DETECTION OF SOIL COMPACTION RELATED STRESS IN *ACER SACCHARUM* MARSH

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Abstract.--A soil compaction and litter removal treatment was applied for two growing seasons to a site in Underhill, Vermont that contained 14 immature sugar maple trees. An adjacent plot also containing 14 trees served as control. The treatment resulted in substantial increases in soil bulk density and moisture. However, no significant differences between the two plots were recorded for average leaf area, shoot elongation, radial growth, shoot water potential, leaf diffusive resistance, or root starch over the 2-year study period. In the middle of the second growing season, leaf scorch injury occurred, and was more severe on trees in the treated plot. At the end of the second growing season, stem electrical resistance was significantly greater in trees of the treated plot and was highly correlated with leaf scorch injury.

Additional keywords: Sugar maple, electrical resistance, diffusive resistance, water potential, root starch, growth, leaf scorch.

A recent forestry research review committee emphasized the need for additional research into abiotic stress (Shigo and Campana, 1976). The early detection of tree stress might allow resource managers to adjust their practices and correct the problem before injury occurs. Previous investigators have applied numerous treatments (drought, defoliation, girdling, etc.) to several species of trees in attempts to create abiotic stress conditions; and a variety of instruments have been used to monitor the induced stress. However, there has been no comparison of these instruments when used on the same group of trees subjected to the same treatment. Such a comparison would enable future research to focus on the most promising approaches, rather than developing a myriad of approaches and/or instruments useful only under specific conditions. In this paper, we compare four stress monitoring techniques and evaluate their usefulness in detecting signs of early abiotic stress in sugar maple (*Acer saccharum* Marsh.) induced by soil compaction.

MATERIALS AND METHODS

Site Selection and Treatment

A site at the University of Vermont's Proctor Maple Research Farm

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in Underhill, Vermont was selected as the study area. The site was approximately 30 by 40m in size and had a Lyman Marlow rocky loam soil. Twenty-eight sugar maple trees, free from obvious defect and disease, were selected as study trees, and all other trees were removed in May 1977. The site was divided into two plots, each containing 14 trees, and treatments of soil compaction or no compaction were randomly assigned. Average breast height diameters were 10.1cm in the control plot and 11.0cm in the treated plot. Differences in diameter between the two plots prior to treatment were not significant. Average total height was approximately 12m in both plots.

The understory vegetation and litter layer were removed from the treatment plot at the beginning of the 1977 and 1978 growing seasons. This removal simulated the condition of exposed mineral soil found in many heavily used recreation areas. Soil in the treated plot was compacted six times: in July, August and September 1977, and May, June and July 1978. Each compaction period consisted of eight passes with a one-ton gasoline powered roller and two passes with a gasoline powered hand tamper which exerted a compactive force of 19.0psi.

Soil bulk density in four 5-cm thick zones (0-5cm, 5-10cm, 10-15cm, and 15-20cm) and surface moisture were measured with a Troxler surface density probe.2/ Eighty-six soil measurement points were located over the entire site following a systematic 2-by-3 m spacing; 47 points were placed in the larger control plot, and 39 points in the treated plot. Measurements were recorded at the beginning and end of each growing season for a total of four measurement periods. The first measurement preceded the initial compaction. Because of equipment malfunction, data collected at the end of the 1977 season were considered unreliable and were discarded.

Stress Detection Techniques

Four techniques were evaluated for their applicability in detecting soil compaction-related stress: shoot water potential, leaf diffusive resistance, electrical resistance and root starch content. Water potential, diffusive resistance and electrical resistance were recorded monthly during the 1977 and 1978 growing seasons. Root starch content was evaluated at the end of the 1978 season.

Shoot water potential.--A portable pressure chamber (Waring and Cleary, 1967) designed after Scholander *et al.* (1964), was used to estimate the xylem water potential of shoots. The crown of each study tree was divided into four 90° quadrants, with NE, SE, SW, and NW midpoints. Two shoots from the outer portion of each quadrant were selected during each measurement period, one from the upper half of the crown and the other from the lower half. This provided a total of eight water potential estimates on each study tree in each measurement period. The order of measurement for study trees was determined randomly; however, we alternated between treated

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2/ Model 2401, Troxler Laboratories, Raleigh, North Carolina.

and control trees to reduce possible time-of-day bias. One randomly selected leaf from each shoot was retained for subsequent leaf area measurement.

