1}$ or more[13]) it is important to monitor the nutritional status of otherwise unfertilized coniferous forests, in order to detect any nutrient imbalances and subsequent changes in stand growth as soon as possible. If, on previously nitrogen-poor sites, nitrogen shortage is removed, tissue nitrogen and tree growth may increase to limits imposed by the availability of some other element. This suggests that, in the case of Douglas fir in the Netherlands, phosphorus concentrations may decrease, since positive reaction to phosphorus fertilization has already been observed in many experiments in the Netherlands[2,10,15,18] and in Germany[3,12].

A tree's nutrient status is best examined by foliar analysis. Considerable variation in tissue concentrations of nutrients can occur as a result of differences in the time of sampling, between trees, within the tree itself, and between foliage of different age classes[11]. Thus careful and consistent sampling is required. Current practice in the Netherlands consists of sampling during the dormant season, and use of current (½ year old) needles from the upper part of the crown[16]. Foliar analysis can involve comparing nutrient concentrations in the foliage with literature data on critical levels below which growth reduction can be expected, and examining nutrient ratios to detect any imbalances. Table 1 gives minimum, critical and sufficient levels of nitrogen and phosphorus for Douglas fir, based on available published data[2,5,17].

Table 1. Indicative values of nitrogen and phosphorus concentrations for assessing nutrient status of Douglas fir needles. Critical levels in % of needle dry matter are defined as the concentration below which growth is reduced by more than 10%[1]. Data from Blok *et al.*[2], Mead[5], and Van den Burg[17]

	Minimum level	Critical level	Sufficient
Nitrogen	0.8–1.2	1.7	1.7–2.5
Phosphorus	0.06–0.10	0.15–0.20	0.20–0.30

Experimental data

In the second half of the fifties, a large number of fertilization experiments in Douglas fir were carried out in the Netherlands by Blok *et al.*[2]. Of the field plots used in their study, two experimental sites with plots which received various combinations of nitrogen, phosphorus and potassium fertilizer, still exist up to date. The sites are located near the townships of Kootwijk and Ulvenhout. In these experiments the nitrogen and mineral concentrations in the needles, as well as the growth response to fertilization were measured at the end of the fifties and at the beginning of the sixties. The two sites were re-sampled after 25 years in November 1984 to study possible changes. A summary of the foliar analysis carried out in the re-sampled fertilization plots is presented in Table 2, together with the data from 1957, 1958, 1959 and 1960.

The 'Kootwijk' site consists of former heathland on a dry humus podzol soil in red cover sand, afforested in 1954 with 4-year-old Douglas fir. pH-KCl of the uppermost soil layer (0–25 cm) was 4.1, total nitrogen was 0.1% of soil dry weight, and total phosphorus amounted to 18 mg P/100 g soil. The phosphorus content of the soil at this site was considered sufficient for Douglas fir growth[2]. Phosphorus fertilization consisted of 35 kg phosphorus ha^{-1}, applied as basic slag at the beginning of 1956. At the end of 1956, needles on the phosphorus fertilized plots contained 1.06% N, 0.24% P and 0.64% K. These figures differed only slightly from the concentrations in the unfertilized plots (O) where the needles contained 0.98% N, 0.20% P, and 0.64% K. Nitrogen and potassium fertilization was carried out in the beginning of 1957 using 100 kg nitrogen in the form of calcium ammonium nitrate in the first treatment (N), 66 kg potassium as muriate of potash in the second treatment (K), and 100 kg nitrogen combined with 66 kg potassium in the third treatment (NK, all quantities per hectare). Calcium content of the needles in 1957 varied between 0.3 and 0.4%, and had decreased to a value of 0.2–0.3% in 1984. Calcium is not included in Table 2 as only data from 1957 and 1984 were available, and because calcium did not show any significant correlation with treatment.

