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Effect of dolomite lime and wood ash on peat substrate and development of tree seedlings

Risto Rikala & Helen J. Jozefek

TIIVISTELMÄ: DOLOMIITTIKALKIN JA PUUN TUHKAN VAIKUTUS KASVUTURPEESEEN JA TAIMIEN KEHITTYMISEEN

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Effect of dolomite lime and wood ash (0, 0.5, 1, 2, 4, 8 and 16 kg m^{-3}) on the chemical composition of low humified Sphagnum peat was studied. Germination of Scots pine, Norway spruce and silver birch and the subsequent growth of these seedlings were investigated in a greenhouse experiment. Nutrient concentrations in shoots and roots of pine seedlings were also analyzed. The pH of peat increased asymptotically from 3.8 to about 7.0 with increasing lime regimen and to about 8.0 with increasing ash regimen. Wood ash linearly increased electrical conductivity and P, K, and Ca concentrations of peat. Rate of germination, within 7 days, of pine and spruce was best at low pH (<5) while birch seeds had a slightly higher pH optimum (4–6). Germination capacity, within 21 days, was not affected by pH or application regimen of either lime or ash. Pine and spruce seedlings grew best with lime and ash doses of 0.5–2.0 kg m^{-3}, the pH of peat being 4–5. Lime and ash treatments did not affect the growth of birch seedlings, but wood ash increased nutrient concentrations of pine seedlings.

Kasvihuonekokeessa tutkittiin dolomiittikalkin ja puuntuhkan (0, 0.5, 1, 2, 4, 8 and 16 kg m^{-3}) vaikutusta vaalean rahkaturpeen kemiallisiin ominaisuuksiin sekä männyn, kuusen ja rauduskoivun siementen itämiseen ja taimien kasvuun. Lisäksi määritettiin männyn taimien ravinnepitoisuudet. Kalkkimäärän lisääntyessä rahkaturpeen pH kohosi 3,8:sta asymptoottisesti lähelle pH 7:ää ja puuntuhkalla pH 8:aa. Tuhka nosti voimakkaasti myös turpeen johtolukua ja P-, K- ja Ca-pitoisuuksia. Männyn ja kuusen siementen itämistarmo (7 vrk) oli suurimmillaan kun kasvualustan pH oli alle 5, kun taas koivun siemenet itivät parhaiten pH-alueella 4–6. Itämiskykyyn (21 vrk) ei kasvualustan happamuudella eikä kalkki- ja tuhkakäsittelyillä ollut vaikutusta. Männyn ja kuusen taimet kasvoivat parhaiten 0,5–2,0 kg m^{-3} tuhka- ja kalkkilisäyksillä pH:n ollessa 4–5 kun taas koivun kasvuun niillä ei ollut juuri vaikutusta. Tuhka kohotti selvästi männyntaimien ravinnepitoisuuksia.

Keywords: *Pinus sylvestris*, *Picea abies*, *Betula pendula*, nutrients, pH, electrical conductivity, dry weight, height, germination, Sphagnum peat.
ODC 232.4 + 237

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1. Introduction

Soil acidity has a pronounced effect on soil processes and on plant roots. Direct effects of acidity (pH < 3.0) on plants are the impairment of cell membranes and the outward diffusion of ions, especially K+ ions (Mengel and Kirkby 1982). Many effects of acidity are, however, indirect, for example the occurrence and activity of soil micro-organisms, which in turn affect the nitrification (Evers 1963) and availability (van den Driessche 1978) of NO_3-N and NH_4-N as well as the availability and uptake rate of other plant nutrients (Lucas and Davies 1961).

Hydrogen-saturated organic soil usually has a pH of about 3.0 and calcium-saturated soil has a pH of 7.2–7.8 (Lucas and Davies 1961). The natural pH of low humified Sphagnum peat is 3.5–4.0. The most common way to neutralize acids in peat is by liming. The amount of lime to be applied depends on the required rise in pH and on the present cation exchange capacity, plus the type and decomposition grade of the peat (Puustjärvi 1978, 1987). Furthermore, when lime is applied the neutralizing value of the liming material should be taken into consideration, for example, calcium oxide is twice as powerful a liming material weight for weight as calcium carbonate (Mengel and Kirkby 1982).

Wood ash is alkaline and its neutralizing capacity is comparable to that of calcium oxide (Puustjärvi 1981b). In addition, wood ash contains many nutrients (e.g. Hakkila 1989), and it has been long known that the growth of forest trees on peatlands is increased after fertilization with wood ash (e.g. Lukkala 1951, Silfverberg and Huikari 1985).

There are many opinions as to the importance of soil acidity (pH) in seedling nutrition (e.g. Landis 1989). In general, to produce a good commercial nursery crop, a soil pH value of 5.0–6.0 for conifers and 6.0–7.0 for hardwood species is considered desirable (Tinus and McDonald 1979, Landis 1989). Lower pH values (4.5–5.0) in the growth medium have also been recommended for conifers (e.g. Brix and van den Driessche 1974).

