URBAN VS. NATURAL SUGAR MAPLE GROWTH: I. STRESS SYMPTOMS AND PHENOLOGY IN RELATION TO SITE CHARACTERISTICS

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Abstract. This study provides a profile comparison of several tree growth, phenology, and site characteristics. The comparisons are between sugar maple trees in a forest stand and those in tree lawns on urban streets, both sites within 2 km on the Michigan State University campus in East Lansing. Sampled trees are from a stratified random group of healthy sugar maples. The study reports on significant terminal growth differences and much earlier leaf drop from the urban street site. Site soil moisture, air temperature, leaf temperature, relative humidity, and vapor pressure deficit were all significantly less favorable along streets, as was soil bulk density. Soil pH and the foliar nutrients N, K, Ca, Mn, B and Na were significantly less favorable along streets. The net effect of these urban conditions is a slow growing, restricted, low-density root system. This, in combination with prolonged water stress and high atmospheric demand, producing chronic water deficits in the tree crown, results in low vitality and reduced growth rates in the street trees.

Key words. Sugar maple, growth, phenology, urban stress, water stress, street trees, natural forest, foliar nutrients, soil exchangeable cations, site characterization.

In recent years, foresters have adopted an ecosystem approach to manage forest resources. This is a result of research that led to a comprehensive understanding of a tree species' interactions with site conditions, microclimate, and other species so that healthier, sustainable forests, properly suited to the species, can be established. This ecosystem approach may also be applied to urban forests. By quantifying the interactions of trees with their urban habitat, and comparing to the interactions with their natural habitat, urban foresters can clearly understand the differences between urban and natural sites, and how trees adapt to their urban settings. Because trees evolved over thousands of years in forest conditions, quantitatively measuring how the urban habitat differs is educationally beneficial. By also examining tree physiologic factors, definitive knowledge can be gained as to how the tree is responding to urban conditions, and this helps to identify the specific site factors that have the most influence on trees. In practical terms, it will enable accurate and effective selection of remedial procedures for stressed and declining trees. It may also aid in the validation and development of selection criteria for new cultivars, as well as improvements to landscape construction site specifications.

This study used an ecosystem approach to quantify the urban environment, rather than using conventional generalizations to develop management solutions. The species selected for the study was sugar maple (*Acer saccharum*), a valuable urban tree that is among the 5 most common urban trees in the midwestern United States. This species, however, has exhibited problems for at least the last 30 years in adapting to urban conditions. In examining the decline and dieback of sugar maples in both forest and urban settings, studies have identified a number of factors as possible causal agents, including drought, nutrient deficiencies, salts, and disturbed soils (8,9,17,18,19,20,22). Certain of these studies, as well as others (7,15,21), have provided indirect evidence on the response of this species to water stress. The sugar maple has been called drought intolerant (3,16) and, due to its sensitivity to stress-related factors, including road salt, heat, soil compaction, and drought, the species is currently not recommended for street tree planting (8).

The Michigan State University campus has approximately 210 sugar maple street trees that are especially appropriate for the study of this species in urban conditions because they have been established for over 25 years, and because most of the trees are exhibiting varying degrees of stress, poor vitality, and decline, including leaf scorch and dieback. Because many studies identify individual causes of poor sugar maple performance, it could be difficult for an arborist to select the proper remedial treatments for these street trees without a comprehensive knowledge of the

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urban site. To select effective remedial cultural treatments, it is important to provide a quantitative description of the urban site conditions and the trees' physiologic adaptation.

The objectives of this study are to describe the urban sugar maple ecosystem by characterizing site conditions and the microclimate, and by determining the stress-related effects on the growth, phenology, and vitality of sugar maples associated with the urban, as compared to forest conditions. Tree water relations measurements were also taken in conjunction with this study (reported in a separate paper) to gain a more complete understanding of sugar maple adaptation to the urban environment.

