RESPONSE OF POTTED NORTHERN RED OAK AND HAY-SCENTED FERN TO ADDITIONS OF CALCIUM, MAGNESIUM, POTASSIUM, AND PHOSPHORUS

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Abstract: The objective of this study was to determine if addition of Ca, Mg, K, and P to an extremely acidic forest soil would increase early northern red oak (*Quercus rubra* L.) seedling growth. The O through B2 horizon of a Dekalb soil from Pennsylvania's Bald Eagle State Forest was placed in plastic cores and utilized as a growth medium for northern red oak seedlings in a greenhouse environment. After 150 days, fertilization with the selected nutrients Ca, Mg, K, and P increased greenhouse seedling height, leaf area, leaf dry weight, stem diameter, stem dry weight, and tap root diameter. Fertilization also resulted in increased foliar concentrations of P, K, Ca, and Mg and decreased foliar concentrations of Mn and Al. Hay-scented fern (*Dennstaedtia punctilobula* (Michx.) Moore), grown in the same containers with the northern red oak seedlings, demonstrated the potential to be an effective sink for applied fertilizers containing Ca, Mg, K, and P. These results imply that on extremely acidic sites where soils are nutrient deficient, fertilization with Ca, Mg, K, and P may enhance early northern red oak seedling growth.

INTRODUCTION

There has been considerable debate over the decline of temperate-zone forests in Europe and North America. In Pennsylvania, it has become quite clear that adequate advance regeneration of hardwood forests is lacking in many areas of the state (McWilliams and others 1993). One commercially valuable hardwood timber species experiencing this regeneration problem is northern red oak. Chapman and Gower (1991) reported that northern red oak is rapidly disappearing from natural forests in the eastern United States due to the high demand for red oak lumber and the inability of forest managers to consistently promote its natural regeneration.

Possible causes of failed northern red oak regeneration include soil acidification and reduced nutrient availability (Lyon 1995), interference by hay-scented fern (Kolb and others 1989), and herbivory by deer (Stout and others 1995). Because soil acidification and dense hay-scented fern cover could both have detrimental effects on red oak seedling growth, a hypothesis combining the two would seem presumable in some areas where a regeneration problem exists. Soil acidification increases leaching of exchangeable plant nutrients, reduces the availability of phosphorus, and increases the solubility of other elements, some of which are phytotoxic (Cowling and Linthurst 1981). The possibility of red oak growth declines as a result of Al toxicity on Northeastern Spodosols was noted by Joslin and Wolfe (1989), and Sharpe and others (1993) reported that the loss of Ca from forest soils as a consequence of acidic deposition may be important in the height growth of red oak seedlings. On the other hand, the distribution of calcifugous fern types is associated with acid soils where a large amount of aluminum is available, and hay-scented fern, in particular, also may be adapted to the relatively high availability of manganese in acid soils (Hou 1950).

Lorimer (1989) noted that techniques for enhancing the early growth of northern red oak seedlings will hopefully reduce the need for tall oak advance regeneration. One such technique is the placement of fertilizer in the planting hole as part of a regeneration method where the young plant is ensured a sufficient supply of nutrients during the first years of growth (Baule and Fricker 1970). Tomlinson and Tomlinson (1990) reported that fertilization and liming can effectively revitalize forest ecosystems and work to alleviate forest damage associated with nutritional disturbance of soils by atmospheric deposition.

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The objective of this research was to determine if addition of Ca, Mg, K, and P to an extremely acid soil from a site with failed northern red oak regeneration would improve northern red oak seedling growth, with and without competition from hay-scented fern.

METHODS

The soil used in this greenhouse study was a Dekalb (loamy-skeletal, mixed mesic Typic Dystrochrept) from Pennsylvania's Bald Eagle State Forest (USDA Soil Conservation Service 1985). Soil from this site was selected because it was a piece of uncut forest within deer exclusion fencing, and although both northern red oak and chestnut oak trees were located in the overstory, there were no northern red oak seedlings in evidence. A plastic protection collar with a 15 cm diameter was used as a reference device to remove adjacent and intact 15 cm diameter circles of the organic soil layer. The mineral soil underneath the removed organic layers was collected down to a depth of 25 cm (B2 horizon) and sifted through a 1 cm sieve.