Low humified Sphagnum peat (H 1–3, v. Post) is virtually the only medium used for growing containerized tree seedlings in Finland. In horticulture, at one time the recommendations for addition of lime to peat were 8–10 kg per cubic metre of low humified peat (Puustjärvi 1973); however, this recommended rate was later decreased to 6–8 kg m^{-3} (Puustjärvi 1982). In the beginning of the 1960's when low humified Sphagnum peat was being used as the growing medium for forest tree seedlings, it was recommended that 8.0 kg of dolomite lime be added for every m^3 of peat used (Lehto and Simolinna 1966). In the 1970's peat producers decreased the amount of dolomite lime to 5–6 kg m^{-3} and later decreased it still further to 2–3 kg m^{-3} peat.

In recent years emphasis has been placed on the role and utilization of waste wood-ash in forests (Hakkila and Kalaja 1983, Haveraaen 1986) and also on its use as a fertilizing and neutralizing agent in nursery peat (Rikala 1986). No recommendations for adding wood ash to neutralize acid peat in nursery seedling production have been presented previously in literature. It is only known that an excess of wood ash inhibits germination of tree seeds and causes root deformation in germlings (Heikinheimo 1915).

The aims of this study were 1) to determine the effects of dolomite lime and wood ash on peat substrate, especially their effects on pH and electrical conductivity, and 2) to find the optimum pH for growing pine, spruce and birch seedlings in low humified Sphagnum peat.

This study was part of a research program of the Department of Silviculture in the Finnish Forest Research Institute. We thank Dr Hannu Raitio and Dr Heikki Smolander for comments on the manuscript, Ms Ritva Pitkänen for technical assistance, and Dr Joann von Weissenberg for checking the English language of this paper.

2. Materials and methods

21. Experimentation and growing conditions

The experiments were carried out during March through June for two successive years (1982 and 1983), and were conducted in a controlled greenhouse at Suonenjoki Research Station (62° 40'N, 27° 03'E). Temperature was regulated at 20 °C during the day and 15 °C at night, using an ITU-automatic ventilation system (Itumic Oy, Finland). Actual temperatures and relative air humidity in the greenhouse were measured by a Fuess thermohygrograph. Because of climatic conditions, the greenhouse temperatures could not be held constant, and diurnal temperatures varied from 16 °C to 26 °C. Relative humidity inside the greenhouse also varied, being on average 44% during the day and 74% at night. A 16-hour photoperiod was provided by Osram Power Star HQI-T 400W/DH mercury-halogen lamps, which produced a photon flux density of about 120 μE m^{-2} s^{-1} at seedling level. During the daylight hours, natural light increased the illumination threefold.

The peat substrate used in the experiments was unfertilized and unlimed, low humified, medium-coarse Sphagnum peat (VAPO B0, Finland), degree of decomposition 2–3 (v.Post). The chemical (Kurki 1982) and physical properties (Puustjärvi 1969) of the peat (analyzed by Viljavuuspalvelu Oy, Soil Analysis Service Ltd.) were:

electrical conductivity	1.0	(10xmS/cm)
pH	3.8	
total N	0.84	%
soluble S	9.3	mg l^{-1}
exangeable Ca	375	mg l^{-1}
exangeable K	15	mg l^{-1}
soluble P	7.0	mg l^{-1}
water soluble B	0.2	mg l^{-1}
acid soluble Cu	1.2	mg l^{-1}
acid soluble Fe	0.17	mg l^{-1}
acid soluble Zn	2.1	mg l^{-1}

The bulk density of peat was 85 g l^{-1}, solid density 1.42 g l^{-1}, total porosity 94%, water capacity 72.5% and air capacity 21.5%.

The acidity levels (treatments) were established by adding various amounts of dolomite lime or wood ash to the substrate before potting. The amounts added were 0.0, 0.5, 1.0, 2.0, 4.0, and 16.0 kg m^{-3}. Lime and ash were mixed into the peat substrate separately for each growing pot.

The dolomite limestone (Paraisten kalkki 2, Finland) used in these experiments contains neutralizing calcium and magnesium calculated as 33%, of which at least 7% is magnesium. More than 98% of the lime powder penetrates a 2 mm ø sieve and more than 50% of the powder penetrates a 0.15 mm ø sieve. The ash used was fly ash from bark and wood residues burned at the Heinola Mills branch of the Enso-Gutzeit company. Total nutrient concentration of the ash was as follows (g kg^{-1}): Ca 239, K 59.5, P 14.4, S 28.3, Mg 25.6, Cl 19.0, Fe 14.9, Mn 14.1, Na 7.2, and (mg kg^{-1}): Zn 1230, Cu 839, Cr 820, B 358, Mo 104, Co 47. Macro nutrient content was fairly high compared to the content range in ash residue from bark-fired power plants in Finland (Hakkila 1989). The values of copper and chromium were high, indicating that the burned wood must have contained impregnated wood. The concentration of boron was also rather high.