Methods and Materials

The study was conducted on the campus of Michigan State University in 1993. Trees were selected from 2 sites: along urban streets (referred to as the campus site) and a native forest stand (referred to as the Minnis forest site). At the campus street site, 7 sugar maples with dbh from 12 to 20 cm were selected. All were growing in a tree lawn 9 m wide between the sidewalk and the curb, and were surrounded with turf grass. The nursery seed source of these trees was native sugar maple forests near Minneapolis, Minnesota. The trees were planted bare root on the campus in 1970. The Minnis site is a 5-acre natural forest approximately 1.6 km south of the campus site, and consists predominantly of naturally regenerating sugar maples from seedlings to mature trees. Seven accessible dominant trees from small windthrow gaps were selected for the study. All selected trees were free of visual decay symptoms, damage, and dieback.

Tree growth and phenology. Tree height was measured using a Biltmore stick, and dbh with a diameter tape. Terminal shoot growth of 3 selected sun branches at the mid-crown of each tree was measured weekly from initial budbreak to budset. Terminal shoot growth for the 5 previous years (1988–92) was measured on the street trees from terminal bud scars. Fall coloration and leaf fall were recorded at the following points: initiation of color change, peak color, and 100% leaf fall. The age of the campus trees was determined to be 28 years by counting growth rings from increment cores using a dissecting microscope.

Three 5-cm-long root samples 1.5 cm in diameter were collected on December 3, 1993, from each tree at both sites and immediately frozen using dry ice. Starch concentration of root samples, an indicator of overall tree vigor, was assayed colorimetrically using glucose oxidase.

Site characterization. Air temperature, leaf temperature, and relative humidity were obtained as part of the leaf water relation measurements on 6 dates from July through September, using a Li-Cor LI-1600 Steady State Porometer. Vapor pressure deficit (VPD), which is related to the rate of leaf water loss, was calculated at each tree from the air temperature and relative humidity data. Rainfall data for each week of the season were obtained from published data of the National Oceanic and Atmospheric Administration's National Weather Service office in Lansing, Michigan.

Soil moisture content was determined using a time domain reflectometer (Tektronix TDR 1053C), and 0.6-cm-diameter stainless steel rods to measure average soil moisture within the top 15 and 30 cm of soil. Sets of 2 rods each were hammered into the soil on opposite sides of each tree for each depth at a distance of 1 m from the trunk. They were left in place throughout the study. Weekly measurements began on May 14, 1993, and continued through November 6, 1993, in order to obtain a season-long determination of soil moisture content changes. Soil bulk density (BD) was obtained at each site using the Core Method. Soil cores were taken at the Minnis site from the A horizon (surface soil) and B horizon (at approximately 25 cm in depth). The soil profiles at the campus site showed no distinct horizons, but cores were taken from the surface soil and at a depth of 25 cm. Soil texture was determined mechanically by the Buoyocous method. Soil organic matter analysis was performed using the wet digestion method. Soil oxygen diffusion rate (ODR) was determined with a Jensen Instruments Model A Oxygen Diffusion Ratemeter.

Soil samples were taken in spring (May 31) and late summer (August 3) to determine chemical properties, using standard methods (14). Soil exchangeable Ca, K, Mg, and Na were determined spectrophotometrically from 1 *N* NH_4OAc extract. Soil pH was determined with an ion analyzer equipped with a combination electrode, using a 1:1 soil to water mixture. Soil organic matter (OM) analysis was performed with the wet digestion method.

Site nutrient availability was assessed by determining foliar levels of essential elements. Samples were collected from the mid-crown of sunlit branches on August 7, as per Smiley (19). Leaves were oven-dried at 70°C and ground in a Wiley mill with a 40-mesh screen. Total Kjeldahl nitrogen and total phosphorus of leaf tissue were colorimetrically determined on a Technicon Autoanalyzer II following digestion with sulfuric acid. Determination of total metals (Al, B, Fe, Mg, Ca, Mn, Na, Zn, K), following digestion of subsamples with nitric and perchloric acids, was performed using a spectrophotometer.