Forty-eight clear plastic cores, covered with aluminum foil to prevent light entry, were arranged on a greenhouse table. The cores were 15 cm in diameter, 25 cm in height, and had a 0.6 cm hole in the bottom for drainage. To aid in drainage, a layer of small pebbles was spread evenly across the bottom of the cores, and cheesecloth was placed on top to prevent soil from eroding through. Twenty-four of the cores were fertilized in the following manner: mineral soil, placed in a sample core to a height of 21 cm, was thoroughly mixed with 10 g of crushed dolomitic limestone (Baule and Fricker 1970); a portion of this soil was used to make a 2 cm high layer above the cheesecloth; next, 20 g of granular phosphorus in the form of P_2O_5 (0-44-0) was placed to one side of the core (Baule and Fricker 1970); subsequently, the rest of the mineral soil was added, and an intact 15 cm diameter organic layer was placed on top; lastly, around the outside of the organic layer, 5 g (224.5 kg/ha) of 60% KCl fertilizer (0-0-60) was distributed (Walker 1956). For the 24 unfertilized cores, everything was done in the same manner except that no fertilizer was added.

A hole was cut through the middle of the organic layer, and germinated northern red oak seeds from the same mother tree located on the Penn State University Campus were placed on top of the mineral soil-one seed per core. Additionally, 8-10 cm long hay-scented fern rhizomes were added to 12 of the fertilized and to 12 of the unfertilized cores. These rhizomes did not grow and were replaced 40 days into the study with two rhizomes of similar length placed underneath the organic layer on each side of the acorn.

The greenhouse lights (400 watt High Pressure Sodium) were set at 16 hours per day (DeWald and others 1990), and a hygrothermograph was setup along with a Taylor Model 5458 maximum/minimum thermometer to monitor the temperature on the table holding the cores. During the time period of the study, the temperature on the greenhouse table ranged from 9-33°C (48-91°F). A 20% black shadecloth was placed over the seedlings for the entire duration of the study. The seedlings received 125 ml of deionized water twice weekly for the first 90 days of the study; for the remaining 60 days, the amount was increased to 150 ml twice weekly (Lyon 1994).

Height growth of the seedlings was measured at 30 day intervals over the course of the study. After 150 days of growth, the seedlings and ferns were sacrificed, and additional measurements were collected. Fern fronds were cut at ground level, oven dried at 85°C for 33 hours, weighed to the nearest 0.01 g on a Mettler PR1200 balance, and frozen for 10 weeks prior to chemical analysis. Oak seedling leaf areas were measured to the nearest 0.01 cm^2 using a LI-3100 Leaf Area Meter (Sharpe and others 1993) before the leaves were washed with deionized water. The leaves were then placed in an oven at 85°C (Joslin and Wolfe 1989) for 36 hours. Upon removal, they were weighed to the nearest 0.01g and frozen for 10 weeks prior to chemical analysis (Sharpe and others 1993). Starrett digital calipers were used to measure oak seedling diameters to the nearest 0.01 mm at a height just above the root collar (DeWald and others 1990). Seedling stems were cut from tap roots at the root collar, and the root diameters were taken just below the root collar (Sharpe and others 1993). The seedling and fern root systems were carefully removed from the cores and washed over USA Standard Testing 2 mm and 0.5 mm sieves to retain any fine roots that broke off (Safford 1974). Oak seedling lateral roots were removed from tap roots with scissors. Total tap root lengths were measured by using a string to trace the path of each root and measuring the string to the nearest 0.1 cm. The seedling lateral and tap roots were placed in an oven at 85°C for 36 hours and weighed to the nearest 0.01 g upon removal (DeWald and others 1990). Fern rhizomes and roots and red oak stems were oven dried at 85° C for 48 hours and weighed to the nearest 0.01 g upon removal.

For chemical analysis of seedling leaves and fern fronds, samples were submitted to the Agricultural Analytical Services Laboratory Plant Analysis Program (Penn State University), and concentrations were obtained by an inductively coupled plasma emission spectrometer according to methods outlined by Dahlquist and Knoll (1978). Calibration of the spectrometer was performed using reference samples which were obtained from the National Institute of Science and Technology (NIST) and with in house check samples. Analysis included concentrations of P, K, Ca, Mg, Mn, Fe, Cu, B, Al, Zn, and Na; however, only the results concerning P, K, Ca, Mg, Mn, and Al are discussed.

