RELATIONSHIPS BETWEEN CHEMICAL AND PHYSICAL PROPERTIES OF A TYPIC FRAGIUDALF AND GROWTH OF SCARLET OAK

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Five stands of scarlet oak (Quercus coccinea Muenchh.) on a fine-silty, mixed, mesic Typic Fragiudalf were studied to determine the relationship between various soil properties and site quality. Site index was greatest on those sites where tree roots were able to grow through the fragipan. Annual volume growth was positively correlated with nitrogen and carbon content of the A1 horizon, as well as with soil depth and base saturation or calcium content. An increase in exchangeable aluminum was associated with a reduction in annual volume growth and adversely affected the overall fertility relationships of the soil. Soil productivity is closely related to fertility of the A1 horizon.

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INTRODUCTION

The relationships between soil characteristics and the growth of oak have been investigated in a number of studies (Carmean 1975). However, the wide geographic distribution of oak and the differing site conditions on which the various species occur permits only a broad interpretation of those soil properties influencing tree growth. In general, oak site studies and the predictive equations developed from them have shown three site factors--topography, aspect, and soil depth--to most markedly affect growth. Such all-encompassing factors tend to obscure those soil properties which directly determine tree development. Hodgkins (1959) has suggested that either reducing the size of the study area or the complexity of the factors involved would improve the effectiveness of soil-site studies.

Unfortunately, efforts to reduce soil-site studies to stands of oak growing on fragipan soils have not clarified the situation. In some cases depth to fragipan was related to tree growth (Broadfoot 1969; McQuilkin 1972) while in other cases it was not (Hannah 1968).

This study evaluates soil characteristics in relation to tree growth under conditions such that aspect and topographic influences were minimized. In addition, the effect of fragipans on tree growth was examined.

METHODS

The area studied was a portion of the University Forest located in the Ozark Plateau (northeastern Butler and southeastern Wayne counties) Missouri. The forests of the areas are generally composed of mixed oak and hickory. Loess covers most of the ridges and gentler slopes; on the uneroded summit divides, it is about 1.5 m deep; a fragipan is usually present. The underlying rock strata are Roubidoux and Gasconade limestones of Ordovician age. Both are siliceous and weather to a cherty residuum. The substratum of the region consists of mixed chert and clay. The bedrock is decomposed to a depth of 6 to 16 m. The lack of free carbonates and the weathered surface of the chert indicate that the residuum is highly weathered. The soils are classified as fine-silty, mixed, mesic, Typic Fragiudalfs.

Five forest stands were selected for study. Stand composition was mixed upland oak: scarlet oak (*Q. coccinea* Muenchh.), southern red oak (*Q. falcata* Michx.), black oak (*Q. velutina* Lam.), post oak (*Q. stellata* Wengenh.), blackjack oak (*Q. marilandica* Muenchh.), and hickory (*Carya*). All stands had been subject to repeated harvesting and wildfire although neither had occurred in the past 25 years. The stands were even-aged and varied from 50 to 65 years in age.

In each of the five stands, one 0.1 ha plot was established to determine volume and basal area. On each plot, three dominant or codominant scarlet oak trees were cut, and age, site index, and periodic annual increment between 45 and 50 years were determined from stem analysis. No scars were found on any of the trees cut for stem analysis.

The plots were located on broad ridge tops where slopes did not exceed 3%, depths to the fragipan did not vary more than 3 cm for a given plot, and no chert or gravel fragments were present in the upper 90 cm of soil. At the plot center, a soil pit, 3 m long, was excavated to consolidated parent material or a depth of 2 m and the soil profile described. Soil profiles were similar above the fragipan horizon. A profile description of a deep soil follows.

Horizon	Depth (cm)	Horizon Description
A1	0-5	Dark brown (10YR 4/3; grayish brown 10YR 5/2 dry) silt loam; weak very fine granular structure; very friable; strongly acid; abrupt smooth boundary.

