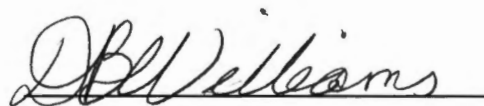


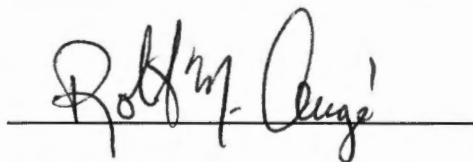
To the Graduate Council:

I am submitting herewith a thesis written by Joel Franklin Keebler entitled, "Influence of Vertical Mulching and Irrigation on the Water Status and Growth of Urban Red Maple (*Acer rubrum*).” I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Ornamental Horticulture and Landscape Design.

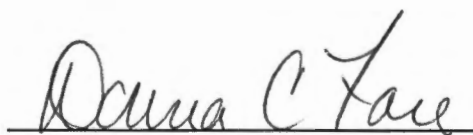
A handwritten signature in cursive script, reading "Don B. Williams", written over a horizontal line.

Don B. Williams, Major Professor

We have read this thesis
and recommend its acceptance:

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Donna C. Fare

Accepted for the Council:

A handwritten signature in cursive script, reading "C. Mink", written over a horizontal line.

Associate Vice Chancellor and
Dean of The Graduate School

**INFLUENCE OF VERTICAL MULCHING
AND IRRIGATION ON THE WATER STATUS
AND GROWTH OF URBAN RED MAPLE (*Acer rubrum*)**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Joel Franklin Keebler

December 1998

~~Ag-VetMed~~

Thesis

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ABSTRACT

Mulching has long been recognized as a treatment to improve the health and vigor of cultivated plants. In recent years, vertical mulching has been much discussed although, to date, there has been little research. Vertical mulching involves the removal of soil and its replacement with an organic amendment. In **urban forestry**, vertical mulching might be used to ameliorate difficult cultural conditions (especially soil compaction). I tested **vertical mulching (radial trenching)** on **red maple** (*Acer rubrum*) and compared it against surface mulching and no mulch. The study trees represented two cultivars ('Franksred' and 'October Glory'), and were established and growing near a major urban highway. I tested both types of mulching in conjunction with **drip irrigation**. My research focused on **water status, growth, and phenological parameters** over two growing seasons. The installation of the vertical mulch trenches resulted in some root damage but did not cause any long-term stress. Vertical mulching did not much improve the water status or growth of the red maples when compared against the control (no mulch). The surface mulch treatments tended to outperform the rest in most parameters of this short-term investigation.

TABLE OF CONTENTS

I. INTRODUCTION AND LITERATURE REVIEW

Mulching.....	1
Vertical Mulching.....	3
Water Relations.....	10

II. MATERIALS AND METHODS

Plant Materials.....	14
Study Area.....	15
Tree Culture.....	16
Treatments.....	17
Treatment Summary.....	21
Irrigation.....	22
Tree Growth.....	23
Phenological Analysis.....	24
Evaluating Water Status.....	25
Gas Exchange Instrument Measurements.....	29
Root Investigations.....	30
Statistical Analysis.....	30

LIST OF FIGURES

FIGURE	PAGE
1. 1996 monthly precipitation.....	32
2. 1997 monthly precipitation.....	33
3. 1996 daily maximum temperature.....	35
4. 1997 daily maximum temperature.....	36
5. Leaf area by treatment, averaged for 1996 and 1997.....	38
6. Leaf area by treatment, averaged over 1996 and 1997.....	40
7. Tree height by treatment, averaged for 1996, 1997, and 1998.....	41
8. Tree circumference by treatment, averaged for 1996 and 1998.....	43
9. Tree circumference by treatment, over time for 1996 and 1997.....	44
10. Phenological study averaged over 1996 and 1997.....	45
11. Pre-dawn xylem water potential by treatment, over time for 1996 and 1997.....	47
12. Pre-dawn xylem water potential by treatment, averaged over 1996 and 1997.....	48
13. Mid-day xylem water potential by treatment, averaged over 1996 and 1997.....	51