At the conclusion of the study, soil samples were collected from the intact organic soil surrounding the seedlings and from the previously mixed mineral soil at a depth of 10-11 cm beneath the organic soil layer. Thus, one organic soil sample and one mineral soil sample was collected from each core. Soil analysis was completed on both organic and mineral soils for exchangeable Mn and Al using a 0.01M $SrCl_2$ extraction (Joslin and Wolfe 1989). Concentrations were obtained using an Instrumental Laboratory Video 22 aa/ee spectrophotometer. Additionally, pH, available P, and exchangeable concentrations of K, Mg, and Ca were obtained from the Agricultural Analytical Services Laboratory (Penn State University) according to methods outlined in North Dakota State University (1988).

Since data were not normally distributed, nonparametric procedures were used in the analyses. Kruskal-Wallis one-way analysis of variance was used to test for differences among 4 treatments: fertilized with fern, unfertilized with fern, fertilized without fern, and unfertilized without fern (Daniel 1978). When treatment effects were significant (e.g, $P < 0.05$), multiple-comparison procedures (Dunn 1964) were used to detect differences between individual treatments. Kruskal-Wallis statistics (H) were corrected for ties, and an experimentwise error rate of 0.20 was used for multiple-comparison procedures (Kurtz and others 1965).

RESULTS

Soil Chemistry

In the organic soil chemistry comparison (Table 1), changeable Mn concentrations for the fert. & no fern treatment were significantly higher than those for the fert. & fern treatment. Exchangeable Al concentrations were not significantly different among treatments. The fert. & no fern and the no fert. & fern pH values were significantly higher than the fert. & fern pH values. The fert. & no fern available P concentration was significantly higher than the no fert. & fern concentration. Exchangeable K and Mg concentrations were significantly higher in the fertilized than the unfertilized treatments while the exchangeable Ca level was significantly higher for the fert. & no fern treatment than the no fert. & no fern treatment.

In the mineral soil (Table 1), pH was significantly higher in the fertilizer treatments than the no fert. & fern treatment. The fert. & fern pH was also significantly greater than the no fert. & no fern pH. Exchangeable Mn and Al levels were significantly higher for the unfertilized than the fertilized treatments. Exchangeable K, Mg, and Ca levels were significantly higher for the fertilized treatments than the unfertilized treatments. The available P was not significantly different among treatments due to the methods of fertilization and sampling. Overall, the mineral soil chemistry results indicated that the fertilizer treatments impacted the mineral soil through a higher pH, increased levels of exchangeable K, Mg, and Ca, and decreased concentrations of exchangeable Mn and Al.

Table 1. Median organic and mineral soil chemical parameters at the conclusion of the 150 day greenhouse study

Variable	Fert. & Fern	No Fert. & Fern	Fert. & No Fern	No Fert. & No Fern	H Test Statistic
Organic Soil					
Mn (mg kg^{-1})	63.0a	72.1ab	101.6b	68.8ab	7.06
Al (mg kg^{-1})	1.5a	4.4a	3.3a	5.2a	1.73
pH	4.0a	4.3b	4.3b	4.2ab	9.93
P (mg kg^{-1})	26ab	21a	34b	24ab	8.45
K (meq/100 g)	3.68a	0.55b	4.24a	0.39b	28.86
Mg (meq/100 g)	0.7a	0.6b	1.3a	0.5b	30.53
Ca (meq/100 g)	1.5ab	1.5ab	2.0a	1.5b	9.13
Mineral Soil					
Mn (mg kg^{-1})	1.0a	4.4b	0.5a	3.7b	35.34
Al (mg kg^{-1})	0.4a	12.7b	0.4a	12.2b	36.86
pH	5.9a	4.6b	5.8ac	4.6bc	18.46
P (mg kg^{-1})	36a	26a	36a	31a	3.74
K (meq/100 g)	0.57a	0.11b	0.56a	0.09b	31.05
Mg (meq/100 g)	1.5a	0.2b	1.4a	0.2b	35.19
Ca (meq/100 g)	2.0a	0.5b	2.0a	0.5b	36.41

Different letters within a row indicate significant differences among treatments at an $\alpha \leq 0.05$ according to Dunn's (1964) multiple-comparison procedures.

