MACRONUTRIENT DEFICIENCY SYMPTOMS IN SEEDLINGS OF FOUR NORTHERN HARDWOODS

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Presently very little is known about the inorganic nutrient requirements of our important northern hardwood species. Little information concerning optimum nutrient levels, critical ranges for essential elements, visual deficiency symptoms, and physiological effects of nutrient deficiencies has been published.

Detecting deficiencies is essential if timely corrective action is to be undertaken. A visual foliar symptom approach is rapid, inexpensive, and reliable as leaves are especially sensitive indicators of deficiencies (Kramer and Kozlowski 1960). However, before any corrective action is taken, supplemental chemical analyses of foliar tissue should be made to verify suspected nutrient deficiencies (Phares and Finn 1972).

Deficiency symptoms for some hardwoods have been described: basswood (Ashby 1959, Ashby and Mika, 1959); pin oak (Hacskaylo and Struthers 1959); locust and sweetgum (Hacskaylo 1960); American elm, box elder, hackberry, Russian olive, and silver maple (Sucoff 1961, Perala and Sucoff 1965, Lamb and Murphy 1968); eastern cottonwood (Hacskaylo and Vimmerstedt 1967); yellow-poplar (Ike 1968); black locust, black walnut, eastern cottonwood and pin oak (Hacskaylo *et al.* 1969); black walnut (Phares and Finn 1972); red maple, gray birch, and black cherry (Walker 1956); and red maple (Smith 1976). Except for Ashby, Walker, and Smith, little information is available on the effects of deficiencies on the growth of northern hardwood species.

Several related studies have dealt with potassium deficiencies in American elm (Perala and Sucoff 1965), effects of macronutrient and molybdenum deficiencies on yellow birch growth and nutrient uptake (LaFlamme and Lafond 1967, Hoyle 1971, and Hannah 1973), effects of various levels of N, P, and K on paper birch growth (Bjorkbom 1973), the relation of nitrogen deficiencies to sugar maple decline (Mader *et al.* 1969), and the effect of Mn and Cu on P uptake in sugar maple. (Gysi *et al.* 1975).

Our studies were established to observe, photograph, and report distinctive visual deficiency symptoms for the macronutrient elements (N, P, K, Ca, Mg, and S) in sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.), white ash (*Fraxinus americana* L.), and paper birch (*Betula papyrifer* Marsh.) seedlings. Deficiency symptoms illustrated in this paper together with supporting foliar analyses and growth data are presented as preliminary guides in diagnosing nutritional disorders of these seedlings grown under nursery, greenhouse, and laboratory conditions.

The chemical composition and ovendry weights of foliage, stems, and roots of seedlings grown in complete single element deficiency solutions and distilled water were compared. Seedling

height growth and the number of leaves produced per seedling under the various treatments were also compared.

METHODS

Sand culture nutrient deficiency studies with young sugar maple, red maple, paper birch, and white ash seedlings were conducted in the Forestry Sciences Laboratory greenhouse at Marquette, Michigan. The maples were studied in the summer of 1972; the ash and birch were studied in the summer of 1973.

Sugar maple seeds with protruding radicles and emerging red maples in the cotyledon stage were gathered, rinsed thoroughly with distilled water, and planted directly in pots. Paper birch seeds were germinated in distilled water in petri dishes under fluorescent light until cotyledons expanded. The radical end of white ash seed, which was difficult to germinate, was clipped to promote uniform germination. After clipping, the seeds were placed on damp filter paper in petri dishes until seeds with elongating radicles were available for planting.

Two to three germinants were planted in 660 grams of high-grade silica sand in 550 cm^3 clay pots lined with inert, clear polyethylene bags. Pin holes were pricked into the plastic bags through the basal hole of the clay pot for bottom drainage. The sand in the 1973 birch and ash trials was leached with 20 percent cold hydrochloric acid (for 3 days followed by washing with distilled water until there was no change in pH of the standing water); unleached sand was used in the earlier 1972 maple trials. The improved procedure in 1973 was thought necessary to produce Fe deficiency symptoms and a better procedure for producing Ca deficiency symptoms with the high-grade silica sand.

Germinants were grown in distilled water and then conditioned in gradually strengthened complete nutrient solutions for 46, 25, 65, and 33 days for sugar maple, red maple, paper birch, and white ash, respectively. Seedlings in each pot were thinned to leave the most vigorous individual.

Following the development of the first true leaves, the seedlings were given a complete nutrient plus Fe-EDTA solution (Hacskaylo 1960) until 120 ml of full strength solution per pot was accumulated and retained by capillary action. At the end of the conditioning period the pots were flushed with 150 ml of distilled water and the deficiency treatments were begun. Thereafter pots were reflushed with distilled H_2O and replenished with appropriate fresh nutrient solutions at 2-week intervals.

