EXCESS CALCIUM AND MAGNESIUM ASSOCIATED WITH LOWER CROWN MORTALITY OF PIN OAK

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Abstract. The ornamental value of pin oak trees is reduced when their descending lower branches die. In the upper Midwest, USA, premature dieback of lower branches is common among pin oak trees planted in soils that are calcareous within 1.5 m of the surface. Of 11 mineral nutrients, only Ca and Mg were more concentrated in the leaves of lower branches than in those found higher in the crown. The Ca concentrations of leaves of lower branches of trees showing dieback were much higher than those from trees without dieback. Small necrotic spots of apparently abiotic origin developed in early summer on either green or chlorotic leaves of lower branches and consistently formed before dieback occurred in the subsequent year. Excessive Mg was closely associated with this condition. Green pin oaks at dieback sites had actively absorbing roots within calcareous C horizons of otherwise acidic soils suggesting a source for absorption of the high concentrations of both Ca and Mg in the leaves. Methods of reducing Ca and Mg uptake are discussed.

Shading often induces death of lower branches of tree stems (10, 11). Consequently, after the crowns of trees in dense stands close, the lower branches begin to die, leading to a progressive decrease in the live-crown ratio (percent of total tree height occupied by functional branches). When the live-crown ratio decreases to a critical value, about 40% in many species, the rate of wood production decreases greatly (10, 11).

The lower pendulous branches of pin oak (*Quercus palustris*) make it very distinctive and a widely used tree for landscaping in the United States (4). Thus, when pin oak is grown as an ornamental tree, loss of its lower limbs has a special aesthetic significance.

The loss of lower branches of open-grown pin oaks has been reported, but only as a function of old age (4). During the past decade, the senior author has observed numerous young (20-30 year-old) chlorotic pin oaks with all their pendulous branches gone, dead, or dying. At first, chlorosis was assumed to be necessary for dieback of the lower branches of relatively young, open-grown trees, but continued observations proved otherwise. Loss of lower branches also was observed on green trees in old fields and lawns. Several of these trees were in the Morton Arboretum, Lisle, Illinois, and had been planted in Mollisols with seasonally high water tables, or in Alfisols that were well-drained to somewhat poorly drained. Regardless of the soil type, the upper solum (solum = A+E+B horizons) associated with each arboretum tree was slightly to moderately acid, and the lower solum and/or C horizon was calcareous within 1.5 m of the surface. These calcareous conditions are a function of the dolomitic limestone fragments in the Wisconsinan glacial till present throughout northeastern Illinois (21).

Toxicity in higher plants can be an effect of high concentrations of any essential or non-essential mineral element. For example, Ca^{2+}, Mg^{2+}, K^+, or NO_3^- can be toxic if present in high concentration (7).

Calcium is considered to be an immobile element because there is little translocation of calcium in the phloem. Consequently, calcium concentrations in leaves tend to increase with leaf age. Excesses may exist as deposits of calcium oxalate, carbonate, and phosphate which accumulate in cell vacuoles (20). Ca is generally considered to be non-toxic even at high concentrations, and very few symptoms of Ca excess have been reported (2,12). However, some woody acidophytes (plants with an affinity for acid soils) may accumulate toxic concentrations of Ca as in the case of an acid soil ecotype of *Eucalyptus obliqua* (1). In this case, seedlings did not show leaf necrosis at foliar concentrations of 0.50% Ca, but most died when concentrations reached approximately 1.0%. Leaf Ca concentrations of most woody plants are considered intermediate (neither deficient nor excessive) when they range between

1.0 and 5.5%. Soil-grown blueberries (*Vaccinium* spp., also acidophytes), however, have an intermediate range of 0.31 to 0.54% (2). Pin oak trees in northeastern Illinois soils, whether green and growing on acid soils or chlorotic and growing on calcareous soils, had average Ca concentrations ranging from 0.36% in early June to 0.50% in late August (14).

Magnesium is a mobile element and is readily translocated from older to younger plant parts in the event of a deficiency (20). Excess Mg is stored predominantly in vacuoles as inorganic salts (12). Magnesium occurs in toxic concentrations in certain soils and locations, particularly in semi-arid regions. Possibly because there has been far more agricultural interest in Mg deficiency than in Mg toxicity, little information is available on visual symptoms of Mg excess or toxicity, or associated tissue concentrations (5,7). Embleton (5) concluded that in most studies of Mg excess, Mg in the plant was high enough to become unbalanced with one or more other elements within the plant. Important interactions of this kind include Mg/Ca, Mg/N, and Mg/Mn (8).