Seedling Foliar Chemistry

Foliar chemistry comparisons (Table 2) revealed that seedling foliar P and Mg concentrations were significantly greater in the fertilized than the unfertilized treatments. Foliar K concentration was significantly greater in the fert. & fern treatment than the no fert. & fern and no fert. & no fern treatments. Foliar Ca concentration was significantly higher in the fertilized treatments than the no fert. & no fern treatment, and concentrations of Mn and Al were significantly greater in the unfertilized than the fertilized treatments. In effect, the fertilizer treatments increased the seedling foliar concentrations of the selected nutrients P, K, Ca, and Mg and decreased the foliar concentrations of Mn and Al.

Table 2. Median northern red oak seedling foliar element concentrations at the conclusion of the 150 day greenhouse study

Element	Fert. & Fern	No Fert. & Fern	Fert. & No Fern	No Fert. & No Fern	H Test Statistic
P (%)	0.19a	0.12b	0.18a	0.12b	24.37
K (%)	0.95a	0.73b	0.84ab	0.72b	10.14
Ca (%)	0.77a	0.63ab	0.78a	0.59b	11.57
Mg (%)	0.30a	0.10b	0.29a	0.07b	34.47
Mn (mg kg^{-1})	3775a	11550b	2950a	15655b	25.65
Al (mg kg^{-1})	29a	68b	29a	80b	29.47

Different letters within a row indicate significant differences among treatments at an $\alpha \leq 0.05$ according to Dunn's (1964) multiple-comparison procedures.

Hay-scented Fern Frond Chemistry

Hay-scented fern frond concentrations of P, K, Ca, and Mg were significantly higher in the fertilized than the unfertilized treatment (Table 3). The concentration of Al was significantly higher in the unfertilized treatment, and the concentration of Mn was not significantly different between the treatments (Table 3). Thus, with the exception of Mn, the hay-scented fern frond chemistry response to the fertilization corresponded with that of the northern red oak seedlings.

Table 3. Median hay-scented fern frond element concentrations at the conclusion of the 150 day greenhouse study

Element	Fert. & Fern	No Fert. & Fern	H Test Statistic
P (%)	0.13a	0.07b	7.14
K (%)	3.20a	1.13b	10.50
Ca (%)	0.41a	0.24b	9.42
Mg (%)	0.29a	0.12b	10.61
Mn (mg kg^{-1})	1231a	1166a	0.21
Al (mg kg^{-1})	65a	141b	3.88

Different letters within a row indicate significant differences between treatments at an $\alpha \leq 0.05$ according to Dunn's (1964) multiple-comparison procedures.

Growth Parameters

Growth comparisons among treatments (Table 4) tended to reflect the changes evidenced in the soil chemistry and foliar chemistry comparisons. The comparison of seedling heights at 150 days showed that the fert. & fern treatment was significantly taller than the no fert. & fern and the no fert. & no fern treatments, and the fert. & no fern treatment was significantly taller than the no fert. & no fern treatment. The fert. & fern treatment leaf area and dry

Table 4. Median northern red oak seedling and hay-scented fern growth parameters at the conclusion of the 150 day greenhouse study

Growth Parameter	Fert. & Fern	No Fert. & Fern	Fert. & No Fern	No Fert. & No Fern	H Test Statistic
Seedling					
height (150 d) (cm)	28.9a	18.9bc	27.6ab	15.0c	18.07
leaf area (cm^2)	797.9a	365.4bc	632.3ab	343.9c	17.06
leaf dry weight (g)	3.95a	1.92bc	3.66ab	1.84c	15.23
stem diameter (mm)	6.87a	6.07ab	6.97a	5.14b	13.44
stem dry weight (g)	2.24a	1.63ab	2.56a	1.13b	12.55
tap root diameter (mm)	10.72a	8.14ab	9.73a	7.38b	14.30
tap root length (cm)	47.7a	43.7a	47.1a	58.3a	1.44
tap root dry weight (g)	4.51a	4.53a	3.94a	3.81a	0.44
lateral root dry weight (g)	1.72a	1.11a	1.71a	1.02a	0.32
Fern					
frond dry weight (g)	0.29a	0.33a			1.02
rhizome & root dry weight (g)	0.57a	1.31a			3.23