The 'Ulvenhout' site also consists of a humus podzol in cover sand, formerly occupied by a stand of Scots pine mixed with red oak. The site was planted in 1952 with 3-year-old Douglas fir. pH-KCl in 1956 of the upper soil layer (0–25 cm) was 3.4, total nitrogen was 0.1% of soil dry weight, and total phosphorus in the same layer amounted to 9 mg P/100 g soil. According to Van Goor[18] this value is too low for Douglas fir. The treatments were carried out in May 1958 and consisted of the following amounts per hectare:

P : 40 kg P as superphosphate;
PK : 40 kg P as superphosphate and 47 kg K as sulphate of potassium;
n2 : 150 kg N as calcium ammonium nitrate given as 15 g per tree;
n2P : 150 kg N as calcium ammonium nitrate given as 15 g per tree, together with 40 kg P as superphosphate;
n2K : 150 kg N as calcium ammonium nitrate given as 15 g per tree, together with 47 kg K as sulphate of potassium;
n1PK : 75 kg N as calcium ammonium nitrate given as 7.5 g per tree, together with 40 kg P as superphosphate, and 47 kg K as sulphate of potassium;
n2PK : 150 kg N as calcium ammonium nitrate given as 15 g per tree, together with 40 kg P as superphosphate, and 47 kg K as sulphate of potassium;

Table 2. Nitrogen and phosphorus concentrations of current needles from 2 fertilizer experiments, 1, 2, and 28 respectively 27 years after fertilizer application. 1957, 1958, 1959 and 1960 data taken from Blok *et al.*[2]. See text for a description of the fertilizer treatments

Kootwijk

	Nitrogen			Phosphorus			N/P ratio		
Treatment	'57	'58	'84	'57	'58	'84	'57	'58	'84
O	1.04	0.91	2.01	0.12	0.11	0.09	9	8	22
N	1.46	1.02	1.96	0.10	0.10	0.11	15	10	18
K	1.31	1.15	1.91	0.15	0.14	0.09	9	8	21
NK	1.71	1.20	1.76	0.10	0.13	0.10	17	9	18
P	1.01	0.98	1.76	0.19	0.17	0.10	5	6	18
PN	1.54	1.03	1.87	0.13	0.14	0.10	12	7	19
PK	1.41	1.53	1.88	0.22	0.23	0.10	6	7	19
PNK	1.68	1.41	2.16	0.15	0.17	0.09	11	8	24

Ulvenhout

	Nitrogen			Phosphorus			N/P ratio		
	'59	'60	'84	'59	'60	'84	'59	'60	'84
O	1.56	1.47	1.75	0.09	0.08	0.07	17	18	25
n2	1.91	1.55	1.91	0.08	0.08	0.08	24	19	24
n2K	1.88	1.68	1.95	0.09	0.08	0.08	21	19	24
P	1.26	1.28	1.87	0.16	0.16	0.08	8	8	23
PK	1.25	1.32	2.04	0.15	0.15	0.08	8	9	26
n2P	1.32	1.25	1.77	0.16	0.13	0.10	8	10	18
n1PK	1.32	1.24	2.05	0.14	0.17	0.09	9	7	23
n2PK	1.35	1.22	1.90	0.13	0.12	0.10	10	10	19
N1PK	1.37	1.35	2.05	0.17	0.15	0.10	8	9	21
N2PK	1.22	1.23	2.28	0.13	0.14	0.08	9	9	29

N1PK : 75 kg N as calcium ammonium nitrate, together with 40 kg P as superphosphate, and 47 kg K as sulphate of potassium;
N2PK : 150 kg N as calcium ammonium nitrate, together with 40 kg P as superphosphate, and 47 kg K as sulphate of potassium.

Discussion

Kootwijk

Blok *et al.*[2] evaluated the effects of the fertilization treatments by measuring leader shoot growth in 1957, 1958 and 1959. They concluded that phosphorus fertilization alone did not result in a significant increase in growth, but that the use of combinations of phosphorus with nitrogen, potassium or both, did so. In general the data from before 1960 reveal a clear response to nitrogen and potassium fertilization. N/P ratios were low to average in this period, with a considerable increase in 1957 in the case of nitrogen fertilization in the absence of phosphorus. Thus, the Kootwijk site showed a relative nitrogen deficiency at the time that the fertilization experiments were laid out.