While the Mg requirement for optimal plant growth generally is near 0.5% of the dry weight of the vegetative tissues (12), trees may require considerably lower concentrations (11). For example, intermediate concentrations of Mg in the needles of pines range from 0.12% to 0.18%, and those of Norway spruce from 0.07% to 0.17% with 0.11 to 0.17% considered high. Leaves of azalea, a woody acidophyte like pin oak, have been reported to have an average intermediate concentration of 0.17% (5). In northern Illinois, the leaves of green, apparently healthy pin oaks had mean Mg concentrations of 0.18% in late spring and ranged to 0.21% in mid- and late summer. Leaves of chlorotic trees had seasonal Mg means of 0.19% to 0.26%. Since late summer concentrations of Mg varied appreciably between green and chlorotic trees, the chlorotic trees were considered to have excessive foliar Mg concentrations (14).

In accord with the rationale used in interpreting the pin oak data, similar studies indicated that late summer Mg concentrations of 0.30% and 0.48% were excessive in chlorotic white oaks and red maples, respectively. Late summer concentrations of Mg in green leaves of apparently healthy trees of these two species were 0.22% and 0.40%, respectively (15, 16). The interveinal chlorosis in each case apparently was lime-induced (15), pointing to an association between excess foliar Mg and dissolution products of dolomitic limestone. These studies suggest that the concentrations of Ca and Mg that are normal for leaves of many plants are likely to be excessive and possibly toxic to acidophytes or calcifuges (plants with obligate relationships to acid soils).

The research reported here investigated the spatial distribution of mineral nutrients in the crowns of green, apparently healthy pin oaks grown in soils with acid solums and calcareous C horizons. The study also investigated soil moisture depletion at various soil depths to determine if pin oak roots of green trees absorbed water from the deeper calcareous horizons. This investigation also compared concentrations of mineral nutrients in the lower branches of trees with varying degrees of health. Lastly, it analyzed leaves with small necrotic spots which developed before death of lower branches.

Methods and Materials

In the period 1984-1988, four green, previously well-formed pin oaks at the Morton Arboretum began to show dieback of lower branches. In July and August of each year, leaves of the lower branches of trees undergoing dieback at the time were collected and analyzed. Later their mineral nutrient composition was compared with samples taken from nine nearby, unaffected trees in July and August of 1984 through 1988 using the statistical technique described by Kenny (9), whereby concentrations two and one-half of the standard deviations from the healthy tree means are classed as "outliers", and would represent abnormal physiological concentrations.

The leaves of seven healthy pin oak trees with pendulous lower branches were sampled to determine if the mineral composition of leaves of the upper and lower crowns differed significantly. Upper, middle, and lower crown leaf samples were taken from each tree in June, July, and August during the span 1985-1988. The samples were prepared for chemical analysis as previously described (14) and the analytical results subjected to an automated analysis of variance F-test (19). All seven trees were rooted in soils derived from calcareous clay loam glacial till. Three were situated on a well-drained hilltop, while the four remaining trees were growing on a somewhat poorly drained site. Soil samples were collected to a depth of one meter or more at several locations within each site. Electrometric pH determinations were made on fresh soil samples (13).

Dieback of the lower branches of both green and chlorotic trees was consistently preceded by small (approximately 1 mm in diameter) necrotic spots which developed on lower-crown leaves in mid- to late summer. To test for leaf nutrient implications of these spots on chlorotic leaves, all chemical element data for whole crown leaf samples collected in mid- to late summer from local pin oaks were acquired and subjected to a Student's t-test (22) for significant differences between trees having chlorotic leaves with numerous spots and trees having chlorotic leaves with few or no spots. To test for leaf nutrient implications of the spots on green leaves, whole crown comparisons of three green trees with necrotic spots on lower leaves and three green trees without necrotic spots were made by sampling each tree in June, July, and August for a three-year period. To test for differences in nutrient concentrations, sample data were subjected to a computerized t-test (19).