Cultural solutions were complete except for the omission of one of six elements: N, P, K, Ca, Mg, or S. Treatments also included controls: one with the complete nutrient solution, and one with distilled water only. Controls were used as checks on contamination and to provide a basis for judging growth responses after deficiency treatments were applied. Solutions were prepared with reagent grade or high purity chemicals and Pyrex-glass distilled water (See Appendix, table 25 and 26 for composition, substitutions, and strength of the solutions used). Cultural solution pH values used in the pots ranged from 4.8 to 5.5 and were 5.8 for the distilled water. Watering and flushing kept pH values above pH 5.0 in all treatments. Moisture losses were monitored with

weighed representative pots and replaced once or twice daily with distilled water. Nutrient status in the pots was maintained by adding 10 ml of cultural solution once each week and completely flushing and replenishing with new nutrient solution every two weeks. Injurious surface concentrations of salts, formed by rapid evaporation of cultural solutions added from above during hot weather (Hewitt 1966), were avoided by top watering, breaking up surface crusts weekly, and biweekly flushing. Maples were grown in deficient cultural solutions for 117 days; ash and birch for 113 days.

A randomized block design with 5 replications of the 6 deficiency and 2 control treatments was used for each species. Individual potted seedlings within each replication were the experimental units to which treatments were randomly applied. Each replication was formed by selecting seedlings of uniform heights. There were two complete nutrient controls in each birch and ash replicated, but only one for the maples.

Plants were grown under at least a 16-hour photoperiod with supplemental fluorescent and incandescent lighting of 200- to 300-foot candles at the leaf surface. The greenhouse was covered with a shade cloth to reduce normal daylight intensity by 50 percent and to lower summer greenhouse temperatures. Day temperatures were kept below 34C and night temperatures above 12C. Insects were controlled by hand. Pots within replications and entire replications were rotated twice weekly to equalize bench and lighting effects.

Visual deficiency symptoms were described as they appeared, followed at weekly intervals throughout their development, and photographed at significant stages. Symptoms included unusual color, necrosis, wilting, distortions; general size and growth of leaves, petioles, buds, and stems. Also noted were changes in color of interveinal areas, veins, bases, margins, and tips of young and old leaves. Types of necrosis in leaves included: marginal scorch, tip scorch, salting, spotting, and blotching. “Salting” refers to grain-sized spots of salt; “spotting” to pinhead-sized spots; and “blotching” to individual, usually irregularly-shaped areas larger than spots which became necrotic all at once. Significant growth reductions in seedling height growth and in ovendry weights of component parts as compared to the complete nutrient controls were also considered diagnostic of a sever nutrient deficiency.

Seedling height growth was measured at 2-week intervals. At completion of the study, leaves were counted and plants were separated into leaves, stems, and roots. Chemical analyses of these components were made on composited samples from the five replications, ovendried at 70C , and ground in a Wiley mill to pass a 20-mesh screen. Various stages of deficiency symptoms and leaf maturity are represented in the analyzed material. Total nitrogen was determined by the semimicro-Kjeldahl method (Bremner 1965); total S was by nitric perchloric acid digestion (Tabatabai and Bremner 1970); and P, K, Ca, Mg, Fe, Al, Cu, Zn, B, and Mn by emission spectrography of dry-ashed (485C for 4 to 5 hours) samples. Checks with duplicate samples proved to be satisfactory.

Treatment effects on seedling growth, weight, and size were evaluated with an analysis of variance and Duncan’s New Multiple Range test. Compositing samples to obtain sufficient material for chemical analyses ruled out statistical tests of the influence of treatments on nutrient content.

Supplemental laboratory studies were run in the summer of 1975 to get better quality photos for P and K in sugar maple and P and S in white ash seedlings.

VISUAL DEFICIENCY SYMPTOMS, EFFECTS ON GROWTH AND CHEMICAL COMPOSITION OF SEEDLINGS

Visual foliar symptoms of nutrient deficiencies are described separately for each species because symptoms for a given element often varied markedly among species. This approach should make it easier to pinpoint deficiencies within a species. Color photographs illustrate plants exhibiting distinguishing foliar symptoms and advanced stages of each deficiency.

Seedlings grown in complete nutrient solutions were healthy plants with normal leaves (figs. 1A, 2A, 3A, 4A). Their foliage was dark green except for white ash which varied from green to dark green. Expanding apical leaves on all species normally were light colored or reddish. These colors were not indicative of deficiencies.