Different letters within a row indicate significant differences among treatments at an $\alpha \leq 0.05$ according to Dunn's (1964) multiple-comparison procedures.

weight were significantly greater than the no fert. & fern and the no fert. & no fern treatments. The fert. & no fern treatment leaf area and dry weight were significantly greater than the no fert. & no fern treatment. Stem diameter and stem dry weight were significantly larger in the fertilized treatments than the no fert. & no fern treatment. A belowground response was only apparent in the tap root diameter which was increased by fertilization. Seedling tap root lengths, tap root and lateral root dry weights, and the lengths and diameters of the 5 longest lateral roots did not significantly differ among any of the treatments. Hay-scented fern frond dry weights and hay-scented fern rhizome and root dry weights also did not significantly differ between the treatments.

DISCUSSION

Soil Chemistry

The only fertilizer applied directly upon the organic soil was the 60% KCl fertilizer. Soil analysis results showed that it was still having an impact through increased exchangeable K concentrations in the organic soil at 150 days.

For the mineral soil, the results showed that the 60% KCl fertilizer applied on the surface of the organic soil was impacting the mineral soil through increased exchangeable K concentration at 150 days. The crushed dolomitic limestone application led to significantly higher exchangeable concentrations of Ca and Mg in addition to a pH increase in the mineral soil of the fertilized treatments. Due to the placed application of P fertilizer, the method of sampling could not accurately indicate the amount of available P. The foliar analysis, however, showed that the P fertilization did increase the P available to the northern red oak seedlings. The fertilization significantly decreased the mineral soil exchangeable concentrations of Mn and Al. Since soil Al has been closely and negatively correlated with root system branching and development (Joslin and Wolfe 1989), a decrease in the exchangeable Al concentration might benefit the growth of red oak seedlings.

Seedling Foliar Chemistry

As indicated by the general trends in the soils, the fertilizer applications increased the foliar concentrations of the selected nutrients P, K, Ca, and Mg and decreased the foliar concentrations of Mn and Al. Over the course of the 150 day study, older leaves on unfertilized seedlings displayed interveinal chlorosis and interveinal stippling. Since precise critical values could not be found for northern red oak, the reported range or minimum foliar element concentrations for other dicotyledonous tree species displaying visual symptoms of nutritional deficiency were used as references to explain the yellowing and the stippling of the unfertilized seedling leaves. A combination of nutrient deficiencies and toxicities appeared to cause the visual symptoms.

The foliar K concentrations in both the fertilized and unfertilized seedlings were above the 0.29-0.66% range that Walker (1956) cited for display of visual deficiency symptoms in red maple. The foliar Ca concentrations in the fertilized and unfertilized seedlings were also above the 0.30% critical value cited by Huttl (1986) for the display of visual deficiency symptoms in European beech. The foliar P and Mg concentrations of the unfertilized seedlings were below the reported critical values, 0.15% for both P and Mg in European beech (Huttl 1986), for the display of deficiency symptoms while their concentrations in the fertilized seedlings were above the critical values. Therefore, these nutrients may have been limiting factors in the unfertilized seedling growth.

Although the foliar Mn concentration was high for all of the treatments, it was extremely high for the unfertilized seedlings. Messenger (1984) noted that 100 to 280 ppm foliar Mn is evident in green and apparently healthy red maple leaves. Bergmann (1992) reported that in most cases, the symptoms caused by toxic manganese concentrations usually are seen on the older leaves first, appearing initially as brown spots (deposits of MnO_2) or chlorotic and necrotic lesions, which generally spread from the tips and margins to the center of the leaf and are often accompanied by rolling of the leaf edges. These symptoms were evident on the older leaves of many of the unfertilized seedlings in this experiment. Thus, Mn concentrations were possibly at toxic levels in the foliage of the unfertilized seedlings. Bergmann (1992) reported that the most important factors encouraging the release of Mn^{2+} cations into the soil solution are low pH values (below 5.5/6.0) and a high reduction capacity of the soil, particularly if it is poorly drained or occasionally flooded.