Data analysis was conducted with the Systat statistical software using the nonparametric Mann-Whitney 2-sample Rank Sum test. Results of statistical analysis were judged significant and highly significant when probability levels were less than or equal to 5% (0.05), and 1% (0.01), respectively.

Results

Tree growth and phenology. Growth rates are compared graphically in Figure 1. Terminal shoot growth showed significant differences ($p < 0.05$) between Minnis trees (39.4 cm) and campus trees (27.3 cm). Annual terminal growth for the trees on the campus site was 2.8 cm, 4.4 cm, 15.9 cm, 18.0 cm, and 16.9 cm from 1988 through 1992, respectively.

Phenology data related to budbreak and budset compared identically between sites—April 28 and July 7, respectively. Fall coloration of the campus site street trees, however, began nearly 3 weeks before the Minnis site—September 22 versus October 12. Peak color occurred on October 8 for street trees and October 24 for woodlot trees. Leaf drop of the street trees was completed on October 21, whereas it occurred on November 6 at the Minnis site.

There were no significant differences in root starch concentrations between sites due to high variability among trees on both sites.

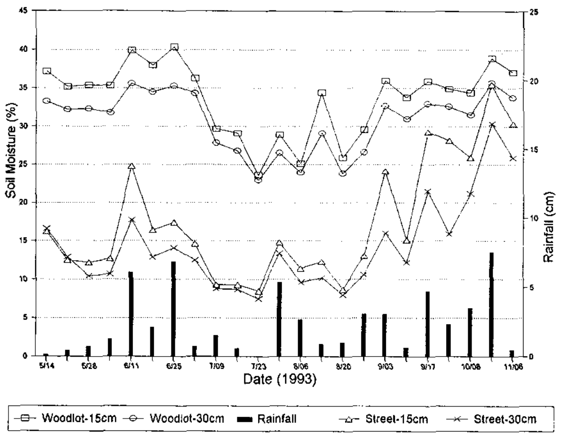

Figure 1. Terminal growth rates of sugar maples at the 2 study sites in East Lansing, MI, during the 1993 growing season.

Site characterization. On all measurement dates, there were highly significant differences between sites for the atmospheric factors: air temperature, leaf temperature, relative humidity, and the calculated vapor pressure deficit (Table 1). The campus site recorded higher air and leaf temperatures, lower relative humidity, and greater vapor pressure deficits on all dates. Rainfall throughout the 1993 growing season, April through October, was 69.2 cm, which was more than 17 cm above the 30-year average of 52.1 cm for the area. Each month recorded above-normal precipitation, except May, which was 3.2 cm below normal. Average annual rainfall in the Lansing, Michigan, area is 78 cm.

Soil at both sites was of sandy loam texture at both horizons. There was a strong correlation between precipitation and soil moisture content at the 2 measured depths at both sites (Figure 2). Differences in soil moisture level between the 2 sites were highly significant ($p < 0.01$) on all measurement dates throughout the season, with Minnis having consistently higher levels at both sampling depths. Minimum soil moisture of the campus site was 8.5% and 7.5% at 15-cm and 30-cm depths, respectively. Highest soil moisture levels occurred

Table 1. Atmospheric/climatic factors on 6 measurement dates from July through September 1993 at the campus and forest sites. Values are means of 7 trees per site.

Date	7/9	7/20	7/31	8/14	9/4	9/24
Air temp (°C)**						
Campus streets	30.6	29.2	30.6	32.6	25.3	19.8
Forest site	28.2	26.1	28.5	30.2	23.1	17.4
Leaf temp (°C)**						
Campus streets	29.7	28.3	29.7	31.6	24.6	19.8
Forest site	27.2	25.5	27.6	30.0	22.3	16.9
Relative humidity (%)**						
Campus streets	30.0	36.8	35.6	45.4	46.5	35.4
Forest site	41.6	46.0	48.9	48.8	56.9	53.6
Vapor pressure deficit (KPa)**						
Campus streets	2.9	2.4	2.7	2.5	1.7	1.5
Forest site	2.2	1.7	1.9	2.2	1.2	0.9