Leaf diffusive resistance.--Leaf diffusive resistance was measured with a diffusive resistance porometer[3/] (Kanemasu et al., 1969). Measurements were made concurrently with water potential measurements, and followed the same sampling scheme. After diffusive resistance was recorded, the sample leaf was retained for leaf area measurement.

Electrical resistance.--Xylem resistance to a pulsed electric current was measured with a portable DC ohmmeter[4/] (Wargo and Skutt, 1975) using uninsulated stainless steel electrodes.[5/] Two measurements were taken on each tree at heights varying from 0.3 to 1.5m, and 180° apart. Height and direction of probe points varied between measurement periods to ensure that a given point was not measured twice, thus avoiding the possible measurement of injured tissue.

Root starch.--At the end of the 1978 growing season, one root sample was collected from each study tree, and root starch level was categorized according to Wargo's (1975) procedure. A 1.3cm thick root segment, approximately 7cm long and within a 1m radius of the root collar, was removed from each tree. Samples were immediately labeled, bagged and packed in ice. Root samples were transferred to a freezer within 10 hours of collection, and stored at -20°C. Root samples were sectioned and stained with an aqueous solution of potassium iodide and crystalline iodine according to Wargo's (1975) procedure, and were visually grouped into his five categories depending on the density of stain. The darker the stain, the higher the root starch content.

Growth Parameters

Leaf area, shoot elongation, radial growth and visible leaf injury were monitored during both growing seasons.

Leaf area.--The 16 leaves kept from each study tree (eight from water potential and eight from diffusive resistance measurements) during each measurement period were labeled, pressed and air dried. The area of each leaf was measured with an optical planimeter.

Shoot elongation.--In September 1978, following the final water potential and diffusive resistance measurements, shoot elongation was measured on 16 branches from each study tree. Four branches were selected from each quadrant, two in the upper half of the crown, and two in the lower half. On each sample branch, elongation was recorded for each year between 1973 and 1978, and the 16 values were averaged to provide a mean annual elongation by tree for each of the six years. Growth was expressed both as actual annual elongation and as a ratio of the 1978 elongation to the average elongation

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[3/] Model LI-65 Autoporometer, Lambda Instruments Corp., Lincoln, Nebraska.

[4/] Model 7950 Shigometer, Northeast Electronics Corp., Concord, New Hampshire.

[5/] Type A-106, Delmhorst Electronic Supply Co., Boonton, New Jersey.

of the 1973 through 1976 growing seasons. Growth ratios were used to remove the effects of past growth on current elongation. Elongation during the year following terminal bud abortion was eliminated from the yearly average.

Radial growth.--Concurrent with the collection of branches for shoot measurement, breast height increment borings were taken from the north and south sides of each study tree for radial growth measurements. Measurements were made under a 10-power microscope fitted with a stage micrometer, and, as with shoot elongation, data were expressed both as actual annual radial growth and as a ratio of the 1978 elongation to the average elongation of the 1973 through 1976 growing seasons.

Leaf scorch rating.--On 21 and 29 August and 13 September 1978, all study trees were rated according to the estimated percentage of leaves in the crown exhibiting marginal necrosis (leaf scorch injury). The rating system ranged from 1 to 10; a score of 1 indicated some leaf scorch on 1-10 percent of the leaves, and a score of 10 indicated some leaf scorch on 91-100 percent of the leaves. The crown of each tree was visually divided into four quadrants with cardinal direction midpoints. On each date, two observers independently rated each tree by quadrant. The eight observations were averaged to give a mean leaf scorch rating for each tree.

