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Greenhouse and Laboratory Evaluation of Two Soils Derived from Volcanic Ash

Abstract

This study assessed the mineral nutrient status of two volcanic ash derived soils from SW Oregon. There are extensive areas of such soils in the Pacific Northwest, developed from prehistoric volcanic deposits. The study was initiated because conifers in some of the field plots on such soils had failed to give an expected yield response to the application of nitrogen fertilizer. Soil pot tests were carried out using both Romaine lettuce (*Lactuca sativa*) and Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] seedlings, with a wide range of fertilizer treatments. Heavy phosphorus fertilization was necessary for satisfactory growth of lettuce, which also showed a 26% response to sulfur addition. With Douglas-fir, pot tests showed no response to nitrogen alone, but gave a statistically significant response to phosphorus fertilization together with nitrogen (seedlings were non-mycorrhizal), and some suppression of yield with sulfur additions, probably from osmotic effects. There was a favorable effect of sulfur fertilization on foliar color, and a chlorosis in younger foliage probably attributable to iron deficiency. Most of the tissue analyses showed low concentrations of magnesium ($<0.05\%$), and also of calcium ($\leq 0.08\%$), iron (< 70 mg kg^{-1}), boron (mostly < 20 mg kg^{-1}) and copper (≤ 2.6 mg kg^{-1}) in the younger foliage. Thus there is an implication from the field trials and evidence from the greenhouse and laboratory study that elements besides nitrogen need to be added to provide proper nutrition on these volcanic ash soils. This information can aid in guiding further fertilizer trials in forests on volcanic ash derived soil in SW Oregon and elsewhere.

Introduction

Research on forest soils in northwestern United States has demonstrated the importance of added nitrogen for optimal tree growth. Other elements also may sometimes be deficient, because concentrations of calcium, magnesium, phosphorus, sulfur, boron and even iron, molybdenum and zinc are often low in some soils and in forest tree foliage (Walker and Gessel, 1991; Zasoski *et al.*, 1990). Moreover, local agricultural experience demonstrates that sulfur deficiency often can limit crop growth, especially in soils derived from volcanic ash, and low sulfur supply may limit growth of Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] at some locations (Chappell and Miller, 1988; Blake *et al.*, 1990). Soils derived from volcanic ash are extensive in the Pacific Northwest, with many originating from the Mt. Mazama volcanic explosion in the Oregon Cascade Range about 7,500 years ago. Substantial areas of these soils are in national forests which have been important timber-producing areas in addition to other values. Several fertilizer field trials on volcanic ash soils in the Rogue River National Forest in Oregon have shown variable response to nitrogen application (Opalach and Peterson, 1986).

This study was initiated, 1) to ascertain why in some instances there has been little or no response in forest growth from addition of nitrogen fertilizer alone to volcanic ash derived soils, and 2) to determine if plant growth on such soils is stimulated by addition of one or more other essential mineral elements. Previously the usefulness of greenhouse studies with both tree seedlings and other plants for assessing the fertility status and fertilizer requirements of forest soils has been demonstrated (Vandecaveye, 1948; Walker and Gessel, 1991).

Thus two soils of volcanic ash origin were collected from areas of poor forest growth in the Rogue River National Forest in which growth response to nitrogen fertilization had been variable. Then greenhouse and laboratory studies were conducted using these soils to ascertain which mineral elements were in low supply or deficient. Douglas-fir seedlings were used for the main experiment, but Romaine lettuce (*Lactuca sativa*) plants were grown in a short-term preliminary trial. The results were expected to give guidance for improved multielement fertilizer trials on plots in forests growing on volcanic ash soils in SW Oregon or elsewhere.

Methods

Locations of the collections, identified as soils I and II, are indicated in Table 1. The soil I collection

TABLE 1. Information on the two soils (from the upper Rogue River area, Josephine County, Oregon).