To ascertain whether or not the roots of green pin oaks at the study sites had absorbed appreciable amounts of water from the calcareous C horizons, soil moisture monitoring data derived from 18 neutron probe access tubes were used. Six 1.5 m long tubes were installed around each of three trees with root systems isolated by lined trenches. The isolated areas were kept free of other plants. The soil around one tree was monitored weekly during three successive growing seasons (1986-1988). The soil around each of two other trees was monitored weekly during the 1988 growing season only.

Results and Discussion

Average soil pH profiles for each of the two sites involved in this study indicated that the solum was more acid at the somewhat poorly drained site, but, as is typical of glacial till and loess-derived soils of northeastern Illinois, soils at both sites were alkaline within 1.5 m of the surface (Figure 1).

The seven healthy pin oaks with pendulous lower branches monitored seasonally during the period 1985-1988 revealed that only foliar Ca and Mg concentrations varied significantly with crown position on visibly healthy trees. Both nutrients were consistently most concentrated in lower crown leaves (Table 1).

During dieback of the lower branches of four otherwise healthy-appearing pin oaks, the green leaves adjacent to dying branches contained mid- to late summer Ca concentrations equivalent to 3 - 9 standard deviations above the mean concentration of 49 mid- to late summer samples from healthy lower branches of nine trees (Table 2). In the four stressed trees, foliar concentrations of

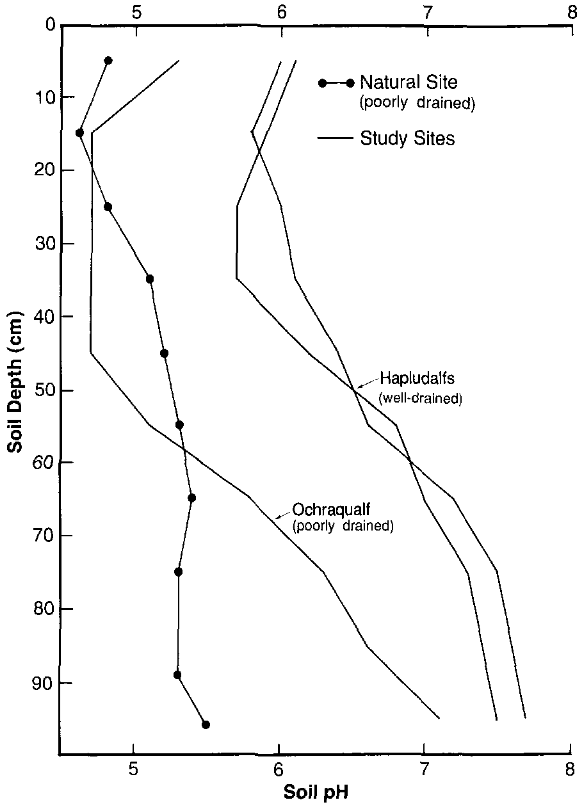

Figure 1. Soil pH profiles at the Morton Arboretum study sites and at the nearest natural pin oak site.

Table 1. Mean concentrations of mineral nutrients in leaves of seven green pin oaks at three crown levels, 1985-88.

		Macronutrients (% dry weight)						Micronutrients & Aluminum (µg/g)					
		N	S	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu	Al
June	U	2.14	0.12	0.13	0.69	0.20	0.33*	28	38	282	105	9.0	40
	M	2.11	0.12	0.12	0.67	0.21	0.35*	26	38	301	97	9.2	38
	L	2.13	0.11	0.13	0.67	0.23	0.43*	27	40	353	105	9.2	43
July	U	2.23	0.18	0.12	0.71	0.23*	0.41*	37	42	369	106	8.4	52
	M	2.28	0.17	0.12	0.71	0.23*	0.45*	38	45	372	107	8.3	43
	L	2.25	0.16	0.12	0.67	0.26*	0.54*	35	45	423	113	8.6	50
Aug	U	2.32	0.14	0.11	0.74	0.26*	0.44*	47	50	497	111	8.0	59
	M	2.30	0.15	0.11	0.73	0.26*	0.47*	45	51	505	117	8.0	58
	L	2.25	0.13	0.12	0.71	0.28*	0.54*	44	48	443	125	7.0	74

U = upper third, M = middle third, L = lower third of the live crown
* significant differences ($p = 0.05$, $n = 153$) among crown levels

other nutrients were mostly within one standard deviation of the mean concentrations of healthy trees. Not only were Ca concentrations extremely high for pin oaks, but they were also in the range considered toxic for the acidophytic ecotype of *Eucalyptus obliqua*.