The growth medium was watered thoroughly at the time of preparation, and one week after watering 25 seeds of Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst) and silver birch (*Betula pendula* Roth.) were sown into 1-litre plastic pots. Seed origins were from Central Finland. Approximately 4 weeks after sowing, the seedlings were thinned to 10 seedlings per pot. In addition, after 2 more weeks birch was thinned again to 5 seedlings per pot. In 1982 seedlings of pine, spruce and birch were replicated in 4 pots/treatment, while in 1983 only pine seedlings were grown. These were replicated in 3 pots/ treatment.

In both experiments seedlings were given fertilizer top-dressings of 0.1% nutrient solution (Kekkilä 9 Superex, Finland; N 19%, P 5%, K 20% + micronutrients) at a dosage of 2 l m^{-2} twice a week. Total amounts of top-fertilizer given in 1982 and 1983 were 54 g m^{-2} (10.3 g N m^{-2}) and 76 g m^{-2} (14.4 g N m^{-2}) respectively. The need for watering the pots was determined by weighing them once a week and keeping them at a target weight corresponding to an optimum water content of 45 % (vol.).

22. Measurements

Substrate

In pilot studies the effect of dolomite lime in the soil appeared in one week. At the beginning of the experiments, three samples of substrate mixtures were taken and water was added until a water content of 50% (vol.) was reached. After one week, fresh peat samples were mixed with distilled water (1:2.5), and after a further 24 hours the pH (Schott Geräte CG819-meter) and electrical conductivity (Philips Laboratory Conductivity Meter PW9501) of these suspensions were measured.

At the end of the study period in 1982, peat from the treatment pots was dried in an oven at a constant temperature of 50 °C for 48 hours. Electrical conductivity and pH were measured from a sample suspension in distilled water (1:2.5). Exchangeable calcium, potassium and soluble phosphorus were analyzed from the extract of acidic (pH 4.65) ammonium acetate (Vuorinen and Mäkitie 1955). Soluble nitrogen was determined by distillating the 0.2-N K_2SO_4 extract from the peat sample with NaOH and Dewarda's alloy and subsequently titrating the ammonia released into boric acid. The peat samples were analyzed by Viljavuuspalvelu Oy (Soil Analysis Service Ltd.).

Seedlings

In both years, the number of germinating seeds was counted 7 and 21 days after sowing. After the study periods (17 weeks in 1982 and 14 weeks in 1983) seedlings were gently removed from the peat substrate. Height (mm), root collar diameter (0.01 mm), length of needles/leaves (mm), and length of longest root (cm) were then measured. The number of root tips (1982: > 10 mm, 1983: > 5 mm) was also counted.

Furthermore, in 1983 the total concentrations of nitrogen, phosphorus, potassium, calcium, magnesium, manganese, copper, boron, zinc and iron in both the shoots and roots of pine seedlings were analyzed. These analyses were carried out at the Parkano Research Station of the Finnish Forest Research Institute, using the methods described by Halonen et al. (1983).

23. Statistical analysis

Differences in germination, height, diameter and dry weights of seedlings between liming agents (dolomite lime and wood ash) and application doses were tested by two-way analysis of variance (BMDP). Before the analysis germination data were arcsin transformed. Means were compared for significant differences by Tukey's test. To estimate relationships between application doses and soil reaction, and between pH and total dry weight of seedlings, regression analyses were conducted.

3. Results

31. Effect of lime and wood ash on the chemical composition of peat substrate

One week after the experiment was established, the pH of the peat substrate increased asymptotically from 3.8 to about 7.0 with increasing lime and to about 8.0 with increasing ash (Fig. 1). In 1983 the pH levels were about half a pH-unit lower than in 1982 in both treatment groups. Electrical conductivity (EC) (Fig. 1) showed a slightly concave relationship to ash dosage. For dolomite lime, during both years EC remained fairly constant at all treatment levels. The measurements of pH and EC made at the end of the study period were similar to those presented in Fig. 3, with the exception that the EC of peat in pots containing birch seedlings decreased by about 30 % compared to pine and spruce.

The highest dosages of lime and ash significantly ($p<0.001$) increased the concentration of soluble nitrogen in peat (Fig. 2). Soluble phosphorus and exchangeable potassium remained fairly constant in dolomite lime treatment groups, while the concentrations of these elements increased linearly with increasing ash dosage. In both lime and ash treatments the concentrations of exchangeable calcium increased linearly with increasing treatment level.