							Exchange Cations[e]					
Soil	Collection area	Origin of soil	pH[b]	Organic matter[c]	Available p[d]	Total p[f]	Ca	Exch. Mg	Cation K	Na	cation esch. capacity	cation saturation
				g kg^{-1}	mg kg^{-1}	mg kg^{-1}	----------c mol kg^{-1}----------					%
I	Lat. 42° 49′ Long. 122° 29′ W	Volcanic ash (13.7% rejected)[a]	5.5	21.7	21	870	2.7	0.29	0.41	0.11	10.8	33
II	Lat. 43° 5′ N Long. 122° 20′ W	Volcanic ash (13.6% rejected)[a]	5.1	26.8	20	830	0.80	0.09	0.13	0.13	7.8	15

[a] Soils were passed through 2 mm square hole sieve before analyses

[b] Saturation-paste method with water, using a Beckman model 76 glass-electrode pH meter (Richards, L.A., 1950).

[c] Dichromate oxidation procedure (Jackson, 1958)

[d] Truog-type extraction (0.3%$(NH_4)_2SO_4$ in 0.002 N H_2SO_4) (Peech et al., 1947)

[e] Ammonium acetate extraction (pH 7). Determination of cations by atomic absorption spectrophotometry.

[f] Extraction with boiling 6 N HCl (Piper, 1944)

area was near the Pacific Northwest Stand Management Cooperative fertilizer installation 106 (Table 6). Soils were collected in autumn 1980 and sieved in the field to remove small pumice and organic fragments. This sieving removed less than 15% of the total volume, because the soils were not stony. The air-dried soils were analyzed for pH, organic matter content, available and total phosphorus, and exchangeable cations using standard techniques specified in the footnotes of Table 1. The fertilizer treatments (listed in Table 2) followed methods modified from Jenny *et al.* (1950). After thoroughly mixing the soil with liquid nutrient additions, according to the fertilizer treatment, the mixture was poured into one L plastic pots (13.7 cm top diameter) with moistened filter paper in the bottoms to cover drain holes; each pot was then placed in a saucer to collect and recycle any drainage water.

Pot Test Using Douglas-fir

Prior to potting in March 1981, one-year-old Douglas-fir seedlings from the U.S.D.A. Forest Service nursery at Medford, Oregon, were stored in a waterproofed paper bag for about one month at 5°C. Plants selected for potting had 11 to 13 cm long shoots and vigorous root systems; roots were trimmed to 12 cm. Occasional branch roots were also trimmed. Stem diameters just above the root collar were 2.0 to 2.5 mm. Some seedlings were obviously more vigorous, and most of these were deliberately planted as "controls" to ensure a conservative test of fertilization. Planting consisted of excavating a hole in the soil to accommodate the roots, then replacing the soil and adding water to ensure good root-soil contact. Treatments were prepared in six replications and "controls" in twelve replications.

The pots were distributed systematically on benches to ensure equivalent exposure to the greenhouse environment (at University of Washington, Seattle). Seedlings were periodically watered with distilled water, but excess watering was avoided. Early seedling mortality was about 10%, and dead seedlings were replaced with seedlings from refrigerator storage.

A considerable number of seedlings in soil I died in the ensuing months, so the remaining live seedlings were harvested in mid-November 1981. Plants in soil II, however, were maintained through the winter using fluorescent lights to extend day length to 16 hours. Plants were harvested from soil II in late June-early July 1982.

Measurements and Statistical Methods

At both harvests, the following measurements were recorded: height, diameter above root crown, and weights of older and younger needles, stems and roots after drying at 70°C. Visual appearance was also recorded. The yield values were evaluated statistically by both a standard t test and by using a Kruskal-Wallis non-parametric analysis (Zar, 1984).

Plant Tissues Analyses

After grinding, samples of leaf tissues were digested in strong nitric-perchloric acid. Analyses for macro- and micronutrient cations were made on an emission spectrophotometer (Jarrell-Ash Model 96-955 ICAP), and phosphorus was determined by the Zinzadze colorimetric procedure (Peech *et al.*, 1947).

Pot Test Using Romaine Lettuce (*Lactuca sativa*)

Tests with a rapidly growing herbaceous species can give quick indications of elemental deficiencies in soils. Fertilizer response in greenhouse pot tests needs to be substantial, however, to predict even modest response in the field. A lettuce pot test was set up, using the criteria of Vandecaveye (1948) for fertility evaluation. Only soil I was available in sufficient amounts for this test. Fertilization and soil handling were similar to that used with Douglas-fir. Romaine lettuce was sown on sand flats; when about 5 to 6-cm tall, one seedling was transferred to each pot of soil and allowed to grow for about six weeks in the University of Washington Botany Greenhouse. After harvest, leaves and stems were oven dried at 70°C, then weighed. Each treatment had four replicates.