All seedlings grown in distilled water without nutrients were stunted and had small yellow-green, yellow, or red foliage and petioles (figs. 1B, 2B, 3B, 4B). Height growth on sugar maple and red maple seedlings, ceased immediately after they were put in distilled water cultures, while white ashes and paper birches stopped growing after 14 and 21 days, respectively. Foliage on distilled water seedlings was borne at abnormal angles to the stem.

Besides foliar symptoms, many deficiencies caused obvious growth reductions and other effects on the above-ground parts of seedlings. These growth losses often occurred before any visual foliar symptoms appeared, particularly in the cases of nitrogen, phosphorus, or calcium deficiencies. As with visual foliar symptoms, the impact of a certain nutrient deficiency on growth often differed among species.

The effect deficiencies had on height growth varied with species. The height growth of white ash and sugar maple seedlings was not as greatly affected by deficiencies because they stopped growing soon after treatments were begun. Paper birch and red maple seedlings, on the other hand, continued growing longer, allowing more time for the deficiencies to influence growth. (Only statistically significant effects of seedling growth responses are given in this section (tables 1-24).

Chemical analysis of seedling parts verified the deficiencies, while the data provide a guide to the magnitude of the differences that can be expected between abnormal and healthy seedlings elsewhere. Nutrient content in stems, roots, and all foliage of seedlings is expressed as the percent composition (concentration) and the total weight (total or absolute amount) of the element taken up.

SUGAR MAPLE

Nitrogen

Deficiency symptoms

Initially, entire leaf surfaces throughout the plant gradually changed from dark green to light green. Some leaf lobe tips turned yellow and subsequently scorched. After this the lower pair of leaves turned completely yellow to contrast distinctly with light-green upper leaves. In advanced stages this yellowing in lower leaves was followed by more necrotic tip and marginal scorching and extensive blotching with gradually progressed up the stem.

Growth

Shoot elongation almost stopped as soon as seedlings were switched from complete to N-deficient cultural solution. As a result, they appeared stunted and had fewer and smaller leaves than complete nutrient control seedlings. Omitting N caused significant losses in total seedling dry weight (table 1) and all component parts (foliage, stem, roots) of it. N-deficient seedlings weighted 74 percent less that the complete nutrient controls and were comparable to the distilled water controls except root weights were greater for N-deficient seedlings.

Nutrient content

Total uptake in deficient seedlings was a fourth of that in complete controls. Concentrations in various deficient seedling tissues fell to near 1 percent (table 1).

Phosphorus

Deficiency symptoms

First, all leaves throughout the plant quickly developed distinctive dull dark-green surfaces; light-green and yellow-green mottles and necrotic tips showed up shortly thereafter. Later the mottles became yellow and necrosis spread along the leaf margins. Finally, discolored, water-soaked-appearing spots developed on interveinal tissues of the lower leaves. These spots enlarged and rapidly coalesced into larger blotches. Spotting symptoms progressed upward from the lower leaves.

Growth

Phosphorus, like N, was crucial to growth; its omission caused stunting and fewer leaves were produced. All aspects of seedling growth were comparable to growth of the distilled water controls.

Nutrient content

P-deficient seedlings took up 9 times less P and concentrations were a third of normal (table 2).

Potassium

Deficiency symptoms

Yellow leaf tips, petiole drooping, and necrotic spotting were the earliest signs of K-deficiency. Symptoms developed slowly, beginning with lower leaf margins turning yellow green and then gradually yellow. Yellowing widened inward between the green midrib and main veins, giving

the remaining green tissues the appearance of a deeply lobed white oak leaf. Similar symptoms appeared later in upper leaves, but the green-patterned edge was fringed with a purple tint. Finally, yellow areas bronzed or scorched and leaf margins curled up. Leaf petioles were also purple. Dead leaves remained attached to the stem.

Growth
Dry weight for all component parts were reduced by omitting K, but stem and root weights were reduced more than foliage weight. Yields in both stems and roots in K-deficient seedlings were comparable to those in the distilled water controls.

Nutrient content
Deficient seedlings showed 8 times less uptake and lower concentrations of K, especially in the leaves and roots, than normal seedlings (table 3).

Calcium
Deficiency symptoms
Newly formed upper leaves were greatly reduced in size by Ca deficiency. Overall fading from light- to yellow-green occurred first in upper leaves and then in lower leaves. Yellowing began simultaneously in all upper leaf tips and progressed inward toward the leaf base. Yellowing began simultaneously in all upper leaf tips and progressed inward toward the leaf base. Yellow leaf tips turned bright red before dying while the rest of the leaf remained yellow green. In more advanced stages, the first or lowest pair of true leaves turned yellow before drying and rolling up.