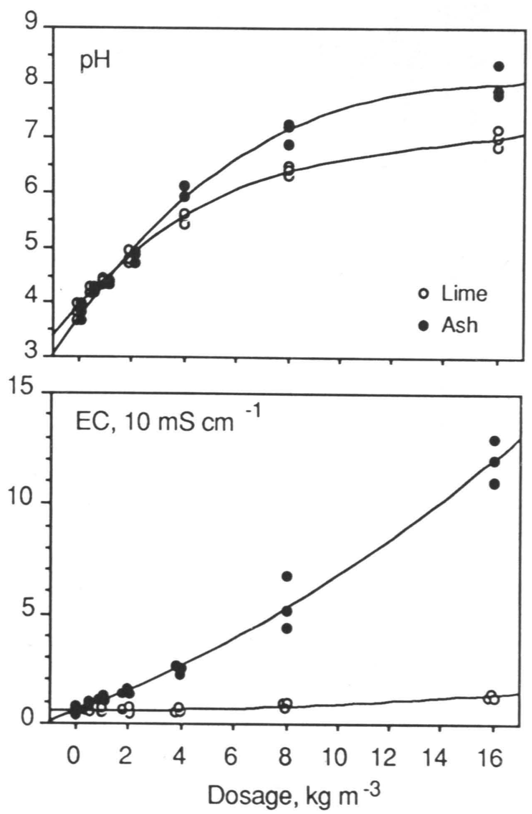

Fig. 1. Acidity (pH) and electrical conductivity (EC) of the peat substrates by application regimen of lime (open dots) and ash (closed dots) one week after mixing in 1982 experiments. One dot is a value of a pooled sample for each tree species.
pH, lime $y=3.949+0.5247x-0.0388x^2+0{,}00081x^3$; $R^2=0.991$
ash $y=3.735+0.6709x-0.0355x^2+0.00064x^3$; $R^2=0.988$
EC, lime $y=0.5618+0.005060x+0.002757x^2$; $R^2=0.901$
ash $y=0.5697+0.45610x+0.016264x^2$; $R^2=0.983$

32. Germination and growth of seedlings

No significant differences were detected in the capacity or rate of germination between liming agents in any of the tree species studied. Therefore in the figures the values obtained for both ash and lime were combined. The germination capacities (21 days) of pine, spruce and birch seeds were 92 %, 66 % and 79 %, respectively. Furthermore, there were no significant differences between applications (Fig. 3).

The rate of germination (7 days) of pine seeds was highest when the pH was less than 5.0, while for birch the germination rate was highest at pH of 4–6. The application regimen significantly affected the germination rate of pine ($p=0.001$) and birch ($p=0.001$) but not of spruce ($p=0.320$).

During the germination period when the

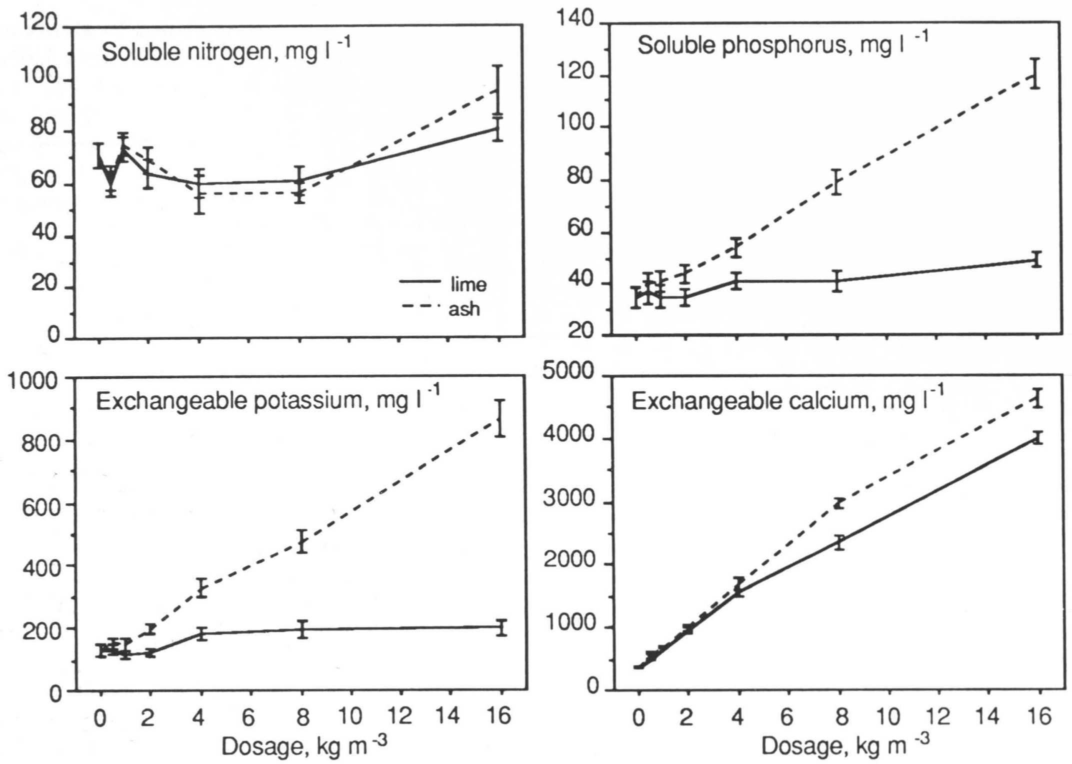

Fig. 2. Concentrations of soluble nitrogen and phosphorus, and exchangeable potassium and calcium in peat of 1982 experiment at the end of the study period. The treatment means ±1SE are calculated from the values of 12 pots.

peat surface was kept moist by frequent watering, mold appeared on the surface of the peat in pots receiving the highest applications (8 and 16 kg m^{-3}) of lime and ash. The mold disappeared after the watering interval was decreased.