Experimental Design and Data Analysis

Although the 14 trees within each plot were subjected to the same treatment, each tree was considered to be an independent observation of that treatment. Strictly random and independent treatment of each tree, while statistically preferable, was not logistically feasible. Since the root systems of study trees were thought to overlap, the random and independent treatment of individual trees would be biologically confounded by the effects of treatments on adjacent study trees. For this reason, treatments were assigned randomly to each 14-tree plot, and a buffer zone was maintained between the plots. Experimental replication was not considered necessary as the primary purpose of the experiment was to compare and evaluate stress detection techniques, rather than to examine the effects of soil compaction treatments.

Two-tailed t-tests with 26 degrees of freedom were used to test the significance of treatment differences for leaf area, shoot elongation, radial growth, leaf scorch, shoot water potential, diffusive resistance and electrical resistance. Simple linear correlations were used to evaluate relationships between these parameters when treatment differences existed. A Chi-square test with 4 degrees of freedom was used to test the significance of difference in root starch. Significance was determined at the 5% level for all tests.

RESULTS AND DISCUSSION

Soil Response to Treatment

Soil bulk density.--In June 1977, preceding the initial compaction, soil bulk density did not differ significantly between plots in any soil

zone. By May 1978, bulk density in the 0-5cm zone of the treated plot had increased significantly from the original 0.75g/cm^3 to 1.02g/cm^3, and was significantly higher than in the control plot. During this period, bulk density in the 0-5cm zone of the control plot increased significantly from 0.71g/cm^3 to 0.85g/cm^3. This increase may have been due to foot traffic. Although we attempted to minimize disturbances, numerous measurements required activity in the control plot. Soil density in the 0-5cm zone did not increase significantly between May and August 1978, in either plot. By August 1978, density in the 5-10cm zone of the treated plot (1.25g/cm^3) was significantly greater than in the control plot (1.15g/cm^3). Compaction did not cause significant increases in bulk density in the deeper 10-15cm, or 15-20cm zones.

Soil moisture.--Soil moisture in the treated and control plots increased significantly between each measurement period. In June 1977, prior to compaction, moisture in the control plot (35% by volume) was significantly greater than in the treated plot (32% by volume). But in May and August 1978, the treated plot was significantly wetter, i.e., 45% vs. 40% in May, and 49% vs. 45% in August. This relative increase is consistent with several reports in the literature (Proctor, 1933; Lull, 1959) indicating a greater moisture content in compacted soils resulting from an increase in number and relative volume of micro-pores (Hill and Sumner, 1967).

While differences in moisture content between the two plots during 1978 appear to be due to differences in soil bulk density, it is unlikely that the continued increases in moisture content within both plots are due to changes in soil density. Moisture content continued to increase during the 1978 growing season, while surface bulk density remained stable. Moisture increases may be due to increases in the amount of precipitation at the site prior to each measurement. In the two weeks prior to the June 1977 measurement, only 0.7cm of rain fell, while 3.7cm of rain fell before the May 1978 measurement, and 6.3cm fell before the August 1978 measurement.[6/]

Growth Parameters

Leaf area.--Mean leaf area for all sampling dates, averaged over the entire study, was 70.6cm^2 in the treated plot, and 69.6cm^2 in the control plot. Differences were not significant in any measurement period.

Shoot elongation.--Mean annual shoot elongation in the 1973 through 1976 growing seasons was 9.0cm in both the treated and control plots. During the 1978 growing season, mean elongation was 6.2cm in the treated plot, and 8.1cm in the control plot. Mean growth ratios, calculated as the average of the individual tree growth ratios, were 75.1% in the treated plot, and 92.0% in the control plot. Although there appeared to be a tendency for trees in the control plot to grow faster, these differences were not statistically significant.

[6/] Personal communication with F. M. Laing, Research Associate Professor, Department of Botany, University of Vermont.

Radial growth.--Mean annual radial growth for the four growing seasons prior to treatment was 2.1mm in the treated plot, and 1.8mm in the control plot. During the 1978 growing season, mean radial growth was 3.2mm in the treated plot, and 3.5mm in the control plot. Mean growth ratios were 166.9% in the treated plot, and 205.4% in the control plot. As with shoot elongation, there was a tendency for trees in the control plot to grow faster, but differences were not significant.