Results and Discussion

Chemical Properties of Soils

Both soils were moderately acid, as expected. Soil I, with higher base status, was somewhat higher in pH than soil II (5.5 vs. 5.1) (Table 1). Exchange capacity and concentrations of Ca, Mg, and K were markedly higher in soil I than in soil II. Although both soils were rather low in cation saturation percentage, that of soil II was lower. Organic matter content was similar in the two soils (Table 1).

Available Phosphorus

Various techniques can be used to estimate available phosphorus, but none of them are free of criticism. The Truog 0.002 N H_2SO_4 method, however, proved reasonably satisfactory in a study of 30 forest soils in Wisconsin (Kadeba and Boyle, 1978). Our values for soils I and II fell close to the mean in their study (19.7 ppm). Also as expected, the "available phosphorus" was a small fraction of the "total phosphorus" (Table 1).

Pot Test with Lettuce

With tree seedlings, growing for at least several months is needed to attain results, so this trial using Romaine lettuce plants was run for a quick early assessment of fertility. This proved to be useful, because the rapid growth of this herbaceous species accentuates any indications of low supplying capacity of the soil for the mineral elements.

Because of previous experience in growing lettuce on acid forest soils, lime was included in each treatment and phosphorus was added at high dosages. Growth rates were normal and yields were good (Table 2). In addition to a very marked

TABLE 2. Mean dry weights of Romaine lettuce grown on Rogue River Soil I

Treatment[a]	Mean Oven-Dry Weights (g)[c]			±SD[b]	% of NPKL
	Leaves	Stem	Total		
$CaCO_{3\ 2285}$ (=Lime)	–	–	0.12	0.04	3
N_{172}Lime	–	–	0.05	0.01	1
$N_{172}P_{557}$Lime	2.85	0.38	3.23	0.78	91
$N_{172}P_{557}K_{57}$Lime	3.19	0.37	3.56	0.72	100
$N_{172}P_{557}K_{57}S_{57}$Lime	3.95	0.52	4.47	0.51	126[d]
$N_{172}P_{557}K_{57}S_{57}B_{1.1}$Lime	3.03	0.39	3.42	0.74	96

[a] Subscripts refer to mg kg^{-1} of N, P, K, S and B in the chemical form: N as NH_4NO ; P as $Ca(H_2PO_4)_2$ and NaH_2PO_4; K as KCl; S as Na_2SO_4; B as H_3BO_3.

To convert mg Kg^{-1} approximately to lbs Acre^{-1}, multiply by 2; to convert mg kg^{-1} to kg ha^{-1}, multiply by 2.24.

[b] SD = standard deviation

[c] Plants grown for 6 weeks

[d] Possible deficiency of sulfur indicated by this response using criterion of Vandecaveye (1948).

response to phosphorus, some response to potassium and to sulfur was apparent. Although lettuce could be expected to respond to both lime and phosphorus in the field, coniferous trees are not as likely to respond to such additions. Conifers are aided in their absorption of phosphorus by mycorrhizae, and the available-phosphorus concentrations seem to be in the range expected in forest soils. For lettuce, a further probable benefit of both liming and phosphorus addition is reduction in availability of potentially toxic aluminum and manganese; conifers, however, have high tolerance to these two elements even when present in appreciable concentrations (Radwan *et al.*, 1979; Porada, 1987). Response of lettuce to sulfur addition indicates that this soil has a low supplying capacity for this element. Forest tree growth may also be limited by low supplies of sulfur (Chappell and Miller, 1988).

Growth of Douglas-fir Seedlings

Probably as a result of the osmotic effects of added fertilizers, considerable mortality occurred during the early months, especially on soil I. Consequently, seedlings in soil I were harvested in November after 7 months of growth, whereas those on soil II were held over for additional growth to reduce the influence of the initial nutritional status of the seedlings. The results of the 7-month growth on soil I showed limited effects of fertilization, but there were indications of response to phosphorus (data not presented).