A2	5-12	Yellowish brown (10YR 5/4) silt loam; weak very fine granular structure; friable; few very fine black concretions; strongly acid, abrupt smooth boundary.
B21t	12-19	Yellowish brown (10YR 5/6) silt loam; weak very fine subangular blocky structure; friable; very strongly acid; abrupt smooth boundary.
B22t	19-38	Yellowish brown (10YR 5/7) silt loam; moderate very fine subangular blocky structure; firm; few fine black concretions; very strongly acid; clear wavy boundary.
B23t	38-50	Yellowish brown (10YR 5/8) with common fine faint mottles of light brownish gray (10YR 6/2) silty clay loam; moderate fine subangular blocky structure; firm; thin continuous clay films between peds; very strongly acid; clear wavy boundary.
B'&A'	50-61	Light grayish brown (10YR 6/2) with common fine faint mottles of yellowish brown (10YR 5/6) silty clay loam; moderate fine blocky structure; firm; prominent coating of clean silt of pale brown (10YR 5/6) in parting between peds; extremely acid; clear smooth boundary.
B'	61-73	Mottled, light brownish gray (10YR 6/2), yellowish brown (10YR 5/6) and few faint dark brown (7.5YR 4/4) silty clay loam; moderate medium blocky structure; firm; thick continuous clay films on all ped surfaces, clean silt coating not continuous; extremely acid; abrupt wavy boundary.
IIB'31x (Fragipan)	73-95	Mottled light brownish gray (10YR 6/2), yellowish brown (10YR 5/4, 10YR 5/6, 10YR 5/8) and dark grayish brown (10YR 4/2) silt loam and tongues of mottled brown (10YR 5/3) and pale brown (10YR 6/3); weak coarse platy structure; very hard, thin clay films between tongues; extremely acid; gradual wavy boundary.
IIB'32x (Fragipan)	102-145	Mottled yellowish brown (10YR 5/6, 10YR 5/8), grayish brown (10YR 5/2), yellowish red (5YR 5/6) and brownish yellow (10YR 6/6) silt loam; weak very coarse platy structure; extremely hard; clay films less numerous but similar to above, few clean silt coatings, several chert fragments <1.0 cm diameter (<1 percent of volume); extremely acid; diffuse wavy boundary.

IIC	145-175	Very mottled yellowish brown (10YR 5/6, 10YR 5/8), light brownish gray (10YR 6/2), brown (10YR 5/3), brownish yellow (10YR 6/6), yellowish red (5YR 5/8, 5YR 4/6) and dark reddish brown (5YR 3/4) light silty clay; moderate fine subangular blocky structure; firm; many chert fragments 1.0 cm diameter and a few larger pieces 15 cm across, 25 percent by volume, very strongly acid.

Composite samples from each horizon were collected from the entire length of the soil pit and analyzed in duplicate. Such a composite sample, which was collected along a 3 m transect (the soil pit) across the center of the area bounded by the three sample trees, was thought to provide the basis from which valid estimates of soil chemical and physical properties affecting tree growth could be made. Soil moisture retention of undisturbed soil cores was determined at 0.06 atm with a hanging water column and at 0.30 atm with a pressure plate. Soil moisture retention at 15 atm was determined on 2 mm sieved soil with a pressure plate. An ammonium acetate soil extract, pH 7.0, was used to determine exchangeable calcium and magnesium by atomic absorption, exchangeable potassium and sodium by flame emission, and cation exchange capacity (CEC). Available phosphorus (soluble in a 0.025N HCl + 0.03N NH_4F leachate) was determined colorimetrically. Soluble and exchangeable aluminum were determined by the method of Hoyt and Nyborg (1971). Total nitrogen was determined by micro-Kjeldahl and total carbon was analyzed by dry combustion. Soil pH was measured at a 1:1 soil to solution ratio.

Soil chemical properties were averaged for increasing depths (A1, 0-10 cm, 0-20 cm, and 0-30 cm) from the surface; these values were based on the chemical data, thickness, and bulk density of the individual horizons included within each respective depth.