14. Osmotic potential by treatment, averaged over 1996 and 1997.....	52
15. Leaf turgor by treatment, averaged over 1996 and 1997.....	53
16. Stomatal conductance by treatment, averaged over 1996 and 1997..	55
17. Stomatal conductance by treatment, over time for 1996 and 1997.....	57
18. Photosynthesis by treatment, averaged over 1996 and 1997.....	58
19. Photosynthesis by treatment, over time for 1996 and 1997.....	60
20. Transpiration by treatment, over time for 1996 and 1997.....	61
21. Transpiration by treatment, averaged over 1996 and 1997.....	63
22. Leaf temperature by treatment, over time for 1996 and 1997.....	64
23. Leaf temperature by treatment, averaged over 1996 and 1997.....	65
24. Intercellular CO ₂ by treatment, averaged over 1996 and 1997.....	67
25. Pre-dawn and mid-day xylem water potential, and osmotic potential by treatment, for Aug 7 & 24 and Sep 7, 1997.....	69
26. Transpiration, stomatal conductance, leaf temperature and photosynthesis by treatment, for Aug 1, 12 & 28, 1997.....	70

of the urban forest in the Southeastern region of the United States.

Research indicates that young trees that do not shade a substantial portion of their rooting zone may have their potential growth reduced by 50% due to competition from weeds (Neely 1984). The elimination of turfgrass competition may be one of the most significant contributions of a surface mulch. Turfgrass roots and tree roots tend to occupy the same rooting area. The literature on tree root distribution indicates that the highest densities of tree roots occur in the upper soil horizon (Watson 1982a). Turfgrass research indicates that grasses routinely root deeply; tall fescue (*Festuca arundinacea*.) can root to 91 centimeters (36 inches) while bermudagrass (*Cynodon dactylon*) can root to 152 centimeters (60 inches) (Cockerham 1996) or, in at least one instance, up to 213 centimeters (84 inches) (Williams unpublished).

The use of small rings of mulch that cover only a limited area around trees has become commonplace in many parts of the United States even though the benefits (short of reducing damage from mowing equipment) may be mostly perceived. The root systems of most trees can be expected to extend a considerable distance beyond the dripline (Watson and Himelick 1983); thus trees could not be expected to gain much benefit from only a small ring of mulch.

Mulching is also recognized as a beneficial treatments for the amelioration of soil problems. Jim Patterson, with the Center for Urban

Ecology in Washington D.C., estimates that, “probably 80 percent of the decline of urban trees is related to soil stress,” (Stone 1994). Soil compaction is widely recognized as one of the most serious threats to trees as they become established, grow, and survive to maturity in urban environments. A recent survey of arborists estimated that 40 percent of commercial and residential properties had areas of significant soil compaction near trees (Smiley 1997). Compaction is often a problem on newly constructed sites due to the operation of heavy equipment. It is also a problem in many instances due to foot traffic, vehicular traffic, and the impact of water droplets on soil surfaces (Petrovic 1986). In fact, compaction problems have lead to the introduction, in recent years, of several soil fracturing/aeration tools such as the Terra-lift and Grow Gun (Smith 1996).

A typical tree root system is very thin in depth but large in area (Urban 1989). A surface application of mulch can reduce compaction and it has been suggested that the best long-term solution for a tree growing but declining in a compacted site, is the application of a decomposable, organic mulch over a large surface area under and around the tree extending at least to the tree’s dripline (Stone 1994, Fraedrich and Ham 1982).

Vertical Mulching

Recent interest has been generated regarding a different mulching technique that is often referred to as vertical mulching or soil replacement.

In vertical mulching, soil is actually removed from the rooting zone of a plant and is replaced with an organic product that promotes vigorous root growth and development. This technique, if proven feasible, could have widespread application in urban areas due to the fact that there has been a number of recent, conclusive studies which point to the lack of planning for root growth as the overwhelming cause of urban tree failure (Urban 1996). Also, this type of planting area modification could be used to broaden the number of species that could survive and thrive on an adverse growing site (Urban 1992).

Vertical mulching might be used to correct another common cultural problem in urban environments; that of trees growing in compacted soils. Soil compaction can restrict root penetration through the soil, reduce root elongation and branching, crush and kill roots, and restrict the amount of soil oxygen available to roots leading to root suffocation. Unfortunately, soils are slow to rebound from compacting forces (Fraedrich and Ham 1982) and adding a surface mulch could not be expected to lead to quick reduction in soil bulk density (Fraedrich and Ham 1982); although from a long-term perspective it might do much good. The more proactive procedure of vertical mulching might cause a greater and more immediate reduction in soil compaction.