Seedling height in lime and ash treatments did not differ significantly for any of the species studied, and therefore the values obtained for ash and lime agents were combined in the figures. Maximum heights for both pine and spruce seedlings were obtained when the pH of the peat was 4–5. This was achieved with small doses (0.5–2.0 kg m^{-3}) of lime and ash (Fig. 4). The height of birch seedlings did not depend on the pH of the substrate.

The application regimen had a significant ($p<0.05$) effect on the seedling diameter of all species studied. The shape of the curve for diameter dependency on substrate pH was similar to that of the height dependency curve. Even the liming agent had a significant, albeit small, effect on seedling diameter. Compared to ash, the application of lime significantly increased the diameter of pine ($p=0.06$) and spruce ($p=0.015$), while lime decreased the diameter of birch ($p=0.01$).

Maximum total dry weights of conifers were obtained at pH of 4–5 (Fig. 5). Dry weight of spruce seedlings was significantly higher ($p=0.001$) in lime than in ash treatments, while liming agent did not significantly ($p=0.074$) affect the dry weight of pine seedlings. Dry weight of birch remained fairly constant over the pH range 3.0–8.0 and the liming agent had no significant ($p= 0.193$) effect.

The root/shoot ratio of dry weight was significantly ($p<0.001$) affected by the liming agent in all tree species studied (Fig. 5). For both liming agents the root/shoot ratio of pine and spruce increased significantly

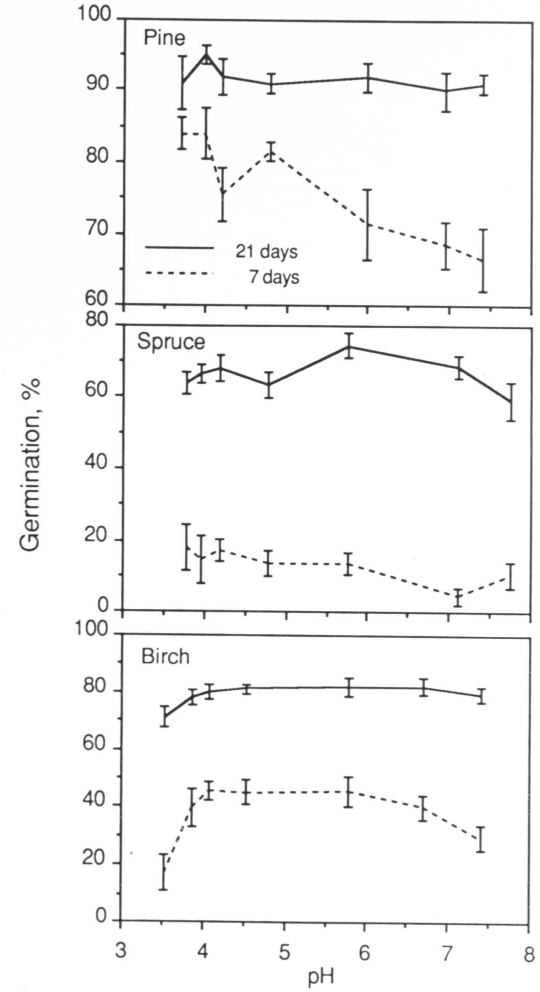

Fig. 3. Germination rate (7 days) and capacity (21 days) of pine, spruce and birch seeds by pH of substrate in 1982 experiment. Lime and ash treatments are combined. The treatment means ±1SE are calculated from the values of 8 pots.

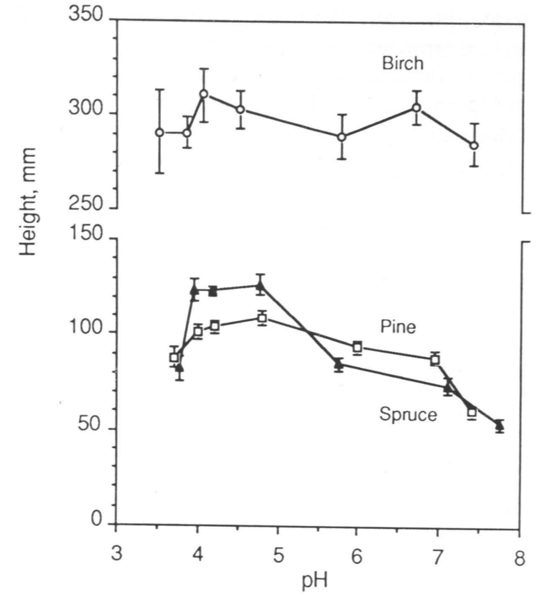

Fig. 4. Height of pine, spruce and birch seedlings by pH of substrate in 1982 experiment at the age of four months. Lime and ash treatments are combined. The treatment means ±1SE are calculated from the values of 8 pots.