In review, the foliar literature values suggested that P and Mg deficiencies and Mn toxicity may have been inhibiting factors in the unfertilized red oak seedling growth. For the fertilized seedlings, the foliar element concentrations were above critical values cited in the literature. Thus, the comparison with the literature values indicated that the combination of different fertilizers was effective in meeting the nutritional requirements of the red oak seedlings.

Hay-scented Fern Frond Chemistry

The effects of the fertilizer applications on hay-scented fern frond chemistry appeared to parallel the effects on the red oak seedling foliage. Concentrations of P, K, Ca, and Mg in the fronds increased while that of Al decreased, demonstrating that hay-scented fern has the potential to be a sink for these nutrients. This could be an important factor for fertilization attempts in areas where hay-scented fern ground cover exists. Fertilizer applied on the ground surface may be taken up by the dense matting of fern roots located in or just below the organic layer before it comes in contact with seedling roots. This type of fertilization could inhibit seedling growth by aiding in hay-scented fern growth. Hay-scented fern resources not used in reproductive or photosynthetic efforts may be stored in rhizomes and can facilitate rapid growth in the next growing season (Hammen 1993). Methods of fertilization which get nutrients well down into the mineral soil layers could make the fertilizer less available to the fern roots and more readily available to the oak seedling roots.

Unlike the red oak seedlings however, the concentration of Mn in the hay-scented fern fronds was not significantly different between fertilized and unfertilized treatments. This lack of a difference suggested that the hay-scented fern had some mechanism of limiting Mn uptake. The northern red oak seedlings did not display this ability to limit Mn uptake. If such an Mn uptake limiting mechanism does exist, it could be an important factor in the growth competition between red oak seedlings and hay-scented ferns on extremely acidic forest soils with high levels of available Mn.

Growth Parameters

The results of the height comparison supported the results of the foliar analysis. The fertilized treatments displayed increased seedling height growth at 150 days, indicating that the fertilization methods were successful in aiding northern red oak seedling growth.

Seedling leaf area, leaf dry weight, stem diameter, stem dry weight, and tap root diameter were greater for the fertilized treatments without regard to fern. This fertilizer effect was hypothesized, and the increase in the above ground growth variables corresponded with the nutrient increases in the foliage of the fertilized seedlings. Except for tap root diameter, the below ground northern red oak seedling variables did not display a response to the fertilization. The fern was probably not a significant factor because the northern red oak seedlings were well established when the hay-scented fern rhizomes were planted. This result indicated the possibility for northern red oak seedlings to effectively compete with hay-scented fern when the seedlings are established first and properly nourished with Ca, Mg, K, and P.

The hay-scented fern frond and the rhizome and root dry weights tended to be higher for the unfertilized treatments, but the differences were not significant. However, in the case of the rhizome and root dry weight, the unfertilized median was twice as high as the fertilized median. The opposite was true for the median northern red oak seedling lateral root dry weight which was higher for the fertilized treatment. Although these differences were not significant, they presented the possibility that the fertilizer applications may have resulted in more and/or larger northern red oak seedling lateral roots which may have contributed to smaller hay-scented fern rhizome and root growth.

SUMMARY

Northern red oak seedling responses to fertilization with the selected nutrients Ca, Mg, K, and P were measured in a greenhouse experiment. Fertilization increased northern red oak seedling height, leaf area, leaf dry weight, stem diameter, stem dry weight, and tap root diameter. Fertilization also resulted in increased foliar concentrations of P, K, Ca, and Mg and decreased concentrations of Mn and Al. Under the conditions of this study, hay-scented fern did not appear to affect northern red oak seedling growth and seemed indifferent to changes in soil Mn availability. However, hay-scented fern demonstrated the potential to be an effective sink for applied fertilizers containing Ca, Mg, K, and P.

Techniques for enhancing the early growth of planted seedlings may have important implications for the regeneration of northern red oak seedlings following timber harvest or other forest disturbance. On sites where extremely acidic soils, high in available Al and Mn but deficient in nutrients, are present, fertilization with Ca, Mg, K, and P by the methods used in this study may enhance early northern red oak seedling growth.

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