Seedlings in soil II grew well during the spring and early summer of 1982, and were harvested in July after 16 months of growth. Yields at harvest are presented in Table 3. Interpretations require caution because of the probable salt effects mentioned previously. Nitrogen alone did not

TABLE 3. Average seedling weights of Douglas-fir on Soil II by fertilizer treatments (grown March 1981 to July 1982).

	Dry weight (g)						
					Total plant		
Treatment[a]	Needles	Stems	Total shoot	Roots	Mean	SD[b]	Relative total yield (%)
Control	3.81	2.27	6.08	7.02	13.1	2.4	100
N_{107}	3.55	2.33	5.88	5.83	11.7	4.7	89
$N_{107}P_{47}$	4.94	2.86	7.80	6.32	14.1	2.5	108
$N_{107}P_{93}$	4.93	2.56	7.49	6.02	13.5	2.1	103
$N_{107}K_{44}$	3.49	2.21	5.70	5.01	10.7	2.4	82
$N_{107}S_{53}$	3.79	2.23	6.02	5.55	11.6	1.3	89
$N_{107}S_{107}$	3.76	2.48	6.24	6.31	12.6	1.5	96
$N_{107}P_{47}K_{44}$	5.17	2.83	8.00	6.63	14.6	3.4	111
$N_{107}P_{93}K_{44}$	5.80	3.28	9.08	8.30	17.4	2.2	133
$N_{107}P_{93}K_{44}S_{53}$	5.50	2.80	8.30	6.62	14.9	3.1	114
N_{214}	2.04	1.53	3.57	3.27	6.84	1.5	52
$N_{214}P_{47}$	5.76	3.42	9.18	5.98	15.2	2.3	116
$N_{214}P_{93}$	5.43	2.89	8.32	8.42	16.7	1.7	127
$N_{214}K_{44}$	3.02	2.12	5.14	5.65	10.8	2.3	82
$N_{214}S_{53}$	3.72	2.63	6.35	5.53	11.9	5.5	91
$N_{214}S_{107}$	2.40	1.3	3.77	2.39	6.16	1.8	47
$N_{214}P_{47}K_{44}$	4.68	2.57	7.25	6.25	13.5	2.6	103
$N_{214}P_{93}K_{44}$	5.51	2.78	8.29	7.64	15.9	2.5	121
$N_{214}P_{93}K_{44}S_{53}$	5.96	3.49	9.45	6.40	15.9	3.0	121
$N_{214}P_{93}K_{44}S_{53}Mg_{54}$	5.20	2.84	8.04	5.11	13.2	2.6	101
$N_{214}P_{93}K_{44}S_{53}Mg_{54}B_{1.1}$	6.51	4.86	11.4	6.68	18.0	3.3	137

[a] Subscripts refer to mg kg^{-1} of N, P, K, Mg, S, and B added in chemical forms: N as NH_4NO_3; P as $Ca(H_2PO_4)_2$; K as KCl; S as Na_2SO_4; Mg as $MgCl_2$; and B as H_3BO_3 (mg kg^{-1} x 2 = lbs Acre^{-1}, mg kg^{-1} x 2.24 = kg ha^{-1})

[b] Standard deviation

TABLE 4. Relative growth and appearance of Douglas-fir seedling on selected treatments of Soil II at harvest.

Treatment[a]	Relative Growth[b]	Appearance and Symptoms	Possible Interpretation
Control	100%	1981 needles: green to light green. 1982 needles: short and yellow	Growth in 1981 was good, but in 1982 N was "exhausted"; some indication of an immobile-type deficiency.
N_{107} N_{214}	89% 52%	Plants yellow-green; 1982 growth very short; some bronzing; N_{107} looks somewhat better than N_{214}	N fertilization is unfavorable; osmotic effect may have been depressive; N may be supressing P uptake.
$N_{214}P_{47}$ $N_{214}P_{93}$	116% 127%	1981 foliage green; 1982 extension good, although needles light green; the plants are among the best in the experiment; somewhat better than $N_{107}P_{47}$ and $N_{107}P_{93}$.	Addition of P was definitely favorable, although possibly confounded by use of $Ca(H_2PO_4)_2$; yellowness of 1982 foliage may show low N, or possibly an immobile-type deficiency, likely Fe.
$N_{107}P_{93}K_{44}$ $N_{214}P_{93}K_{44}$	133% 121%	1981 foliage green; 1982 extension good, but needles light green.	No apparent response to K.
$N_{107}P_{93}K_{44}S_{53}$	114%	1981 foliage: green; 1982 foliage: good growth but yellowish.	Osmotic depression is probably present, but the combination of N_{214} and S_{53} gave the best color in the 1982 needles.