Growth
Leaf number and all other aspects of seedling growth were greatly diminished by the lack of Ca. Calcium-deficient seedlings were similar to the distilled water control seedlings and weighed less than those grown under other deficiency treatments. Calcium-deficient seedlings were about 72 percent lighter than the controls.

Nutrient content
Almost twelve times more Ca was taken up by normal seedlings than those grown without Ca (table 4). Foliar and stem concentrations indicated only a threefold difference and root concentrations were lower.

Magnesium
Deficiency symptoms
The upper leaves developed a distinctive pattern: interveinal tissues turned light green while midribs, main veins, and adjacent tissues remained dark green. Leaf tip and edge yellowing and scorch also accompanied this symptom. Light-green mottles and yellow-green patches began appearing on lower leaves next, but the distinctive margin-to-rib pattern did not develop. Necrosis in old leaves consisted of scattered salting and spotting. In young leaves necrosis finally expanded down between the main veins, and the dried leaf tips curled down.

Growth
Dry weights of component parts of Mg-deficient seedlings declined, but seedling height growth, leaf numbers, and leaf size were not greatly affected by this deficiency.

Nutrient content
Total uptake by deficient seedlings was much lower (10 times), especially in the roots (16 times) than complete control seedlings (table 5).

Sulfur
Deficiency symptoms
First signs of S deficiency appeared on new upper foliage. These leaves were light green with a pinkish cast, cupped downward and curled, and had scorched tips; later they turned yellow-green and developed scorched margins. Lower leaves remained dark green at first, then gradually lightened to a uniform yellow-green color with necrotic tips and interveinal blotches.

Growth
Sulfur deficiency caused a moderate reduction in seedling height growth. Weights of deficient seedlings parts were significantly below those of the complete nutrient controls but yet almost twice as heavy as the distilled water controls.

Nutrient content
Sulfur uptake was reduced about sixfold for the various seedling parts (table 6).

RED MAPLE

Nitrogen
Deficiency symptoms
Nitrogen deficiency first showed up as a gradual fading of the lower leaves from green to lighter green in red maple seedlings. This fading symptom gradually progressed up the stem to the upper foliage. In more advanced stages the lower foliage turned pink, then red, and the basal leaves scorched on the tip, turned brown, rolled up, and finally abscised.

Growth
N-deficient seedlings weighed about half as much as the complete nutrient controls; most of the weight loss occurred in the foliage and roots. Newly formed leaves stayed noticeably smaller than older leaves as the deficiency developed.

Nutrient content
Total amount of N in deficient seedlings was about one-fourth of normal but concentrations were only about one-half of normal (table 7).

Phosphorus

Deficiency symptoms

Brown tip scorch and blotching in the lower leaves were the first signals of P deficiency. Then lower leaves turned dull green as upper leaves gradually became mottled dull green, yellow, and red. As the deficiency advanced young leaf tips often scorched while lower leaves develop dull light-green, yellow-green, and red mottles, and marginal scorch. Lower leaves browned completely before they were finally shed.

Growth

Phosphorus-deficient seedlings were stunted, like the distilled water seedlings, and much shorter than any other deficient seedlings. Phosphorus-deficient seedlings had fewer, smaller, and narrower leaves than normal seedlings. Total oven dry weights of P-deficient seedlings were identical to the distilled water controls and about one-tenth that of normal seedlings.

Nutrient content

Absolute amount of P in deficient plants was about a fortieth of normal, yet concentrations ranged from about a half to a sixth of normal (table 8).

Potassium

Deficiency symptoms

Initially, young foliage became lighter yellow green, except for the veinal network which remained a contrasting darker green. Young leaf tips also curled down and then scorched. Marginal scorching of young foliage followed, along with salting in both young and old foliage. Salted areas on young foliage coalesced into blotches as lower foliage turned light green and began to roll up. Finally lower leaves shriveled up, but they were retained on the stem hanging down from horizontal petioles.

Growth

Potassium-deficient seedlings had shorter, more slender stems with smaller leaves than normal seedlings. Dry weights of K-deficient seedlings were comparable to distilled water seedlings. However, K deficiency reduced root and stem yields more than foliage yields.

Nutrient content

Total content of K taken up in tissues of deficient seedlings was reduced by a factor of 8 or more but concentrations were only 2 to 5 times less (table 9).