In 1984 the situation was completely different: the foliage contained a sufficient amount of nitrogen, whereas phosphorus was diluted to its minimum value. There were no longer any consistent differences between the treatments. Although the stand did not show any visual deficiency symptoms as *e.g.* described by van Goor[18], it must be concluded from the tissue concentrations measured that a relative phosphorus deficiency has developed since 1958 in all treatments, and that at the same time nitrogen concentrations have increased, even in the plots which had already received nitrogen fertilization in 1956. With regards to Douglas fir growth, the site apparently moved from a relative nitrogen deficient situation to a relative phosphorus deficient situation. This is clearly reflected in the N/P ratios given in Table 2.

There are two explanations for this: either phosphorus availability has declined or nitrogen supply has increased. The phosphorus supply for stand growth can decrease as a result of leaching of phosphorus out of the root zone by drainage, as a result of the cumulative effect of phosphorus uptake and subsequent incorporation in the biomass by the vegetation, and due to fixation of available phosphorus in an unaccessible form in the soil.

Leaching of phosphorus in acid, podzolic soils as in Kootwijk is in general negligible. The amount of phosphorus incorporated in the living biomass over the period between measurements is small as only the accumulating stemwood must be considered, and stemwood contains only a very small fraction of phosphorus. Phosphorus incorporated in needle tissue, which makes up the majority of the phosphorus in the living biomass, is continuously returned to the soil compartment with litter loss and decomposition. Increased fixation of phosphorus in the soil due to a decrease in pH did not occur either in Kootwijk, as soil pH did not change over the period under consideration. This means that phosphorus availability in the plots which received no phosphorus fertilization probably remained about the same, and that the change from relative nitrogen to relative phosphorus deficiency must be related to a change in nitrogen availability. Taking into account the considerable increase in atmospheric nitrogen input in recent years[13], this therefore leads to the conclusion that the corresponding increase in nitrogen availability has resulted in the development of phosphorus deficiency.

Ulvenhout

On this site, phosphorus fertilization in 1958 resulted in increased height growth in the same year as the fertilizer application. This effect lasted for several years, and was still visible in 1966 when a total volume increment up to three times the amount in the zero treatment was measured[2]. The effect of phosphorus fertilization on foliar phosphorus content is clear from the data in Table 2. Fertilization with phosphorus, or phosphorus in combination with potassium, tended to decrease foliar nitrogen content as a result of dilution due to increased growth, and therefore combined NPK fertilization gave the best overall results. In contrast to the Kootwijk site, Ulvenhout thus showed a clear response to phosphorus fertilization. At the time of fertilization in 1958, nitrogen apparently hardly limited growth, as can be seen from the nitrogen concentrations in the zero treatment. Combined with low phosphorus availability, this resulted in high N/P ratios in all plots without phosphorus fertilization. From this it can be concluded that the site showed a relative phosphorus deficiency in 1959 and 1960. Phosphorus fertilization alone or in combination with potassium led to moderate nitrogen deficiency and low N/P ratios, suggesting low availability of both nitrogen and phosphorus, with phosphorus having the more pronounced effect in the zero treatment. Combined NPK treatments gave acceptable N/P ratios immediately following fertilizer application, and resulted in the best growth response.

As at Kootwijk, also at Ulvenhout the phosphorus concentrations were very low in the 1984 sampling, whereas nitrogen content was equally high, with the N/P ratios comparable to the zero phosphorus treatment of 1958. Apparently, the fertilizer phosphorus was exhausted and nitrogen was again abundantly available, resulting in a comparable nutrient imbalance as in Kootwijk. Again, no differences remained between the plots but all showed high nitrogen and low phosphorus, with none of the plots displaying any visual symptoms of phosphorus deficiency. However, compared to the Kootwijk site, no conclusions can be drawn from the Ulvenhout data with regards to any presumed change in nitrogen availability, as any effect of the latter will have been blurred by the relative phosphorus deficiency which occurred already at the time of the first sampling in 1959. The considerable increase in N/P ratio of the plots which received phosphorus fertilization can either be the result of the declined availability of the phosphorus fertilizer, or of an increase in nitrogen availability due to atmospheric input. Both effects are plausible, but cannot be distinguished from the present data alone. The only indication of an effect of increased atmospheric deposition of nitrogen is in the zero treatment, were nitrogen content of the needles has increased.