Over a three-year period, at the somewhat poorly drained site, whole-crown comparisons of three green trees with necrotic spots on lower crown leaves vs. three green trees without necrotic spots on lower crown leaves showed that concentrations of mineral elements of leaves changed during the growing season (Table 3). In early June, before the necrotic spots developed, trees that would develop them later in the season had lower whole-crown foliar Mn concentrations, but these were all above 150 µg/g, not nearly low enough to be considered deficient (14). The lower Mn is interpreted as reflecting a relatively high pH of soil in the root zone. When necrotic spots developed in mid-July of each year, the trees with spotted leaves had higher whole-crown foliar concentrations of P, Mg, Fe, and Al and lower concentrations of Mn than trees with unspotted leaves. By

Table 2. Concentrations of mineral nutrients in lower branches of green pin oaks during dieback of lower branches compared to concentrations in lower branches of healthy trees.

		Macronutrients (% dry weight)						Micronutrients & Aluminum (µg/g)					
		N	S	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu	Al
Healthy	$\bar{x}$	2.32	0.15	0.12	0.69	0.27	0.52	38	47	488	119	8.0	60
trees	±SD	0.22	0.04	0.01	0.11	0.05	0.06	9	10	265	28	1.9	25
Trees	1	2.30	0.05*	0.10	0.61	0.29	0.69*	39	26	247	82	7	70
with	2	2.40	0.13	0.12	0.66	0.42*	0.87*	38	28	279	125	6	50
active	3	2.25	0.16	0.13	0.80	0.33	0.88*	36	61	251	111	9	30
dieback	4	1.91	0.15	0.11	0.55	0.36	1.08*	54	62	222	102	7	60

* Equivalent to two and one-half or more standard deviations from the healthy mean.

Table 3. Concentrations of mineral nutrients in whole crowns of green pin oaks with necrotic spots on lower leaves (+) compared to concentrations in trees without spots (0).

		Macronutrients (% dry weight)						Micronutrients & Aluminum (µg/g)					
		N	S	P	K	Mg	Ca	B	Zn	Mn	Fe	Cu	Al
June	+	2.43	0.10	0.18	0.95	0.22	0.43	19	41	197*	103	10.3	59
	0	2.25	0.11	0.17	0.87	0.20	0.41	17	35	472*	100	10.0	53
July	+	2.20	0.14	0.13*	0.90	0.24*	0.52	28	44	276*	121*	8.6	71*
	0	2.09	0.17	0.11*	0.86	0.20*	0.49	28	41	753*	100*	7.9	57*
Aug	+	2.14	0.14	0.13*	0.86	0.30*	0.59*	38	45*	305*	124	6.8	101
	0	2.05	0.15	0.11*	0.91	0.24*	0.51*	49	41*	877*	110	5.6	83

*=*indicate significant differences* (P=0.05)
Each value represents the mean of nine samples

late August, the trees with spotted leaves had higher whole-crown foliar concentrations of P, Mg, Ca, and Zn, and continued to have lower, but non-deficient concentrations of Mn. In these trees, since whole-crown P and Mg were both consistently high when necrotic spots were present, it was assumed that leaves of the spotted lower crowns had an even greater excess of Mg. Hence, they apparently contained excessive amounts of Mg throughout the time of necrotic spot occurrence, whereas excessive Ca was significant only toward the end of this time.

Chlorotic pin oaks in an earlier study (14) had, on average, whole-crown foliar Ca concentrations approximating those in green trees, despite their association with calcareous solums. Instead, chlorotic trees had unusually high whole-crown foliar P and K concentrations in June and July, and excessive Mg concentrations in late August. Separating and statistically comparing the P, K, Mg, and Ca data for chlorotic trees revealed that chlorotic trees with necrotic spots had higher foliar Mg concentrations than those without necrotic spots. This was the only mineral nutrient with concentrations significantly different from those in chlorotic trees lacking necrotic spots, both in late August and mid-July (Table 4). Although excessive Ca was present in some samples, in neither mid-July nor late August was it a statistically significant characteristic of chlorotic trees with spotted lower leaves.