[a] Subscripts refer to mg kg^{-1} of N, P, K, or S added in the chemical form: N as NH_4NO_3; P as $Ca(H_2PO_4)_2$; K as KCl; S as Na_2SO_4 (mg kg^{-1} x 2 = lbs Acre^{-1}; mg kg^{-1} x 2.24 = kg ha^{-1}.

[b] Percentage of the total dry weight (roots + shoot) at harvest: $\left(\frac{\text{wt. of treatment}}{\text{wt. of control}} \times 100\right)$

improve yield and may have depressed growth in the N_{214} (alone) treatment. This depression could have resulted from reduced phosphorus-uptake rather than nitrogen-depression. Phosphorus additions improved growth, especially where combined with N_{214}. Potassium addition did not improve yield consistently. Sulfur often improved foliar color but generally depressed yield, probably because of the salt influence. Magnesium did not improve growth, even though soil magnesium is low. The only treatment that included boron gave the highest yield in the experiment, but the large standard deviation suggested cautious interpretation.

The t test did not reveal any significant differences in mean yields. However the Kruskal-Wallis statistical analysis confirmed the interpretations stated above concerning phosphorus. With nitrogen-phosphorus treatments, yield increased significantly (0.025 level) and linearly with increasing phosphorus. Addition of other elements did not have statistically significant effects on yield, although with less variability among replicates, the trend toward a boron response might have been supported.

Some indications from foliar symptoms were interesting. With nitrogen fertilization alone, bronzing of needles was consistent. This indicated a probable phosphorus-deficiency (Table 4). Although phosphorus fertilization had a favorable influence, mycorrhizal development was visually weak or absent when the roots were washed out, so tree response to phosphorus in the field might not occur. However, this is uncertain since in southeastern United States, phosphorus deficiency has been reported in field trials even in the presence of mycorrhizae, and phosphorus fertilization is operationally used there (Allen, 1987; Pritchett and Comerford, 1982).

Current needles of control seedlings and those receiving both nitrogen and phosphorus were yellow or yellow-green in contrast with greener, older needles. Although this could be caused by slow redistribution of nitrogen, it suggests an immobile element deficiency, perhaps accentuated by phosphorus fertilization. Deficiency of iron is suspected, especially in view of the work of Perry, *et al.* (1984) who found iron limitation in Douglas-fir in pot tests with Douglas-fir on one soil from a site in SW Oregon which had been logged and burned, but not

TABLE 5. Elemental contents of Douglas-fir needles from selected treatments on soils I and II.[a]

Fertilizer treatment[b]	Sample	Concentrations in dry needles								
		%				mg/kg				
		Ca	Mg	K	P	Fe	Mn	Cu	Zn	B
					Soil I					
Control	Upper Leader	0.071	0.045	0.74	0.068	58	282	2.5	15	28
	Lower Leader	0.34	0.076	0.35	0.049	237	614	3.6	27	21
$N_{107}P_{47}$	Leader	0.45	0.15	0.45	0.047	146	233	8.4	25	50
N_{214}	Leader	0.69	0.20	0.59	0.06	157	352	9.8	29	74
$N_{214}K_{44}$	Leader	0.72	0.19	0.80	0.057	143	397	7.3	30	33
$N_{214}Mg_{54}$	Leader	0.87	0.40	0.38	0.081	203	463	–	31	63
$N_{107}P_{93}K_{44}S_{53}$	Upper Leader	0.081	0.038	0.58	0.051	66	146	2.3	27	14
	Lower Leader	0.33	0.044	0.41	0.054	180	398	4.2	13	19
$N_{214}P_{93}$	Upper Leader	0.31	0.061	0.29	0.049	97	454	4.1	26	16
	Lower Leader	0.68	0.086	0.25	0.046	315	389	5.1	42	33
					Soil II					
$N_{214}P_{47}K_{44}$	Upper Leader	0.067	0.031	0.67	0.042	55	258	2.1	14	19
	Lower Leader	0.32	0.050	0.35	0.043	204	573	4.1	31	16
$N_{214}P_{93}K_{44}$	Upper Leader	0.093	0.036	0.47	0.045	62	289	1.6	14	13
	Lower Leader	0.57	0.070	0.39	0.053	213	1000	4.8	40	18
$N_{214}P_{93}K_{44}S_{53}$	Upper Leader	0.10	0.054	0.47	0.055	66	217	2.6	15	10
	Lower Leader	0.44	0.046	0.28	0.059	200	833	5.2	29	17
$N_{214}P_{93}K_{44}S_{53}Mg_{54}$	Upper Leader	0.097	0.12	0.44	0.051	69	416	2.7	15	12
	Lower Leader	0.60	0.29	0.23	0.055	261	1050	9.0	43	23