Calcium

Deficiency symptoms

First, young foliage faded from dark green to light green. Then interveinal tissues turned yellowish green while midribs and veins stayed light green. Next symptoms were the curling down of young leaf tips and the appearance of red tips and margins on older foliage. This was followed by necrotic or discolored spotting on leaves of all ages. As the deficiency intensified, foliage from the bottom up the plant changed to first pink, then red, petioles drooped below horizontal, and leaf blades hung vertically.

Growth
Calcium deficiency caused stunting and a great reduction in leaf numbers and their size. Seedling component weight yields were not different than the distilled water controls.

Nutrient content
Deficient plants had 21 times less Ca in their tissues than normal plants. The amounts of Ca in root tissues were especially low. Although percentage values showed similar trends, none of the values approached the reductions shown by absolute amounts (table 10).

Magnesium
Deficiency symptoms
Initially, Mg-deficient seedlings seemed more luxuriant than seedlings receiving all nutrients. The first characteristic symptom appeared as a prominent pattern in upper leaves. This pattern formed as interveinal tissues faded from the margins inward between veins toward the midrib, leaving a broad, sharp zone of dark-green tissues next to the main veins and midrib. The second characteristic symptom was the deep-purple color that developed in mature leaves as they became dominated by anthocyanin pigments. This coloration progressed up the plant, while young leaves rolled up and developed tip scorch. After this, necrotic blotching intensified in older leaves just before they were shed from the bottom up the stem.

Growth
Magnesium deficiency reduced seedling root weights below the complete nutrient control level but foliage and stem weights were not. During the relatively short duration of these studies, the good height growth of red maple, white ash, and paper birch seedlings in Mg-deficient treatments may be cause by small amounts of Mg remaining in the sand as contaminants, or perhaps by the effect of sodium initially partly replacing these species' needs for Mg. These effects under potassium deficiency are well known (Hewitt 1966).

Nutrient content
Uptake of Mg was reduced considerably. Either the percentage values or the total amount of Mg in the foliage appear to be good diagnostic tools for estimating a seedling's Mg status (table 11).

Sulfur
Deficiency symptoms
First, upper expanding leaf surfaces developed a pink to yellow-green cast and their tips curled under and drooped. Then tip scorch and spotting appeared on these leaves, which was later followed by the spreading of necrotic areas, first along the margins and then inward toward the midrib and petiole. Old lower leaves turned lighter green than normal and finally developed tip scorch.

Growth
Sulfur-deficient seedlings weighed about half as much as the complete nutrient controls after 117 days under treatment. Besides this, the deficiency also noticeably depressed height growth and reduced the size of younger leaves.

Nutrient content
Total amounts of S in deficient seedlings was reduced sixfold, while concentrations indicted about half as much of a reduction from normal levels (table 12).

White Ash

Nitrogen

Deficiency symptoms
Leaves and petioles throughout the white ash plants gradually faded to a uniform light-green color as N became deficient. Following this, the cotelydons and the lowest pair of true leaves quickly changed from light green to yellow green to entirely yellow, while all higher leaves retained their light-green color. This is the characteristic symptom for N deficiency in most plants. As green leaves faded, leaf margins and interveinal tissues often developed a purplish cat but no distinctive patterns were formed. Shortly thereafter, these symptoms began moving up the stem. Necrosis first appeared on the margins of the yellow cotelydons and subsequently as tip and marginal scorch on the lower leaves. Petioles also became more erect than normal, having about a 15 degree angle with the stem.

Growth
Nitrogen-deficient seedlings generally were shorter and had smaller leaves than normal seedlings. Deficient seedlings had the lowest total and component weights of the 7 single-element deficiencies studied. Their weights were comparable to distilled water controls and 62 percent below complete nutrient controls.

Nutrient content
Total uptake was about one-sixth of normal and concentrations about half of normal in N-deficient seedlings (table 13).

Phosphorus

Deficiency symptoms
Although foliage might fade slightly at first and some terminal leaves might scorch at the tip, major P-deficiency symptoms began in the lower leaves and slowly progressed up the stem. Shortly after, lower leaves turned lighter green, and purplish spots appeared on them. Next they developed yellow and brown necrotic areas, while upper leaves remained green. Symptoms in the veinal network of lower leaves developed more slowly; the network remained light green as the leaf yellowed and finally turned yellow as the leaf browns.

Growth
Normally, growth reductions would be expected by omitting P, but white ash is a determinate grower and 60 percent of its height growth was already completed before deficiency treatments were begun. Another growing period would be required for the expected reduction to develop.

Nutrient content
Total uptake in tissues of deficient seedlings was one quarter of normal. The reduction in uptake was much greater in foliage than other tissues (table 14).