RESULTS AND DISCUSSION

Stand Characteristics

Age and growth data are summarized in table 1. Stem analysis showed that growth of the sample trees on each plot had been uniform throughout their life span. At age 50 the difference in height growth of the best (Plot 1) and the poorest site (Plot 5) was 5.4 m. Annual volume growth followed the same trend, i.e., plot 1 had the greatest annual increment and plot 5 the least. Since basal area and stand volume were based on all the trees on the plots, these stand characteristics do not show a well-defined trend.

Table 1. Stand Characteristics

Plot Number	Age[1]	Site Index (m)	Annual Volume Increment (m^3/year/tree)	Basal Area (m^2/ha)	Stand Volume (m^3/ha)
1	58-60	21.3	0.144	20.0	169
2	56	18.4	0.107	24.4	182
3	48-53	16.7	0.056	15.5	95
4	55-60	17.3	0.088	20.5	149
5	62-64	15.9	0.053	23.9	163

[1] Age range of trees cut for stem analysis.

Physical Soil Characteristics

Soil physical properties considered important for tree growth are presented in table 2. The depth to the fragipan varied only slightly except for plot 5. Moisture storage capacities above the fragipan were quite similar. In plots 1 and 2, the material beneath the fragipan was a silty clay loam in contrast to the consolidated parent material of the other three plots. Roots penetrated through the fragipan and grew into the underlying silty clay loam horizon. Root length per unit volume of soil was greater in this horizon than it was in the fragipan where roots are largely confined to the cleavage planes (McNabb 1972). Site index and annual volume growth were greater where the fragipan was underlain by soil material rather than parent material, thus suggesting the importance to tree growth of root penetration into this horizon. The ability to penetrate and utilize the soil underlying a fragipan may be a characteristic of oak species. DeByle and Place (1959) found the rooting depth of northern pin oak and bur oak was greater than pine in soils containing fragipans.

Soil physical properties and depth to the fragipan were not significantly related to either site index or annual volume growth since these characteristics did not vary markedly from one site to the next. Furthermore, the statistical nonsignificance of soil physical properties may have been the result of the inability to define or measure the appropriate variables.

Table 2. Soil Physical Properties of a Typic Fragiudalf. Average value for each plot is given.

Property	Plot 1	2	3	4	5
Depth of fragipan (cm)	73	75	74	76	94
Depth to bottom of fragipan (cm)	145	145	1/	1/	1/
Depth of root penetration (cm)	200	200	134	114	104
Soil moisture storage capacity (%) 2/					
0.30 to 15 atm	7.87	9.75	8.84	9.43	8.93
0.06 to 15 atm	16.34	19.67	18.47	20.06	22.59
Average volumetric soil moisture storage capacity of soil between 0.30 and 15 atmospheres					
Above fragipan ($cm^3 H_2O/cm^3$ soil)	0.108	0.130	0.119	0.124	0.095
Fragipan	0.051	0.068	3/	3/	3/

1/ Occurred over consolidated parent material.

2/ Soil moisture storage capacity of the profile above the fragipan.

3/ Not measured.

Chemical Soil Characteristics

The results of chemical analysis for each plot are presented in table 3. For simplification, the data for each horizon in the five plots have been averaged except the values for the A1 and A2 horizons which have been included because of their variability. The only chemical characteristics whose values appear to differ appreciably throughout the profile are magnesium, potassium, cation exchange capacity (CEC), exchangeable aluminum and carbon. The variability between horizons of the cations and the CEC is reflective of the clay content of the respective horizons. The fragipan horizon does not have characteristics appreciably different from those of the two horizons overlying it. The B'&A' and the B' horizons have a higher percentage clay content than the fragipan and therefore have larger amounts of exchangeable aluminum, magnesium, potassium, and a higher cation exchange capacity than it does. A low percentage carbon content has normally been associated with fragipan horizons (Grossman and Carlisle 1969; Peterson *et al.* 1970).