Maximum availability of Ca and Mg is commonly associated with soil pHs between 7.0 and 8.5 (6). Thus, at the planted pin oak sites used in this study, maximum availability of these macronutrients would be expected below a soil depth of

Table 4. Concentrations of P, K, Mg, and Ca in leaves of whole crowns of chlorotic pin oaks with and without necrotic leaf spots.

	% P			% K			% Mg			% Ca		
	June	July	August	June	July	August	June	July	August	June	July	August
Trees with spots	0.20	0.14	0.15	0.96	0.88	0.89	0.21	0.23	0.30	0.40	0.45	0.57
Trees without spots	0.19	9.13	0.14	0.89	0.78	0.80	0.19	0.21	0.23	0.35	0.40	0.46
Statistical significance	NS	NS	NS	NS	NS	NS	NS	0.05	0.01	NS	NS	NS

n, trees with spots: 28 (June), 25 (July), 30 (August)
n, trees without spots: 19 (June), 17 (July), 14 (Agusut)

Table 5. Variations over time of foliar Mg and Ca concentrations in whole crowns of pin oak trees at two sites differing in depth of soil acidity.

Site	June	July	August		Level of signif. diff.
% Mg	Deeply acid	0.13	0.18	0.17	1%
	Shallowly acid	0.22	0.26	0.24	
% Ca	Deeply acid	0.25	0.43	0.53	Not significant
	Shallowly acid	0.40	0.56	0.52	

values for the deeply acid site represent the means for three trees
values for the shallowly acid site represent the means for four trees

approximately 65 cm at the well-drained site, and below approximately 90 cm at the somewhat poorly drained site (Figure 1). At both of these sites, pH increased sharply between 35 and 65 cm depth. In contrast, at the nearest natural pin oak site, the soil was strongly acid to a depth of one meter. That these differences may affect foliar Mg is suggested by the F-test differences in foliar Mg

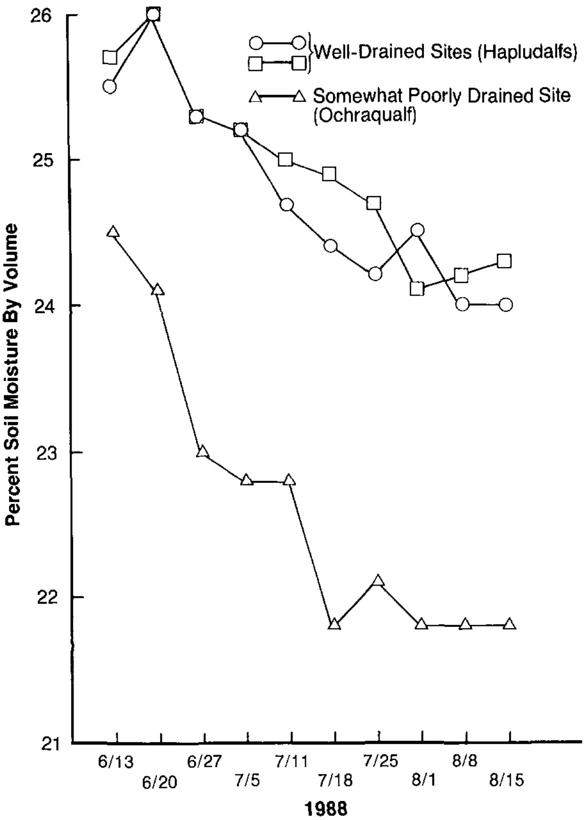

Figure 2. Soil moisture depletion at 1-1.5 m depth around isolated pin oak root systems.

between trees at the planted well-drained sites and those at the deeply acid natural site (Table 5). Whereas no trees at the natural site showed necrotic leaf spots or dieback of lower branches, most trees at the study sites exhibited varying degrees of these abnormalities.

Soil moisture depletion data at 1 to 1.5 m depths showed that pin oak roots absorbed water efficiently from alkaline horizons of the soils at the study sites (Figure 2). The reason for rapid depletion of soil water at the poorly drained site is not clear, but probably reflects a more densely distributed root system.

Methods to curtail excessive accumulations of foliar Ca and Mg have not been reported. Theoretically, their reduction should be favored by leaching the soil of the rooting zone with an acidic solution containing aluminum ions (3). Rainfall infiltration into a calcareous soil treated with a surface application of aluminum sulfate can lower surface soil pH (12). Aluminum sulfate, applied to the surface of a calcareous soil, had a favorable effect on pin oaks planted in holes previously acidified with sulfuric acid (17).