Potassium
Deficiency symptoms
Upper leaves might droop from normally erect petioles before the tips scorched on terminal leaves. This was followed by the light-green fading on upper leaf margins. Finally, all leaf tissue became the same color, but leaf ribs and bases stayed green longer. These symptoms gradually moved down the stem to the lowest leaves. In severe stages of K deficiency, upper leaf tips and margins often became completely scorched resulting in curved-up and rolled-in upper leaf margins. Later, some tips and edges scorched in lower leaves too.

Growth
Height growth was not reduced as expected for the reason discussed under growth of P-deficient white ash seedlings.

Nutrient content
Absolute amounts of K in leaf and stem tissues and K-leaf concentrations reflect the reduced uptake of K which averaged about one-third of normal (table 15).

Calcium
Deficiency symptoms
Early symptoms of Ca deficiency were tip scorching of terminal leaves, death of uncurling new leaves and growing tips, and erect petioles that almost parallel the stem. In extreme cases petioles of terminal leaf pairs crossed each other. Fading at first resulted in uniform light-green leaves and petioles, but then intensified in interveinal areas to a very pale green to whitish green to a whitish yellow, with some areas almost white. Through the early interveinal color changes tissues around leaf midribs and major veins remained light green. In severe stages, water-soaked-looking blotches appeared on the edges, and the inerveinal tissues scorched. Similar symptoms appeared later on lower leaves.

Growth
Stems and leaves appeared smaller than normal on Ca-deficient plants. Root weights of deficient plants were especially low, being 60 percent below normal levels and comparable to distilled water controls.

Nutrient content
Total Ca uptake was a sixth and concentrations about a fourth of normal levels (table 16).

Magnesium

Deficiency symptoms

Distinctive symptoms of Mg deficiency first appeared in the lower two pairs of leaves, but soon were present even in the youngest foliage. Leaf tips, margins, and interveinal areas first faded to a light green, then to a yellow-green, and finally yellow dominated. Tissues next to the veinal network, midribs, and point of petiole attachment remained green, contrasting with other yellow leaf tissues. A purplish discoloration often preceded necrosis that began at leaf tips and later appeared at leaf margins and between veins.

Growth

Root weights of Mg-deficient seedlings were slightly lower (14 percent) than those of complete nutrient controls. Usually, the aboveground portions of Mg-deficient seedlings looked healthy until the deficiency was well developed. (See discussion of growth of Mg-deficient red maple seedlings.)

Nutrient content

Total Mg uptake and concentrations were about one-fourth that of normal seedlings (table 17).

Sulfur

Deficiency symptoms

Characteristic symptoms of S deficiency in white ash first appeared when young upper leaves turned lighter green than lower leaves. Newly emerging upper leaves often rolled under and wrinkled. Then, leaves throughout the plant became a uniform yellow-green color. Tip scorch and spotting also occurred simultaneously on the upper and middle leaves of some plants. In more advance stages new growing points often died, and upper leaves turned entirely yellow except for tips and other scorched spots.

Growth

Root weight was reduced (36 percent) by the omission of S. Other expected growth reductions did not occur as already explained under the growth section for P-deficient seedlings.

Nutrient content

Total uptake of S in deficient seedling was about a third of normal (table 18).

Paper Birch

Nitrogen

Deficiency symptoms

Foliage throughout N-deficient paper birch seedlings quickly faded to a uniform light-green color while midribs and veins on the lowest leaves turned red. Shortly thereafter, oldest (lower) leaves turned yellow but their midribs and veins remained red. These symptoms gradually progressed up the stem while the lower leaves often tip scorched before they turned completely brown and abscised.

Growth
Omission of N caused the greatest growth suppression of the six elements studied. Stunted N-deficient plants looked like those plants grown in distilled water. Leaf production was drastically curtailed in N-deficient plants and leaves were smaller in size. Dry weight yields of leaves, stems, and roots were reduced to only about 10 percent of the complete nutrient controls. (See Appendix tables 31 for more information.)

Nutrient content
Uptake was drastically curtailed in N-deficient plants. Absolute amounts of N averaged one-sixteenth of normal, but concentrations ranged from nearly equal in stems and roots to about half normal levels in the foliage (table 19).

Phosphorus
Deficiency symptoms
Visual foliar symptoms of P deficiency were slow in showing up. At first, all leaves turned darker green and duller than normal. After this, dull light-green and later dull yellow-green areas appeared at the tips, serrated edges, and in irregular patches on the lower leaves. Then, chlorotic leaf tips, edges, and some blotches turned brown as the symptoms spread across the leaf and began to move up the stem. In later stages, brown leaf tips curled up before the leaves became entirely brown and abscised.