The high calcium content of the combined A1 and A2 horizons of plot 4, 3.53 meq/100g, as compared to an average of 0.76 for the other four plots, appears to be the effect of a flowering dogwood understory (*Cornus florida* L.) which was not found on the other plots. Several clumps of

dogwood grew in the plot area; one of the largest trees (3 m tall with a crown diameter of 2.5 m) was only 4 to 5 m from the plot center. Even though dogwood is usually a minor component of the vegetation within a forest stand, the high calcium content of the foliage coupled with the rapid decomposition of the litter results in the accumulation of large amounts of calcium in the surface soil beneath dogwood trees (Fowells 1965, Thomas 1969).

The high calcium content in plot 4 occurred only in the A1 and the A2 horizons which had a total depth of 12 cm. Below 12 cm the calcium content was similar to that of the other plots. Therefore, we attribute the increased content of calcium in the surface soil of this plot to the presence of dogwood.

Relationships were examined between soil fertility and annual volume growth, and between soil fertility and site index with and without consideration of the soil material underlying the fragipan (Table 4). The chemical data utilized were those for the A1 horizon and the weighted averages based on the horizons, their thicknesses, and bulk densities encompassed by the 0-10, 0-20, and 0-30 cm depths of soil, respectively.

Annual volume growth was significantly related to the carbon and nitrogen contents of the A1 horizon (Table 4). These were the only significant correlations between soil fertility and volume growth or site index which did not include the depth of soil over consolidated parent material as a variable. Site quality has been significantly related to organic matter or nitrogen content of the A1 horizon in two previous site studies of oak (Lunt 1939, McClurkin 1963). Soil color and structure, which are influenced by organic matter, are identifying characteristics of A horizon depth. Depth of A horizon has been found significant in a number of investigations relating the growth of oak to soil quality (Arend and Julander 1948, Gaiser 1951, Doolittle 1957, McGahan et al. 1961, Carmean 1965, Hannah 1968, and McQuilkin 1972). Mader and Owen (1961) have reported volume growth is more highly correlated with total organic matter and percentage nitrogen in the A horizon than with either total or annual height growth. Annual volume growth was significantly related to percentage aluminum saturation and pH for the A1 horizon and the 0-10, 0-20, and 0-30 cm depths; it was also significantly related to base saturation and calcium content for the 0-20 and 0-30 cm depths.

Site index was significantly correlated with only two soil chemical factors--percentage base saturation and pH for the 0-20 cm depth and percentage base saturation for the 0-30 cm depth (Table 4). Thus, site index of the study plots was not as well correlated with soil fertility as was annual volume growth. Since the time of major height growth occurs during the period when the soil above the fragipan is saturated (Fletcher and McDermott 1957), it is not surprising that site index of scarlet oak cannot be shown to be definitely related to soil chemical characteristics.

Table 3. Soil Chemical Properties of a Typic Fragiudalf. Average value for each plot is given.

Horizon	Depth	pH	Exchangeable Cations Ca	Mg	K	Na	CEC
	cm		meq/100g				
A1							
Plot 1	0-5	5.20	2.68	1.21	0.29	0.11	9.22
Plot 2	0-5	4.45	0.82	0.38	0.15	0.07	8.12
Plot 3	0-3	4.50	0.24	0.24*	0.13	0.07	6.72
Plot 4	0-6	5.75**	4.43**	0.69	0.15	0.09	8.41
Plot 5	0-5	4.80	0.45	0.35	0.19	0.07	7.00
Average		4.94	1.72	0.57	0.18	0.08	7.89
A2							
Plot 1	5-11	5.15	1.00	0.80	0.18	0.08	5.80
Plot 2	5-12	4.60	0.49	0.26	0.13	0.10	6.17
Plot 3	3-10	4.80	0.17*	1.30	0.09*	0.06*	5.24
Plot 4	6-12	5.60	2.63	0.70	0.11	0.08	5.80
Plot 5	5-12	4.90	0.26	0.42	0.21	0.08	5.10*
Average		5.01	0.91	0.70	0.14	0.08	5.62
B1		4.94	0.92	0.79	0.14	0.09	6.16
B2		4.87	0.82	1.76	0.19	0.12	9.91
B3		4.87	0.67*	2.70	0.21	0.17	13.61
B'&A'		4.66*	0.88	3.83	0.27	0.25	16.86
B'		4.41	0.93	4.67	0.29**	0.37	19.50**
IIB'31x		4.49	0.76	3.53	0.18	0.37	14.87
IIB'32x		4.49	1.06	3.47	0.12	0.52	13.15
IIC		4.78	3.58	7.16**	0.22	1.26**	18.72