Leaf Scorch Injury

Marginal necrosis was observed in mid-August 1978. Average leaf scorch rating in the treated plot was nearly double that in the control plot at each of three measurement dates (Table 1). Trees with slight leaf scorch symptoms on 21 August 1978, had developed severe symptoms by 13 September 1978, to the point where nearly half of the leaves in the crown of an average tree in the treated plot had marginal necrosis. This was more than twice the average leaf scorch in the control plot.

Table 1.--Average leaf scorch in the treated and control plot on three measurement dates.

Measurement Date	Leaf Scorch Rating[a]	
	Control	Treated
21 August 1978	1.3	2.4*
29 August 1978	2.2	4.8*
13 September 1978	2.4	5.6*

[a] Rating system: 1.0=1-10 percent of foliage with some leaf scorch; 10.0=91-100 percent of foliage with some leaf scorch.

*Leaf scorch rating significantly greater in treated plot (5% level).

Leaf scorch injury is a common symptom of moisture stress, and often occurs after periods of short term drought. Sugar maple is very susceptible to this type of injury (Tattar, 1978). Perhaps the greater bulk density of the soil in the treated plot restricted root growth, or otherwise interfered with the process of water absorption, and prevented the roots of these trees from adequately replacing the water lost from transpiring leaves. It is unlikely that these trees were under continual water stress. Rather, the moisture stress and subsequent leaf injury probably occurred over a short period of time, perhaps during an afternoon, or over a few days of warm drying winds.

Evaluation of Stress Detection Techniques

Root starch content.--Six of the eight trees in the highest starch cate-

gory were from the control plot (Table 2), and four of the five trees in the two lowest categories were from the treated plot. While these differences were not significant, there did appear to be a tendency for treated trees to have less root starch. Reduction in root starch within defoliated and/or drought-stressed sugar maple have been reported by Parker (1970), Parker and Houston (1971), and Parker (1974). Parker and Houston (1971) propose that reductions do not result solely from starvation, but may be compounded by complex hormonal changes.

Table 2.--Root starch category of trees in treated and control plots in 1978.

Visual Category	Root Starch[a/]	Number of Trees	
		Control	Treated
	----- % ----		
High	12-25	6	2
Medium	6-11	5	7
Low	2-5	2	1
Very Low	1	1	2
Depleted	0	0	2

[a/] From Wargo (1975).

The visual technique of evaluating root starch content is easily learned, and the five categories were readily discernible from the stained sections. Ten man hours of field time were required to collect the root samples, and an additional 15 man hours were needed to section, stain and evaluate the samples.

Quantitative analysis of root starch might be more sensitive to small differences; however, the visual technique is less costly, less time consuming, and with the proper equipment, can be completed in the field. As the visual categories did not contain equal size intervals of percent root starch, a non-parametric test was needed to evaluate possible differences. A parametric test would have greater power and sensitivity. Thus, equal percentage intervals and a greater number of category classes would improve the visual technique.

Shoot water potential.--Shoot water potential for the eight measurement periods averaged -12.4 bars in the treated plot and -12.7 bars in the control plot. Differences were not significant during any measurement period. Coefficients of variation averaged over all measurement periods were 23.7% in the treated plot, and 19.0% in the control plot. Within tree variation among sample shoots was of a similar magnitude.

This level of variability makes water potential a relatively sensitive physiological parameter to be used in stress detection. However, this technique failed to detect differences between the areas even when a condition of stress is known to have occurred in the treated plot, as shown by leaf scorch injury. Since water potential was measured only once a month during each growing season, it is possible that the measurement period did not coincide

with the time of moisture stress. Apparently, water potential would have to be monitored more frequently. However, the amount of field time required for this would be excessive. A total of twenty-eight man hours of field time were required to complete the observations for one measurement period. Because of the excessive field time involved, measuring water potential cannot be recommended as a useful method of stress detection.

Leaf diffusive resistance.--Diffusive resistance averaged 7.45 sec/cm in the treated plot, and 7.08 sec/cm in the control plot. Treatment differences were not significant during any measurement period. Coefficients of variation, for all sampling dates averaged over the entire study, were 65.5% in the treated plot, and 38.7% in the control plot. Variation among sample leaves within trees was also large, often greater than 100%.