Considering the Ulvenhout data together with the Kootwijk results however, shows that a relative phosphorus deficiency has developed over time on a site which originally exhibited a relative nitrogen deficiency (Kootwijk), that is indistinguishable from a phosphorus deficiency caused by obvious soil phosphorus limitations (Ulvenhout).

Additional data

The same phenomena as described above for the 1984 results, were also found in an independent investigation of a selection of Douglas fir stands in the Netherlands[6,17]. Two *ca.* 40 year-old Douglas fir stands on humus podzol soils, both showing signs of declining vitality (yellowish needles and increasing crown transparency, respectively), were investigated on behalf of local forestry authorities. Both stands had been fertilized at establishment, with 30–40 kg phosphorus per hectare. In the 'Staphorst' stand (pH–KCl = 3.3; total phosphorus = 7.5 gP/100 g soil in top 0–25 cm layer) the needles had a nitrogen content of 2.18% and a phosphorus content of 0.095%, giving an N/P ratio of 23. In the other stand, located near 'De Rips', the needles had a nitrogen concentration of 1.88% and a phosphorus concentration of 0.085% (N/P ratio of 22).

An accompanying survey of needle composition and soil chemical factors was carried out in eight Douglas fir stands of about 30 years old, all containing both apparently healthy and less healthy trees (separated on the basis of crown transparency). In the stands, pH–KCl of the top soil layer (0–25 cm) varied between 3.1 and 4.0, and the total phosphorus content of the top soil ranged from 8 gP/100 g soil to 24 gP/100 g soil. Irrespective of the phosphorus content of the soil, N/P ratios varied from 20 to 24, mean values being 20.4 for the healthy trees (1.94% N and 0.095% P in the needles), and 23.4 for the less vigorous trees (2.06% N and 0.088% P). Thus all stands showed a relative phosphorus deficiency, and taking into account the variation in soil phosphorus encountered in these stands, abundant nitrogen as a result of high atmospheric nitrogen input, more likely than phosphorus availability is the main cause. The nitrogen content of 1½ year-old needles was somewhat higher than that of current year needles, indicating that nitrogen content of the needles still increases after the first growing season.

Conclusions

From the data shown in Table 2 it is evident that in 1984 severe phosphorus deficiencies occur in both fertilization trials. In contrast to the situation 25 years ago, at both experimental sites and in all treatments, a high nitrogen content is combined with a low phosphorus content, resulting in N/P ratios of 20 to 30. With respect to the current situation, the same can be concluded from the additional surveys carried out recently in a range of Douglas fir stands. Considering the change in N/P ratios in the Kootwijk plots, which illustrates a shift from relative nitrogen deficiency to relative phosphorus deficiency, and with phosphorus availability remaining the same, it must be concluded that the reported change in atmospheric nitrogen input and subsequent increased nitrogen availability has resulted in the development of phosphorus deficiency.

On sites with larger pools of phosphorus in the soil, *e.g.* as a result of heavy phosphorus fertilization at stand establishment or during previous agricultural land use, it is possible that mechanisms of this type also cause other deficiencies, *e.g.* in magnesium or potassium[9].

The development of deficiencies in nutritional elements which are not externally supplied to the soil-plant system, or which are not potentially available in unweathered parent soil material, calls for some kind of supplementary fertilization if a balanced forest stand nutrition and stand productivity is to be maintained. In the case of phosphorus shortage this is a particularly attractive option in forestry, since phosphorus export through leaching or volatilization is virtually absent, and because the disadvantage of a low annual recovery from phosphorus fertilizer is less important in a perennial crop with large internal recycling of nutrients as in case of trees. Therefore, given the nitrogen and phosphorus concentrations and ratios reported in this paper, a positive growth response to phosphorus fertilization can be expected. This conclusion holds for a range of sites typically used for Douglas fir forestry in the Netherlands. Given the high atmospheric nitrogen input, it is an important management option for sites where the main emphasis lies in stand vigour and wood production. The latter is the case in the majority of the forested area in the Netherlands.

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