* Lowest value
** Highest value

Fertility of the A1 horizon makes an important contribution to the site quality of a Typic Fragiudalf. Correlations of annual volume growth and site index with soil fertility variables for the A1, 0-10, 0-20, and 0-30 cm depths (depth of solum was not included as a variable) declined markedly with increasing soil depth. For example, for the correlation between annual volume growth and nitrogen content the coefficients declined from 0.88 for the A1 to 0.01 for the 0-30 cm depth. Such relationships would seem to indicate that the trees depend upon the A1 as a major source of nutrients. A further indication of the importance of the A1 horizon's fertility is the presence of a high concentration of roots. McNabb and Cox (1973) found that approximately 30% of the total root length in these soils occurred in the 3 to 6 cm thick A1 horizon.

Table 3. Continued.

Horizon	Al Exch.	Al Sol.	P	Base sat.	Al sat.	C	N
	--meq/100g--		ppm	%			
A1							
Plot 1	0.61	0.02	0.30	46.5	6.6	2.16**	0.15**
Plot 2	1.22	0.18	0.24	17.5	15.0	2.08	0.13
Plot 3	1.95	0.24	0.24	10.1*	29.1	1.43	0.09
Plot 4	0.02	0.01	0.21	63.9	0.2*	1.98	0.12
Plot 5	1.33	0.17	0.22	15.1	19.1	1.38	0.11
Average	1.03	0.12	0.24	30.6	14.0	1.81	0.12
A2							
Plot 1	0.69	0.02	0.09*	35.5	12.0	0.77	0.06
Plot 2	1.50	0.22	0.34	15.0	24.3	1.16	0.05
Plot 3	1.56	0.22	0.58**	31.3	29.8	0.68	0.07
Plot 4	0.01*	0.00*	0.31	60.7	0.2*	1.00	0.08
Plot 5	0.97	0.10	0.51	18.8	18.9	0.63	0.06
Average	0.95	0.11	0.37	32.4	17.0	0.85	0.06
B1	1.15	0.12	0.36	31.1	18.9	0.50	0.06
B2	2.74	0.17	0.24	27.7	28.0	0.30	0.05
B3	5.33	0.22	0.17	27.0	38.5	0.21	0.03
B'&A'	7.30	0.23**	0.22	30.7	43.1	0.18	0.03
B'	8.03**	0.21	0.13	32.4	41.1	0.17	0.03
IIB'31x	6.54	0.17	0.14	33.4	43.8**	0.10*	0.02*
IIB'32x	5.30	0.11	0.18	40.3	41.6	0.10*	0.02*
IIC	2.64	0.03	0.22	70.4**	14.2	0.10*	0.02*

* Lowest value
** Highest value

Aluminum

Magistad (1925) has shown as soil solution pH decreases below pH 5, the solubility of aluminum begins to increase and below pH 4.5, the increase is extremely rapid. In the present study, the average soil pH was less than 5 for all horizons below the B1, inclusive, and the average pH of the B' and the fragipan horizons was 4.5 or less (Table 3).

High solubility of aluminum is physiologically significant to plant growth. Biochemical evidence indicates that aluminum binds phosphorus on the external surfaces, cell walls, and free space of plant roots,

Table 4. Correlation Coefficients for Y = a + bx and Y = a + bx + c (depth)[1] between annual volume growth (Y) and site index (Y) of scarlet oak and soil chemical properties (x) of the A1 horizon and three soil fertility depths.[2]