**Significant differences on all dates between campus and forest trees at 0.01 level.

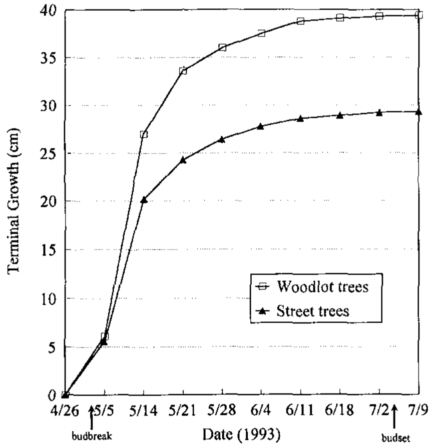

Figure 2. Precipitation and soil moisture content at the study sites.

on both sites in October and November when rainfall had increased and transpiration demand had greatly decreased.

There were highly significant differences in the bulk density (BD) of the surface soils, with the campus (1.47 g/cm^3) being more compacted than the natural forest (1.17 g/cm^3). The BD at the B horizon at Minnis (1.67 g/cm^3) and the 25-cm depth on the campus (1.80 g/cm^3) were not significantly different. The surface BD at Minnis was consistent with studies of undisturbed sites (1), and the campus BD is representative of that found in other urban site studies (5).

Table 2. Mean soil exchangeable cation concentrations (standard deviation) in ppm between the street (campus) and forest sites, 1993.

	May 30		August 3	
Cation	Street	Forest	Street	Forest
Mg	177 (3)	167 (8)	159 (3)	155 (10)
Na	71 (29)**	15 (1)	96 (47)**	14 (1)
Ca	1699 (31)**	1183 (42)	1602 (29)**	1123 (38)
K	100 (15)**	45 (14)	85 (18)**	42 (15)

**Significant difference between campus and forest trees at 0.01 level.

Results of the soil oxygen diffusion rates were *not readily comparable due to significant differences* in soil moisture at the 2 sites. However, data from the street site indicated sufficient levels of oxygen diffusion (0.41 µg/cm^2/min) for root growth (15).

The campus soil pH of 7.29 (SD = 0.11) was significantly higher than that of the Minnis forest site (5.62; SD = 0.51). The high soil Ca level probably contributed to the elevated pH of the campus site. Most pH levels in forests remain low because of the low pH of the forest leaf litter. Soil organic matter was similar between the 2 sites, with the averages of 4.5% and 1.3% for the A and B horizons, respectively. Soil exchangeable Ca, K, and Na levels were significantly higher on the campus site compared to the Minnis site in May and August (Table 2).

Results of the foliar analyses showed that 6 of the elements (N, Na, B, Ca, Mn, and K) were significantly different at the 2 sites (Table 3). Foliage of the street trees was significantly lower in Mn. The forest site had higher concentrations of N, B, and K, but concentrations at both sites were still within the range considered adequate for healthy sugar maples in urban and natural sites (19). The Ca levels of the street trees were significantly higher than at the forest site, but consistent with levels found in healthy sugar maples (19). Foliar Na levels averaged 27 ppm, which is substantially less than levels found in declining sugar maples by Smiley (19), and well within the range for healthy trees.

Discussion

Tree growth and phenology. Although terminal growth at the Minnis site was significantly greater, it could be argued that genotypic differences could be the reason because the streets

Table 3. Mean soil pH and foliar elemental concentrations (standard deviation) of sugar maple street trees (campus) and forest trees (Minnis).