($p<0.001$) with increasing application. The root/shoot ratio of birch increased with increasing ash but decreased with increasing lime, indicating an interaction ($p=0.035$) between the liming agent and the application regimen. The number of root tips correlated positively with the root dry weight of both pine ($R^2= 0.60$; $n=52$) and spruce ($R^2=0.63$; $n=52$).

Pine seedlings remained smaller in the 1983 experiment than in the 1982 experiment, which may have been due to the shorter growing period in 1983. The effects of liming agents and application regimen on seedlings, however, were similar to those in the 1982 experiment.

33. Nutrient concentrations of pine seedlings

Nitrogen and phosphorus concentrations in shoots and roots of pine seedlings remained fairly constant over the application range for both lime and ash (Fig. 6). With higher doses of dolomite lime and ash, calcium concentrations increased in shoots and increased more substantially in roots. Potassium concentration in shoots increased linearly as much as threefold over the range of ash applications, while that in roots increased only slightly.

Magnesium concentrations in shoots remained fairly constant over the application range for lime and ash. Only the highest dose of ash increased the magnesium concentration. With low doses of lime, the concentration of magnesium in roots was lower than in shoots but increased rapidly with increasing doses up to 4–8 kg m^{-3}. Manganese concentration in the shoots increased rapidly and thereafter decreased with increasing doses of ash, reaching a maximum of 2–4 kg m^{-3}. Manganese concentrations in roots increased linearly with ash treatments. Increasing lime doses gradually decreased manganese concentration in shoots but increased it slightly in roots.