Chemical Property Plus Soil Depth When Applicable	Depths Over Which Soil Fertility Was Averaged, cm							
	A1		0-10		0-20		0-30	
	Cor. Coef.	Partial Cor. Coef.	Cor. Coef.	Partial Cor. Coef.	Cor. Coef.	Partial Cor. Coef.	Cor. Coef.	Partial Cor. Coef.
Annual Volume Growth								
N	0.88	0.94	N.S.		N.S.		N.S.	
C	0.85	0.92	N.S.		N.S.		N.S.	
% Base Saturation	0.97	0.94	N.S.		0.97	0.95	0.98	0.97
+ Depth		0.98				0.98		0.99
Ca	N.S.		N.S.		0.96	0.94	0.98	0.96
+ Depth			N.S.			0.98		0.99
% Al Saturation	0.95	-0.92	0.97	-0.94	0.99	-0.98	0.97	-0.96
+ Depth		0.96		0.98		0.99		0.99
pH	0.98	0.97	0.97	0.95	0.98	0.97	0.99	0.99
+ Depth		0.99		0.99		0.99		0.99
Site Index								
% Base Saturation	N.S.		N.S.		0.96	0.93	0.98	0.97
+ Depth						0.98		0.99
pH	N.S.		N.S.		0.95	0.91	N.S.	
+ Depth						0.97		

[1] Soil profile depth over consolidated parent material of 2.0 m., whichever is less.
[2] Other soil variables tested (P>0.05) were K, P, Mg, Na, total bases, soluble Al, and exchangeable Al.

thus making phosphorus less available to metabolic sites within the cells (Foy 1974). Some of the aluminum absorbed by plant roots also appears to penetrate the cells of meristematic tissue and to interfere with cell division, respiration, DNA synthesis and sugar phosphorylation.

Annual volume growth significantly decreased as the percentage exchangeable aluminum increased (Table 4). However, this correlation is probably a combined effect of aluminum and soil fertility on site quality of scarlet oak. A correlation matrix of soil chemical properties by horizon resulted in significant correlations between all combinations of percentage exchangeable aluminum and calcium, percentage base saturation, total bases, soluble aluminum, and pH, indicating the interaction which occurs among these variables. The significant correlations between annual volume growth and site index and soil chemical properties included many of these same variables (Table 4).

In addition, root length of scarlet oak per unit volume of soil was found to be more significantly correlated with percentage exchangeable aluminum than other soil chemical properties, and the root length per volume of soil was found to increase as the percentage exchangeable aluminum increased (McNabb 1972). Thus, at the levels of aluminum found in these soils, the growth of scarlet oak roots was not adversely affected by aluminum toxicity *per se* but by the reduction in availability of calcium. For the horizons analyzed, percentage exchangeable aluminum was significantly correlated with more variables and at a higher significance level than other components of exchange capacity and pH.

For these reasons, the adverse effect of percentage exchangeable aluminum on annual volume growth is more apt to be the result of low availability of phosphorus and calcium rather than aluminum toxicity. The ability of scarlet oak to grow well on soils with a high exchangeable aluminum content and low availability of phosphorus probably represents a physiological adaptation developed over a long period of time.

CONCLUSIONS

The influence of a number of specific soil properties in soil-site studies often may best be determined by minimizing the effect of broad factors such as topography and aspect. While such studies cannot be conducted in all localities, the selection of study areas containing specific soil characteristics of interest can clarify how these factors influence site quality.

Annual volume growth of scarlet oak was more closely correlated with soil chemical composition than was site index. Soil chemical properties most important to volume growth are nitrogen, carbon, calcium, base saturation and pH of the A1 horizon. Neither annual volume growth nor site index was correlated with soil physical factors.

Scarlet oak roots have the ability to penetrate and utilize the soil to considerable depths, even in the presence of a fragipan.

Soil fertility of the surface horizon is of major importance to site quality of a Typic Fragiudalf because of the more favorable supply of nutrients and the increased concentration of roots in the surface horizon. Any forest practice which disturbs the roots or removes the A1 horizon can have an adverse effect on site quality.

LITERATURE CITED

Arend, J. L. and O. Julander. 1948. Oak sites in the Arkansas Ozarks. Arkansas Agr. Exp. Sta. Bull. 484.

Broadfoot, W. M. 1969. Problems in relating soil to site index for southern hardwoods. For. Sci. 15:354-364.