Growth
Height growth was also restricted by the omission of P, but not the same extent as in N-deficient seedlings. Upper leaves on P-deficient seedlings were noticeably narrower in width than normal leaves but not in length. Average dry weight yields of birch foliage, stems, and roots were reduced 62, 47, and 60 percent by P deficiency, respectively.

Nutrient content
Total P uptake - especially in the foliage - was greatly reduced by its omission from the cultural solution. Concentrations showed similar patterns but their magnitude was not as great (table 20).

Potassium
Deficiency symptoms
First symptoms of K deficiency appeared in the upper leaves before any color change in the lower leaves took place. The upper leaves on some plants buckled under along the midribs and curved under at the margins. Then lower leaf tips, serrations, margins, and finally interveinal tissues, from the margins toward the midribs, gradually began to turn from light green to yellow green to yellow. This was followed by leaf tip and edge scorch in the lower leaves.

Growth
After growing in K-deficient solutions for 113 days, birch seedlings exhibited only slight differences in growth from normal seedlings.

Nutrient content
Total content of K was about a third of normal in deficient plants. Percentage values in tissues showed similar decreases (table 21).

Calcium
Deficiency symptoms
All foliage slowly faded to a uniform light green with basal leaves often appearing even paler. Interveinal areas on the lower one or two leaves finally turned pale yellow; narrow bands of light green remained next to the veins and midribs. After yellowing, the tips and serrated edges of lower leaves scorched; water-soaked blotches sometimes appeared on them. Another advanced symptom was the "hooking down" of young leaf tips.
Occasionally veins in basal leaves appeared much like those on N-deficient seedlings. However, in Ca-deficient seedlings the colored vein symptom occurred much later, was not as sharply defined, and appeared more as a reddish or pinkish cast around the veinal network.

Growth
Calcium deficient seedlings had fewer leaves and were about half as tall as normal seedlings. Deficient seedling weights averaged 47 percent below controls; 52 percent reductions occurred in both stems and roots and a 39 percent reduction in the foliage.

Nutrient content
Absolute uptake of Ca in tissues was a tenth to a twentieth of normal, but concentrations were only a fifth to a tenth of normal (table 22).

Magnesium
Deficiency symptoms
A very distinctive chlorotic pattern developed on all but the youngest leaves in Mg-deficient paper birch. Tips, margins, and tissues between veins on mature lower and middle leaves first became light green, while broad bands of tissue adjacent to midribs and main veins, at the base, and sometimes at the tip remained dark green. Light-green margins and interveinal tissues gradually changed to yellow green, then almost white. Some mature leaf tips scorched early, then after tissues had lightened considerably, necrotic spotting and blotching advanced rapidly.

Growth
Omission of Mg inhibited birch root and foliage growth more than stem growth. Toot weights, after 113 days under treatment, were only half of normal, while total weights were about 34 percent below normal levels. (See discussion of growth of Mg-deficient red maple seedlings.)

Nutrient content
The greatest reduction of Mg uptake from normal occurred in the leaves; the entire plant took up one-twelfth of normal amounts. Deficient tissue concentrations ran from one-fourth the one-fourteenth of normal (table 23).

Sulfur

Deficiency symptoms

Curing down and scorching of newly emerging upper leaf tips and edge serrations often were the first visible signs of S deficiency. New paper birch leaves, developing after deficiencies began, were much more yellow-green than the older foliage which remained dark green, except for yellowing of leaf tips and serrations. Later, old foliage faded to the same color as the new foliage, but leaf tips and margins were either yellow or scorched. Finally, necrotic spotting and edge blotching appeared in the oldest foliage.

Growth

Sulfur-deficient seedlings were slightly smaller than normal and the development of new foliage appeared especially limited. Sulfur deficiency, like Mg deficiency, restricted root and foliage development more than stem development. Total seedling dry weights were reduced 37 percent below normal levels by this deficiency.

Nutrient content

S uptake was reduced primarily in the foliage (table 24).

DISCUSSION

Visual foliar symptoms of nutrient deficiencies should not be used alone for diagnosis because deficiencies of one element may be difficult to distinguish from another element and they can resemble damage caused by insects, disease, climate, and pollution. Smith (1976) reported that leaf symptoms of green veins with yellow interveinal tissue in red maple, are similar for manganese and iron deficiency and are often confused. According to Worswick (1950), micronutrient deficiencies of manganese and copper are difficult to distinguish from K-deficiency in fruit trees. Marginal leaf and tip browning caused by high temperature, leaf scorch following hot drying winds, and fluoride injury may all resemble K deficiency (U.S. Department of Agriculture, Forest Service 1973).