Nitrogen absorbed as nitrate can result in excessive foliar levels of Ca, Mg, and K (12,18). To decrease uptake of nitrates, fertilizers containing nitrates should not be used, and conditions should be made unfavorable for the conversion of ammonium to nitrates by soil bacteria. Wet, acid soils such as those supporting natural stands of pin oak inhibit this conversion, an oxidation process usually referred to as nitrification. Additional soil moisture should not be supplied in the form of tapwater or sump pump water drawn from Ca- and Mg-rich groundwater. Instead, an acid-forming mulch should be used to prolong surface soil moisture derived directly from rains or snowmelt.

Conclusions

Premature dieback of the lower branches of pin oak trees was closely correlated with high concentrations of Ca and Mg in lower crown leaves. In northern Illinois, interveinally chlorotic trees can obtain excessive amounts of Ca and Mg from the entire rooting zone, most of which is calcareous. Absorption by roots in the calcareous C horizons of otherwise acid soils contributes to excesses of Ca and Mg in green trees. Application of aluminum sulfate to the soil surface may be useful for reducing or preventing excessive uptake of Ca and Mg.

The high concentrations of Ca and Mg in the lower branches, although highly correlated with lower branch dieback in this study, should not be assumed to be a total explanation of the physiological mechanism(s) which leads to the lower limb mortality. Further experimentation is needed to determine the physiological basis of this association.

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Résumé. Dans le haut Midwest (centre) des États-Unis, le dépérissement prématuré des grosses branches basses est chose commune parmi les arbres plantés dans les sols calcaires à moins de 1.5 mètre de la surface. Les concentrations foliaires en éléments minéraux étaient surveillées à trois niveaux de la cime de sept chênes des marais. Des 11 éléments minéraux foliaires, seul le calcium et la magnésium étaient significativement plus concentrés dans les branches basses que les branches plus élevées. Les concentrations en calcium dans les branches les plus basses des arbres qui éprouvaient un dépérissement étaient excessives et statistiquement plus élevées que celles des arbres qui n'éprouvaient pas de dépérissement. Les petites régions nécrosées, d'origine apparemment abiotique, qui se développaient autant sur les feuilles vertes que chlorotiques des branches basses, tôt au printemps, sont logiquement antérieures au dépérissement de l'année subséquente. Le magnésium en excès fut associé de près à cet état. Un contrôle de l'humidité avec une sonde à neutron sur les sites de dépérissement indiquait que les chênes des marais avaient des racines actives dans les horizons C calcaires de sols autrement acides. Des mesures pour réduire l'assimilation en calcium et en magnésium sont suggérées.

Zusammenfassung. Im nördlichen Teil des Mittleren Westens der USA ist auf Standorten mit kalkreichen Böden bis in 1,5 m Tiefe bei einigen Bäumen ein vorzeitiges Absterben der unteren Äste zu beobachten. Die Nährelementkonzentrationen der Blätter drei verschiedener Kronenhöhen von seiben "pin oaks" (Sumpfeichen) wurden kontrolliert. Von 11 untersuchten Nährelementen zeigten nur in den Blättern der unteren Äste Kalzium und Magnesium signifikant höhere Konzentrationen im Vergleich zu den Blättern der höher gelegenen Äste. Bei absterbenden Eichen waren die Kalziumkonzentrationen signifikant höher als bei Bäumen ohne Schadsymptome. Ein Zusammenhang besteht offenbar zwischen dem Erscheinen kleiner nekrotischer Bereiche, augenscheinlich abiotischen Ursprungs, die sich entweder auf grünen oder chlorotischen Blättern der unteren Äste im Frühsommer entwickeln und dem Absterben in einem der folgenden Jahre. Übermäßiger Magnesiumgehalt war eng korreliert mit diesem Zustand. Die Untersuchungen auf den Absterbeflächen wiesen darauf hin, daß "pin oaks" innerhalb der kalkreichen C-Horizonte aktive Wurzeln bei ansonsten sauren Böden haben. Schritte zur Reduzierung der Kalzium- und Magnesiumaufnahme werden vorgeschlagen.