[a] These are of treatments in which visual symptoms were pronounced. "Upper leader" refers to the needles from the upper half of the leader, and "lower leader" to the needles from the lower half of the leader.

[b] Subscripts have the same meaning as in Table 3.

in soils from undisturbed sites. Also Zasoski *et al.* (1990) found low concentrations of iron in Douglas fir growing in the field in western Washington. Sulfur additions often resulted in needle necrosis, probably from osmotic effects of the sulfate salt, but the best color in current foliage was in treatments which included $N_{214}S_{53}$. A favorable influence of sulfur-fertilization on needle color, and the tendency for current foliage to be lighter green in color than the older foliage, especially when phosphorus had been added, was noted with both of these soils.

Elemental Concentrations in Douglas-fir Needles

Tissue analyses were performed on selected treatments which from presence or absence of deficiency symptoms, yields, and uniformity of foliage seemed to be of particular interest, especially relating to phosphorus and to micronutrients. The results are presented in Table 5.

Soil I—Plants on soil I were grown during only one season and a favorable nutrient status when planted probably had a carryover influence. Some nutrient concentrations in the seedling foliage are of interest, however. Nitrogen fertilization apparently increased calcium and magnesium concentrations. Phosphorus was the only element in a deficiency range (<0.1%), as estimated by Walker and Gessel (1991).

Soil II—These results are more interesting because the seedlings grew longer, minimizing the influence of initial nutrient content, and the tissues were separated into younger and older needles. A number of trends are evident:

1. Calcium concentration was very low in the current foliage when potassium fertilizer was used. This is not too surprising, in view of the low concentration of exchangeable-calcium in the soil. Application of phosphorus as calcium phosphate did not increase calcium concentration in the foliage, probably because the amount of calcium applied in this form was small.

2. Magnesium concentration was also low in all foliar samples, except those from seedlings fertilized with magnesium. Because the soil is very low in exchangeable magnesium, low concentrations in tissue samples are not surprising, especially when potassium was added. Potassium competes with magnesium in absorption, so higher potassium reduces magnesium-uptake in Douglas-fir (Walker and Gessel, 1991).
3. Potassium was at medium concentrations in the current foliage of the control seedlings, but was relatively low in the older foliage. This suggests incipient potassium deficiency. Even in the potassium-fertilized seedlings, potassium concentrations of the older foliage were consistently lower than those of the current foliage, indicating that demand may have exceeded supply.
4. Tissue-phosphorus concentrations were low, even with phosphorus fertilization. This may be due to the well-recognized ability of ash soils to fix both native and fertilizer phosphorus (Macfarlane and Walmsley, 1977). Such fixation is also indicated by the relatively high "Total P" and low "Available P" (Table 1).
5. Tissue iron concentrations were low in the current foliage, and not very high in the older foliage. This may explain the chlorosis observed in younger foliage of plants on both soils.
6. Copper was in the range of expected deficiency in some of the samples (<3 mg kg^{-1}). Also the consistently lower values in current than in older foliage are indicative of deficiency of an immobile element.
7. Zinc and boron concentrations were not low enough to indicate definite deficiency (Walker and Gessel, 1991), although in most instances the boron concentrations were in a low range and less in upper than in lower foliage, suggesting incipient deficiency of this immobile element.