Visual deficiency symptoms usually will not be as well defined in nature as in our experiments because they may be the result of interactions or may be confounded by other deficiency or toxicity symptoms. Thus, visual foliar symptoms can be the first clue to which element might be limiting growth, but chemical analysis should be used to confirm the suspected deficiency.

Samples from the foliage are normally analyzed, but sometimes other parts provide a better critical diagnosis (Hewitt 1966). Often a chemical soil analysis of available nutrients is made, in addition to the other diagnostic measurements, to give a more complete picture of the nutrient status of trees in nurseries and in field fertilization programs. Foliar analysis for trees is reviewed by Leaf (1973) and van den Driessche (1974). These procedures are not yet routine and the results of chemical analysis of soils or plant tissue must be interpreted and applied carefully.

In our study, all leaves, regardless of maturity, were harvested to make chemical analyses. The seedlings we analyzed generally showed moderate to severe deficiency symptoms. Any seedlings at these deficiency levels would be under severe nutrient stress to foliar symptoms would be very apparent. When symptoms are not so clear or when growth is being restricted making a

differential diagnosis requires careful sampling, chemical analysis of the foliage, and expert advice (Phares and Finn 1972). Common sense is required in making a correct diagnosis too, to assure that frost, drought, and diseases (Phares and Finn 1972) or air pollution (U.S. Department of Agriculture, Forest Service 1973) are not causing the suspected nutrient problem.
Users wishing to make comparisons with our data for determining whether a nutrient deficiency exists, should collect all the leaves from a random sample of 10 seedlings in a suspected bed or unit after 115 days or in mid-August. Make sure the leaves are clean and avoid collecting them within several days after rain because of nutrient leaching (Phares and Finn 1972). The samples, including leaves and petioles, should be collected in paper bags and air dried.

Compare the laboratory test results with our "complete" and "deficient" levels. Any levels at or above our "complete" nutrient control levels (except possibly N which should be somewhat higher and is discussed below) are probably within a range of concentrations satisfactory fro growth. Levels approaching our "deficient" levels would limit growth.

Results of these chemical analyses are applicable to seedlings grown under greenhouse, laboratory, and nursery conditions, but *not* to forest-grown seedlings or those under field conditions where only mature leaves are normally collected and analyzed and where leaf maturity, leaf position, and seasonal variation in mineral absorption are taken into account in sampling the nutrient content of foliage.

Critical deficiency, toxicity, and adequate nutrient supply levels have not been established for most of the northern hardwood species. However, Bjorkbom (1973) reported tentative optimum levels of 3 to 4 percent of foliar N as being adequate for birch seedlings. His results indicate that our N level was below that required for optimum seedling growth. Other leads from field studies, although not directly comparable, suggest that the foliar levels of N in our complete nutrient controls were not optimum for seedling growth. From field studies, Mitchell and Chandler (1939) estimated "optimum" foliar N levels for mature sugar maple trees to range from 2.77 to 2.85 percent. Our complete nutrient control foliar N level of 2.24 percent is within their adequate "working region" of 1.75 to 2.77 percent N. Their region where N was limiting growth was below 1.75 percent. Mader *et al.* (1969) considered foliar N levels below 1.50 percent important in sugar maple decline. Mitchell and Chandler (1939) also estimated optimum and other critical leaf N concentrations for red maple and white ash trees. Our foliar N levels of 1.43 percent N for red maple and 1.32 percent N for white ash seedlings (complete nutrient solution) are beginning to limit growth.

In western Massachusetts, Mader *et al.* (1969) associated sugar maple decline with N deficiency, described foliar symptoms typical of N deficiency, and showed a positive response to N fertilization in affected trees.

Bjorkbom (1973) found that paper birch seedlings were not greatly affected by different levels of phosphorus or potassium. In New York, Walker (1956) described foliar symptoms of K deficiency occurring in red maple growing on abandoned farms in K-deficient glacial outwash sands. Walker (1956) considered about 0.60 percent foliar K in mid-August as the point where deficiency symptoms would be expected to appear under field conditions.

Besides the clues from field studies, tables of natural foliar nutrient concentrations have been published that may also be used as guides in forests (Gerlloff, Moore, and Curtis 1964, Henry 1973).

Practical methods for correcting nutrient deficiencies are available from agriculture and various forest studies (Beaton 1973) but very few from fertilization trials of northern hardwoods. In general, success in correcting deficiencies has been achieved with both soil applications and foliar sprays of the appropriate fertilizers. This is a rapidly expanding field and the reader is encouraged to consult the various testing agencies (Auchmoody and Filip 1973) for advise. Foliar and soil chemical analyses can be purchased from state extension services and universities.

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