Fourteen man hours of field time were needed to complete the observations for one measurement period, and an additional three hours of laboratory time were required for porometer calibration and preparation for field use. With large time requirements, excessive variation and sampling problems similar to those of water potential, measurement of diffusive resistance cannot be recommended as a useful method of stress detection.

Xylem electrical resistance.--Differences in xylem electrical resistance between treated and control plots were not significant during the first seven measurement periods. During this time, resistance averaged 10.7 K-ohms in the treated plot and 10.3 K-ohms in the control plot. But trees in the treated plot had significantly greater electrical resistance than controls in September 1978 (11.4 vs. 9.8 K-ohms) and October 1978 (9.8 vs. 8.2 K-ohms). The simple linear correlation between individual tree electrical resistance in September and October was significant (r=0.82). Trees with a relatively high electrical resistance in September also had high resistance in October. These results are consistent with reports in the literature indicating greater electrical resistance in stressed trees (Wargo and Skutt, 1975; Newbanks and Tattar, 1977).

Coefficients of variation, averaged over all measurement periods were 20.2% in the treated plot and 16.5% in the control plot. Thus, variability is considerably less than with diffusive resistance measurements, and slightly less than was observed with water potential measurements. In addition, only one man-hour of field time was required for data collection in each measurement period, and no laboratory time was needed. The meter required frequent calibration when in use, but the procedure was rapidly completed and resulted in little time lost. Electrical resistance was the only parameter that detected significant differences between the treated and control plots. Electrical resistances in October 1978 were significantly correlated (r=0.64) with individual tree leaf scorch ratings of September, 1978. Trees with greater injury had greater electrical resistance.

There are, however, several problems with the use of the meter. The electrode pins are brittle and often break. Broken electrodes could rarely be recovered from the tree and were usually left imbedded in the xylem. In several cases, stem canker and callus tissue formation were later noted at

the points of electrode insertion. Also, differences in electrical resistance between the treated and control plots were not detected until after leaf scorch symptoms were expressed. As water potential differences were not significant when measured in September 1978, trees in the treated plot were not continually under greater moisture stress. It is possible that differences in electrical resistance were not caused by moisture stress, but rather by differences in the severity of leaf scorch injury. Newbanks and Tattar (1977) reported that electrical resistance was significantly correlated with visual crown symptoms of decline in non-urban trees. Wargo and Skutt (1975) found significant differences in electrical resistance between gypsy moth-defoliated and non-defoliated oaks of several species. If visible injury must precede the detection of differences in electrical resistance, the meter would be of little value as a stress detection instrument.

CONCLUSIONS

Because of the problems with excessive amounts of field and laboratory time required to complete measurements, or relatively large coefficients of variation, neither the pressure bomb nor the diffusive resistance porometer are recommended methods of stress detection. However, failure to detect significant differences between the treated and control plots may not be due solely to the insensitivity of the instruments. The pressure chamber and porometer are very precise instruments, and their successful use requires a commensurate precision in the selection of samples and control of environmental variability that was not possible in this field study. The probable statistical consequence of this lack of control, especially with a modest sample size, is an increase in error. This may have reduced the power of the t-test used.

Electrical resistance and root starch content are promising approaches, but further research and procedural changes are needed. If differences in electrical resistance result from the detection of injury rather than stress, the meter has limited value as a stress detection instrument. Further research into electrical resistance is needed to determine exactly what is being measured and how electrical resistance relates to the overall condition of the tree. Without this knowledge, differences in electrical resistance only catalog differences between trees, and tell us nothing about the physiological state of the tree and appropriate correction procedures. However, the ease and speed of measurement, and the relatively low variability between trees show promise for the technique and justify further research.

The analysis of root starch content also shows promise as a stress detection technique; however, Wargo's (1975) procedure does not appear sufficiently sensitive to small differences between trees. If large differences are required to detect conditions of stress, the overall condition of the trees may be so deteriorated that subsequent correction procedures are impractical. The quantitative analysis of root starch content may be more sensitive to small differences between trees with a new and developing stress condition and might enable earlier detection and practicable correction.

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