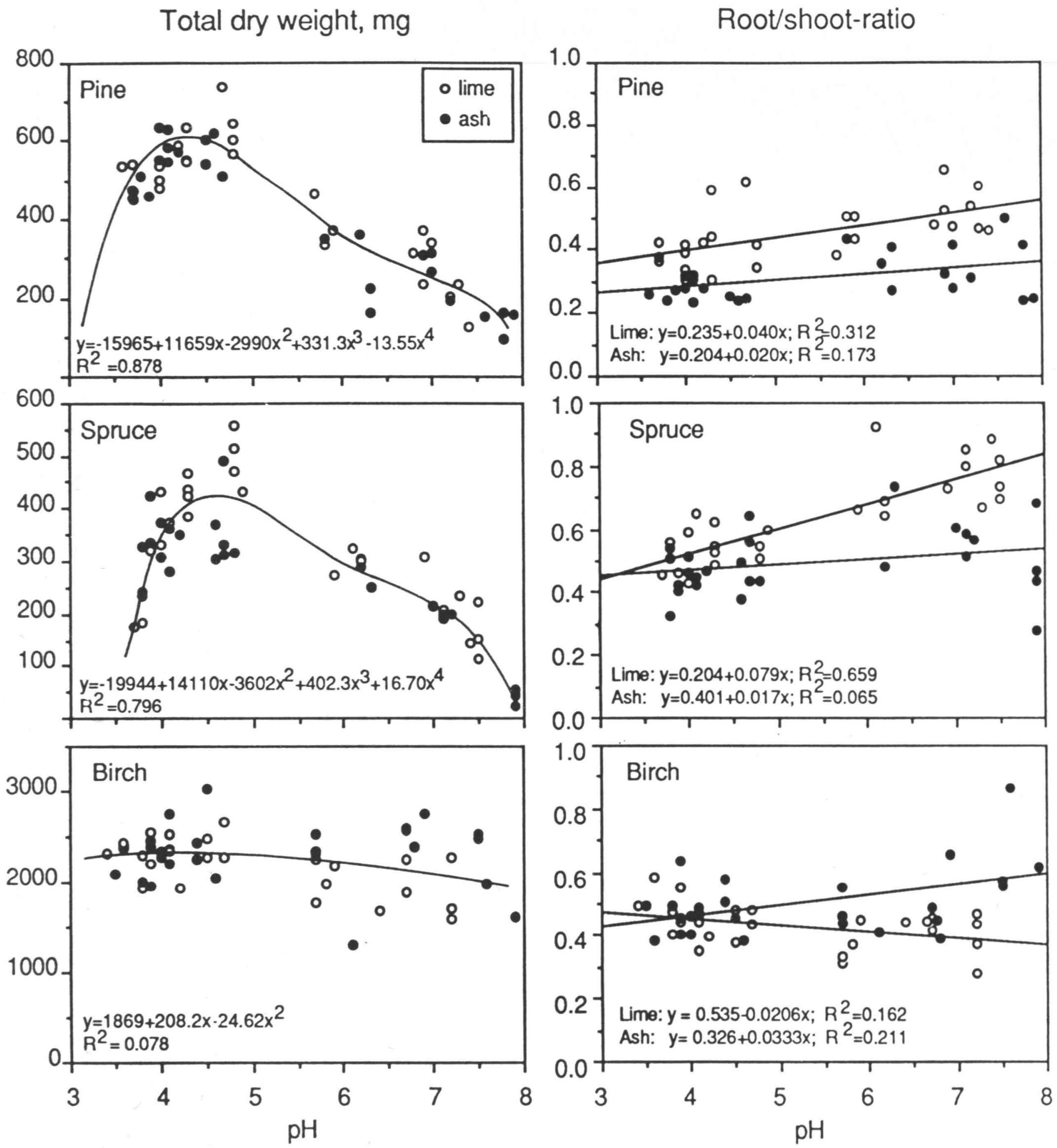

Fig 5. Total dry weight and root/shoot ratio of pine, spruce and birch seedlings by application regimen of lime (open dots) and ash (closed dots) in 1982 experiment at the age of four months. Each dot represents a pooled sample of one pot (10 pine and spruce or 5 birch seedlings in each). Responses of dry weights were smoothed with polynomials of the 4 th degree for pine and spruce and of the 2 nd degree for birch.

With increasing ash dosage, concentration of boron in shoots increased dramatically and thereafter declined, while the concentrations of boron in roots increased more slowly. Increasing doses of lime increased the boron concentration gradually in roots and decreased it in shoots. In general, root concentrations of iron, zinc and copper (Cu not shown) increased rapidly with increasing doses of both ash and lime. In shoots, the concentrations of these nutrients remained fairly constant.

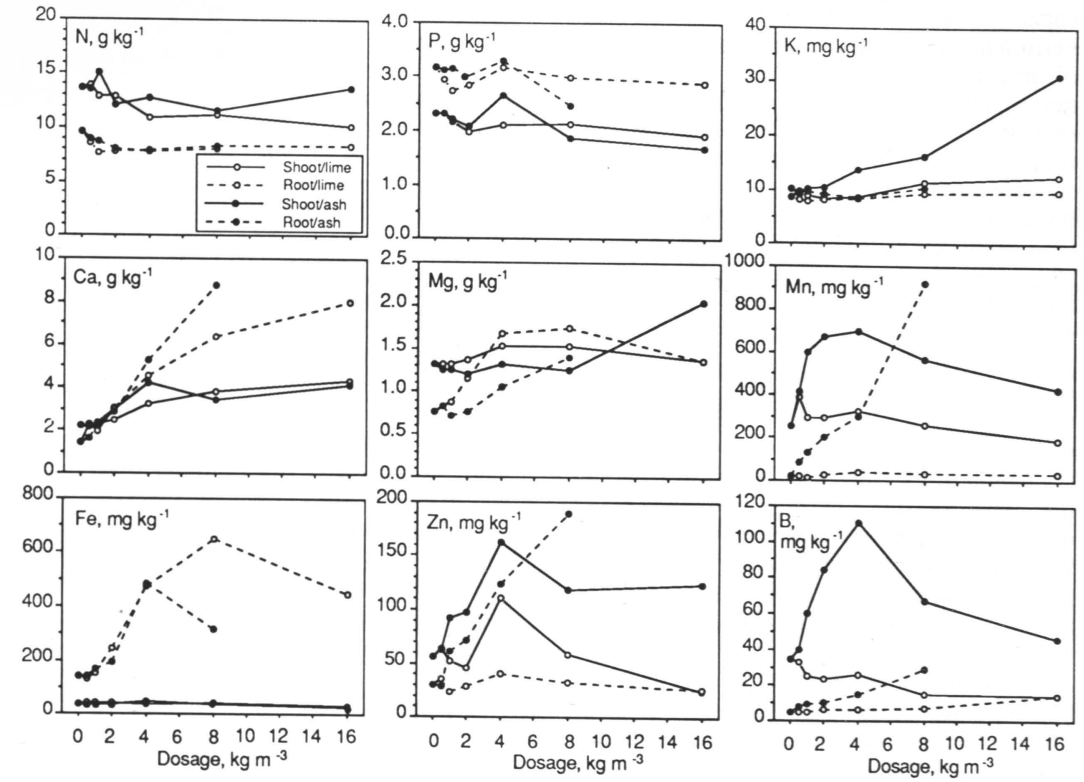

Fig. 6. Nutrient concentrations of shoots and roots of pine seedlings by application regimen of lime and ash in 1983 experiment. One dot represents a pooled sample of 3 pots, each containing 10 seedlings. The root sample of the 16 kg m^{-3} ash treatment was not sufficient for all analyses.