Relationship of These Results to Field Trials

A regionally coordinated program of forest fertilization field trials has been in place in the Northwest since the 1960s (Chappell *et al.*, 1991). Several installations had been established on the Rogue River National Forest but results were not available for guidance at the initiation of our current study. However, for comparison we selected three of the trials on volcanic ash soils near the collection areas for soils of this investigation, and for which growth data are available over a number of years since fertilization. Nitrogen at two levels was the only element tested in these trials. Results are given in Table 6.

TABLE 6. Initial stand characteristics and 8-year response to nitrogen fertilization at three locations in western Oregon with soils of volcanic ash origin.

Installation No.	Location	B.H. Age	50-yr site index	Thinning	RD	RDR[a]	N dosage	Growth (unfertilized)	Adjusted response (fertilized)	
		yrs	m				kg ha^{-1}	m^3 ha^{-1} yr^{-1}	m^3 ha^{-1} yr^{-1}	%
365	Lat. 42°44′ N Long. 122°29′ W	21	27.4	no	11.2	1.07	220	22.1	−4.8	−20
				yes	4.3	1.20	220	10.5	0.3	3
106	Lat. 42°52′ N Long. 122°28′ W	30	27.1	no	7.9	1.62	220	13.7	−0.1	0
				no		1.16	440	13.7	−0.7	−4
51	Lat. 42°44′ N Long. 122°27′ W	42	25.9	no	15.3	1.04	220	16.2	2.6	15
				no		1.00	440	16.2	9.2	57

[a] RDR = relative density ratio = RD of fertilized plots/RD of control plots; observed response was adjusted by this ratio. RD 70 (English) = 10.1 (metric).

With only two replications at each fertilizer installation, combined with the variation in stocking in these stands (as reflected in the relative-densities), gross generalizations are not possible. In the Douglas-fir region, a response to nitrogen fertilization is normally observed (Stegemoeller and Chappell, 1990; Chappell *et al.*, 1991), but here a clear response to nitrogen was seen only at Installation 51 (Table 6). Thus the field trial conclusions reinforce the greenhouse results, with both indicating that elements besides nitrogen need to be added to provide proper nutrition on these volcanic ash soils. Field trials can be improved by using results from short-term greenhouse screening tests to plan these elemental additions. However, combining results from many field trials to provide a wider geographic scope of inference is possible, as pointed out by Miller *et al.* (1988). They described results from 111 installations in Douglas-fir stands in Southwestern Oregon and 3 in Northern California which showed 70 percent responding to nitrogen. In this case the 30 percent not responding to nitrogen would need more specific research, such as pot tests and foliar analyses, to indicate which other elements are needed in a fertilization plan.

Conclusions

The study gave interesting insights into the mineral supplying ability of these volcanic ash derived forest soils, as follows:

1. Pot tests, soil analyses, and foliar analyses showed that the soils derived from volcanic ash used in this study are able to supply only low amounts of a number of mineral nutrients: calcium, magnesium, potassium, sulfur, phosphorus, nitrogen, copper and possibly boron and iron. At a given site and time, tree growth will probably not be limited by a deficiency of more than one or two of these elements. If a deficiency of one element is corrected by fertilization, yield may still be limited by the supply of a second element, and so on. Such multiple deficiencies in the field may not show up until a future time after one or more additional harvesting cycles.
2. Pot tests and related laboratory analyses should not be used exclusively to make recommendations for extensive, operational field fertilization. Rather, they can be a good basis for guiding trials in nurseries or in the forest. In order to understand the full range of forest tree nutritional problems on these Rogue River volcanic ash soils, a coordinated series of nursery and field trials testing individual and combined elemental additions should be carried out. Analyses of field-collected needle samples from these trials could be compared with the pot test tissue analyses (Table 5) and with expected values (Walker and Gessel, 1991).
3. In both pot tests and field fertilization studies, rates of application need to be low or split dosages used to minimize osmotic effects in these light-textured volcanic ash soils.

Acknowledgements

The authors acknowledge the help of George Badura of the U.S. Forest Service in identification of areas, of Robert Gonyea and Mike Rinehart of the Regional Forest Fertilization Program staff in the collection of soil material, and of Ellen Duffield, Richard Sandstrom, and Richard Wagner in laboratory technical assistance. Also we thank Professor William H. Hatheway for statistical analyses.

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Received 19 July 1993
Accepted for publication 9 July 1994

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