	Street	Forest
Soil pH**	7.29 (0.11)	5.62 (0.51)
Element (%)		
N**	1.58 (0.19)	2.04 (0.25)
P	0.19 (0.04)	0.15 (0.01)
K*	0.58 (0.01)	0.69 (0.05)
Mg	0.26 (0.03)	0.22 (0.04)
Ca**	2.01 (0.03)	1.44 (0.04)
Element (ppm)		
Mn**	66 (51)	571 (418)
B*	55 (8)	66 (7)
Fe	120 (29)	140 (28)
Al	108 (28)	106 (24)
Na*	27 (11)	17 (6)
Zn	19 (5)	22 (4)

*Significant difference between sites ($p < 0.05$).
**Highly significant difference between sites ($p < 0.01$).

trees are of Minnesota origin. However, in provenance tests, Kriebel (12) found no indication of variation in rate of growth between sugar maples of differing seed source from throughout the entire native range. His clinal variation details indicate fall coloration in southern Minnesota would be equivalent in timing to south central Michigan. Therefore, the earlier fall coloration and leaf drop of the street trees may be due to environmental stress. Although the growth rates during this 1993 study were substantially better than the 5 previous years, the street trees, having averaged a height of only 6.7 m in 28 years, exhibited poor vitality on this site. They are growing at a rate of 50% to 75% of the rate of healthy sugar maples reported elsewhere (13).

Site characterization. Soil moisture content of the campus street site was consistently lower than that for the Minnis woodlot site throughout the season, despite the fact that the 2 sites are separated geographically by only 1.6 km and would likely have received equivalent amounts of rainfall. Soils on both sites are sandy loam; therefore, water movement and storage properties would be expected to be similar.

Results from the forest site show that throughout the entire season, soil moisture was always near field capacity. In contrast, the street soil was almost always below field capacity at both measured depths throughout the spring and summer, and did not begin to rise until September. At 2 periods, in mid-July and mid-August, soil moisture content at both depths dropped below 10%, and on 2 measurement dates had moisture within the 7% to 8% range (the permanent wilting point in a sandy loam soil). These results were obtained in the 1993 season, which experienced nearly 33% more rainfall than normal. With less rainfall, soil moisture at the street site would likely approach the permanent wilting point for sandy loam on many occasions.

Several factors may be related to the significantly lower soil moisture levels on the campus. Atmospheric conditions can increase evaporation from the soil as well as increase transpiration demand on plants (6). As the results show, air temperature was consistently higher and relative humidity was consistently lower, both contributing to increased evaporation. For plants, these factors are expressed as a vapor pressure deficit (VPD) that influences transpiration. The VPD values recorded in July and August on the campus were all higher than those found in the literature for sugar maples in natural habitats, including forest clearings (Table 1). These street trees were exposed to high VPDs throughout the summer months, which directly influenced their demand for soil moisture in order to maintain transpiration. The significantly higher leaf temperatures recorded on the street trees would also affect transpiration. Additionally, with higher amounts of solar radiation incident on the soil surface as compared to a natural forest, soil temperatures would be elevated (4), resulting in increased soil water loss through evaporation.

Turfgrass is likely a significant factor in the soil moisture regime and sugar maple water stress on the street site. It covers all of the tree lawn, and has been found to greatly influence soil moisture levels. Watson (21) found significantly lower soil moisture at 15 cm under turfgrass compared to that for an organic mulch or bare soil. Sugar maple was the most affected by grass competition of the tree species he studied. The naturally shallow root system of sugar maple predisposes it to competition in the turfgrass rooting zone.

Bulk density is also related to soil moisture content in compacted soils, as found on the campus site. The smaller pore spaces reduce water storage capacity, infiltration rates, and water movement in the soil (18). Therefore, even though the soils at Minnis forest and the campus streets are of the same texture, the water relations properties are significantly different.

BD in the range of 1.47 g/cm^3 found on the campus will likely affect tree growth. Alberty et al. (1) found that BD in the range of 1.40 to 1.65 g/cm^3 and above can limit growth of woody plants. In a container study of sugar maple seedlings grown in a sandy loam at a BD of 1.43 g/cm^3, the leaf area and root volume of seedlings were reduced by 93%, compared to seedlings grown in noncompacted soil (2).