Carmean, W. H. 1965. Black oak site quality in relation to soil and topography in southeastern Ohio. Soil Sci. Soc. Amer. Proc. 29: 308-312.

_____. 1975. Forest site quality evaluation in the United States. In: N.C. Brady (ed.), Advances in Agronomy 27. Academic Press, New York.

DeByle, N. V. and I. C. M. Place. 1959. Rooting habits of oak and pine on Plainfield sand in central Wisconsin. Wisconsin Coll. Agri. For. Res. Note No. 44.

Doolittle, W. T. 1957. Site index of scarlet and black oak in relation to Southern Appalachian soil and topography. For. Sci. 3:114-124.

Fletcher, P. W. and R. E. McDermott. 1957. Moisture depletion by forest cover on a seasonally saturated Ozark ridge soil. Soil Sci. Soc. Amer. Proc. 21:547-550.

Fowells, H. A. 1965. Silvics of forest trees of the United States. USDA Forest Serv. Agr. Handbook No. 271.

Foy, C. D. 1974. Effects of aluminum on plant growth. pp. 601-642. In: E. W. Carson (ed.). The Plant Root and Its Environment. Univ. Press of Virginia, Charlottesville.

Gaiser, R. N. 1951. Relation between topography, soil characteristics, and the site index of white oak in southeastern Ohio. USDA Forest Serv. Central States Forest Exp. Sta. Tech. Paper 121.

Grossman, R. B. and F. J. Carlisle. 1969. Fragipan soils of the eastern United States. pp. 237-279. In: N. C. Brady (ed.). Advances in Agronomy 21. Academic Press, New York.

Hannah, P. R. 1968. Topography and soil relations for white and black oak in southern Indiana. USDA Forest Serv. North Central Forest Exp. Sta. Res. Paper NC-25.

Hodgkins, E. J. 1959. Forest site classification in the southeast: an evaluation. pp. 34-48. In: P. Y. Burns (ed.) Southern Forest Soils. 8th Annual For. Symp. Louisiana State Univ. Press, Baton Rouge.

Hoyt, P. B. and M. Nyborg. 1971. Toxic metals in acid soil: I. Estimation of plant-available aluminum. Soil Sci. Soc. Amer. Proc. 35: 236-240.

Lunt, H. A. 1939. Soil characteristics, topography, and lesser vegetation in relation to site quality of second-growth oak stands in Connecticut. J. Agr. Res. 59:407-428.

McClurkin, D. C. 1963. Soil-site index predictions for white oak in North Mississippi and West Tennessee. For. Sci. 9:108-113.

McGahan, N. W., J. H. Brown, Jr., W. P. Gould, H. C. Lampe, and R. E. Shearin. 1961. Soil conditions and tree growth analyses in Rhode Island forests. Rhode Island Agr. Exp. Sta. Bull. 357.

McNabb, David H. 1972. Some soil-site relationships of a typic fragiudalf. M.S. Thesis. Univ. of Missouri, Columbia. 218 pp.

McNabb, D. H. and G. S. Cox. 1973. Distribution of upland oak roots in a typic fragiudalf. Agronomy Abstracts: 141.

McQuilkin, Robert A. 1972. The relationships of soil and topographic variables to black oak site index in southeastern Missouri. Ph.D. Dissertation. Univ. of Missouri, Columbia.

Mader, D. L. and D. F. Owen. 1961. Relationships between soil properties and red pine growth in Massachusetts. Soil Sci. Soc. Amer. Proc. 25: 62-65.

Magistad, O. C. 1925. The aluminum content of the soil solution and its relation to soil reaction and plant growth. Soil Sci. 20:181-226.

Peterson, G. W., R. W. Ranney, R. L. Cunningham, and R. P. Matelski. 1970. Fragipans in Pennsylvania soils: a statistical study of laboratory data. Soil Sci. Soc. Amer. Proc. 34:719-722.

Thomas, W. A. 1969. Accumulation and cycling of calcium by dogwood trees. Ecol. Monogr. 39:101-120.

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