4. Discussion

Dolomite lime increased the pH and EC of Sphagnum peat substrate in much the same way as described by Puustjärvi (1978, 1987). Wood ash had a slightly stronger effect on the pH of the substrate than lime did, which is in accordance with earlier observations (Saarela 1982, 1987). The effect of wood ash may, however, vary considerably depending on the composition of ash, which is known to vary markedly (Hakkila 1989).

Wood ash also produced a strong nutrient effect. It increased the EC, and also concentrations of soluble phosphorus and exchangeable potassium, and calcium in the peat substrate also increased linearly with rising ash dosage. The concentration of soluble nitrogen was highest with the largest dose of ash or lime, probably due to mineralisation of organic nitrogen at high pH (e.g. Karsisto 1979).

The application regimen of lime or ash did not significantly affect the germination capacity of seeds. Pine seeds, however, germinated most rapidly with no or low doses of lime/ash (pH < 5), while no optimum pH range could be detected for the germination rate of spruce seeds. Raynal et al. (1982) found maximum germination of *Pinus strobus* at pH 2.4–3.0. Similar results have been recorded for *Pinus contorta* and *Pinus banksiana* seeds, while *Picea glauca* and *Picea mariana* had a higher pH optimum (Abouguendia and Redmann 1979). The germination rate of birch seeds in our study was clearly depressed by the low pH of natural peat, a finding which supports the results of Raynal et al. (1982) for *Betula lutea*.

The high EC values in ash treatments did not depress the germination or cause deformations of germlings. This disagrees with the results of Heikinheimo (1915), possibly due to the fact that in this study the substrate was peat, while in Heikinheimo's it was mineral soil.

According to Abouguendia and Redmann (1979), extreme pH has a greater effect on growth than on germination. They found that pine and spruce seedlings grown on filter paper exhibit better early growth at pH 6.5 than at pH 3.0 or 9.0, while the best germination occurred in pH 3.0. In this study the germination rate of pine and spruce correlated with both the height and dry weight of seedlings; maximums were achieved at pH 4.0–5.0.

For dry matter production of birch seedlings no optimum pH range could be found. Total dry weight of seedlings was independent of pH or applied doses of lime and ash. This is similar to the result of Ingestad (1979), who reported that birch seems to be less sensitive to pH than most of the other species studied. He also found that the growth rate of birch was depressed at pH 3.5 or lower, at which point calcium uptake was decreased and observable root damage occurred. Furthermore, in a study by Ericsson and Lindsjö (1981) growth of silver birch was not affected by substrate with a pH of 3.8–6.7.

Wood ash clearly affected the potassium, manganese, zinc, and boron nutrition of pine seedlings. Potassium concentrations of shoots at ash doses of 8 kg m^{-3} and especially at 16 kg m^{-3} were higher than those recommended in the literature (Ingestad 1962, Landis 1989). Boron concentrations in the seedlings reached a maximum value (110 mg kg^{-1})with an ash dosage of 4 kg m^{-3} at a pH of about 6 and thereafter declined with increasing ash dosage, probably due to increasing levels of pH and soil calcium (see Mengel and Kirkby 1982). Symptoms of toxicity do not appear until a boron concentration of 200 mg kg^{-1} in the shoot is reached (unpublished data).

Although the amount of soluble phosphorus in the peat substrate increased with increasing doses of ash, no similar effect was found for the concentration of phosphorus in seedlings. The reason for this could be the ratio of soluble P-containing ions, HPO_4^{2-} /$H_2PO_4^-$, which decreases with increasing pH in the soil solution and it is supposed that only $H_2PO_4^-$ is absorbed actively by plants (Mengel and Kirkby 1982). High concentrations of water soluble salts, especially calcium and magnesium, in soil solution have also been found to decrease phosphorus uptake in plants (Puustjärvi 1981a).

When optimum lime or ash applications are estimated, the health of the seedlings must also be considered. In this study mold formed in the two highest application treatments of both lime and ash, but no damage to seedlings was found. In general, damping-off and root rots are most severe in nursery soils with a pH above 5.5; pH levels above 6.0 have been reported to reduce the development of ectomycorrhizae on conifers significantly (Cordell et al. 1989). On the other hand, it has also been found that too low a pH favours increasing dieback in nursery seedlings (Husted 1988). Low pH has also been found to reduce the number of bacteria present, which in turn would reduce the establishment of *Phytium* along the roots (Elad and Chet 1987). Although no measurements on pathogen attack were recorded in this study results from other studies suggest that when acidity levels of nursery soils are adjusted potential pathogen damage should be kept in mind.

To conclude, as neutralizing agents for low humified Sphagnum peat, dolomite lime and wood ash produce about the same effect. Chemical analyses of peat and seedlings indicated that wood ash ought to be considered a nutrient source as well. Pine and spruce were more sensitive to pH, especially to high pH, than was birch. Low rates of application of both dolomite lime and wood ash (0.5–2 kg m^{-3}) resulted in an optimum pH of 4–5 for growth of conifers.

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