The root growth and the root density of the campus street trees are likely to be severely limited, even in the upper levels of the surface soil. At a depth of 30 cm where BD is 1.80 gm/cm^3, roots are likely to be unable to penetrate any deeper into the soil for water.

Of all foliar nutrients, Mn was the only element found deficient in the campus street trees. Smiley (19) suggested that foliar Mn concentrations below 106 ppm indicated a deficiency. At 66 ppm, these trees would be considered to have a manganese deficiency, although no visual chlorotic symptoms were clearly expressed.

Summary and Conclusion

It appears that nutrient element levels at the campus site are appropriate for healthy sugar maple growth, with the possible exception of Mn. This suggested a need for further investigation of the relationship of Mn to tree growth.

The relatively low soil moisture content at the street site throughout the season is associated with turfgrass competition, high soil bulk densities, and an increased evapo-transpirational demand on the trees due to elevated temperatures and reduced relative humidity.

Root growth and root extension are inhibited by the high soil bulk densities. Rooting is restricted to depths of less than 30 cm due to increasing bulk densities with depth (1.8 gm/cm^3 at 30 cm). The result is a limited rooting volume near the soil surface where the tree roots are in direct competition with turfgrass roots. It may be concluded that the combination of the prolonged periods of low soil moisture content, high atmospheric demand, and limited rooting volume will likely result in chronic water deficits and stress in the crowns of the street trees.

With the stress induced by the site conditions leading to early leaf fall, the length of the growing season is reduced by about 3 weeks for the street trees. This has the potential to greatly reduce production of stored food in the whole tree, adding further to the scenario of stressed urban trees.

This comprehensive site characterization, comparing street side and natural habitat sugar maples, provides evidence that water stress is the factor most adversely influencing the growth of the campus street trees. This information points to the need for remedial tree management procedures aimed at increasing water availability to the crown through soil modification, and the reduction of soil moisture losses.

The data from this study were complemented with data from actual measurements of the internal physiologic water relations of the trees (reported in a separate paper). With those additional data, a comprehensive description of the urban ecosystem and sugar maple's adaptation to it can be understood and specific remedial street tree management procedures specified.

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Résumé. Des mesures physiologiques ont été effectuées au Michigan concernant les relations internes de l'eau de l'érable à sucre en forêt naturelle et le long de rues en milieu urbain. Les études ont permis de déterminer de quelle manière les arbres de rues sont affectés par l'habitat urbain et de confirmer, par le biais d'analyses de corrélation, qu'un site en relation avec un stress hydrique influence négativement la croissance et la vitalité de l'arbre. Le potentiel en eau avant l'aurore, le potentiel osmotique et la conductivité spécifique stomatale étaient significativement plus bas pour les arbres de rues et significativement correlés avec les faibles taux d'humidité du sol et les fortes demandes atmosphériques associées aux rues en milieu urbanisé. Les conclusions de cette étude, en conjonction avec les données de caractérisation des sites, comportent une grande valeur pour la sélection de traitements correcteurs appropriés pour les arbres affectés par le stress de la sécheresse en milieu urbain.

Zussammenfassung. Die physiologischen Messungen der internen Wasserbeziehungen von Zuckerahornen in natürlichen Wäldern und entlang von Strassen innerorts in Michigan wurden hier vorgestellt. Die Untersuchungen bestimmten, inwieweit Strassenbäume durch das urbane Umfeld beeinflußt wurden und untermauerten durch eine Korrelationsanalyse die Annahme, das standortabhängiger Wasserstress das Baumwachstum und die Vitalität beeinflußt. Das Wasserpotential vor Morgengrauen, das osmotische Potential und die stomatische Leitfähigkeit waren bei Strassenbäumen deutlich geringer und standen in deutlicher Korrelation zum niedrigen Bodenwassergehalt und dem hohen atmosphärischen Ansprüchen am urbanen Standort. Die Ergebnisse dieser Studie in Beziehung mit den standortspezifischen Daten sind wertvoll bei der Auswahl entsprechender kurativer Behandlungen von gestressten Strassenbäumen.