Vertical mulching was perhaps first developed and instituted in China (Craul 1994). It was used there by the gardeners and caretakers of

religious sites where there were frequently large, mature trees that had some importance associated with them. Over time, these ancient trees would lose their vigor. In an effort to improve the health of these trees and interrupt mortality spiral, those responsible for the trees would meticulously remove soil from around their root systems and replace it with some type of composted, organic matter in order to improve both soil structure and fertility (Watson 1990). A similar process called hydraulic excavation is used in Europe by commercial arborists who use specifically designed equipment to wash soil away from intact root systems and then replace it with an organic soil mixture. Both labor-intensive procedures have proven to be effective (Watson 1990). Variations on this technique have been proposed, but as of yet, no large-scale, replicated study has been conducted and published. Also, there exists a dearth of guidelines, procedures, or standards that apply to this type of site modification (Urban 1992).

To reduce labor input and to make the use of vertical mulching more economical and practical, tree researchers have proposed the use of mechanical trenching machines to remove soil from tree root systems. This method results in the damage of roots that are severed or removed by the digging action of the trencher. In an effort to minimize root damage trenches are dug radiating out and away from the tree trunk. This would seemingly reduce the opportunity for encountering significant tree roots. However, some roots can be expected to be severed because tree roots do

not grow exclusively in a radiating pattern. The tree size and maturity are considered when determining how close to begin digging to the tree's trunk. Typically, the trenches would radiate out at least to the drip line of the tree (Watson, personal communication 1996).

It is believed that the severed roots quickly regenerate from the area of callus formed near the severed root and that fine, feeder roots will quickly recolonize the vertically mulched areas due to the improved underground environment (Watson and Himelick 1982b, Watson and Himelick 1983). In soil zones that are particularly nutrient rich, there is an increase in branching of lateral roots which leads to an abundance of fine roots (Watson 1994). Studies relating to nursery production have shown that if root pruning is properly executed in the field, it is possible to produce a balled and burlapped plant with several times the amount of fine roots compared to an unpruned plant (Watson 1986).

In order for vertical mulching to have an effective long-term impact on a tree, Watson (1990) surmises that three factors must be taken into account. The first is that no long-term damage be done to the root system of the tree being treated. The second is that a significant amount of soil has to be removed and replaced. This can be daunting considering the large volume of soil that a mature root system can occupy. The third is that the material that replaces the soil must have physical properties similar enough to the surrounding soil so that it does not present a hindrance to

regenerating roots from growing from the surrounding soil into the mulched area.

One recent study did attempt to evaluate the effectiveness of vertical mulching. However, in this study, a 5 centimeter drill was used to bore 16 holes per tree in the ground instead of using the radial trenching method (Kalisz et al. 1994). This resulted in a very small amount of actual soil replacement per tree and essentially no treatment difference throughout the three-year study.

In theory, the radial trenching method of vertical mulching has several advantages. Some of the most important are; it is cost effective by reducing labor through the use of a mechanical trencher which is readily available for purchase or rental, it minimizes damage to existing roots while maximizing the excavated soil volume, and, perhaps most importantly, it would stimulate the *radial* growth of tree roots. Whenever you can provide a radial—rather than linear—volume of soil, you have improved the usefulness of the available soil volume, allowing for greater structural stability as the tree matures (Urban 1996).

As to effectiveness, Watson (Personal communication 1996) speculates that vertical mulching will never be as effective in improving tree health as is surface mulching. However, there may exist situations that limit the application of surface mulch, yet vertical mulching could be implemented. For instance, in an urban situation, vertical mulching might be

preferred over surface mulching in areas where turfgrass is required or preferred to extend all the way up to a tree's trunk. Also, vertical mulching via radial trenches might be a good place to install a drip irrigation system that would be safer and more vandal-proof than an above-ground system. In many urban areas trees are forced to grow with very restricted root systems in limited volumes of soil (Urban 1996). In this type of situation, vertical mulching could provide a tree with the opportunity to create and maintain a more natural percentage of fine, feeder roots in growing areas where the available surface area simply does not allow a tree's root system to grow and develop as it would in a natural or forested situation. Preliminary research has shown that root growth in trenches can be four times greater than in surrounding soil in only two growing seasons (Smiley 1997). This contrasts with a previous study on the effectiveness of amending backfill at the time of planting which showed there to be no justification for this very popular landscape practice (Hummel and Johnson 1985).

Urban street trees often survive for a few years before they begin to decline. Trees planted on sites that restrict root development, often result in restricted growth and reduced longevity (Watson 1990). Perhaps 80 percent of all landscape tree problems start below ground (Watson 1994b). Many problems with older trees are the result of poorly developed or declining root systems (Watson 1990). Vertically mulched radial trenches

could also provide passageways for root growth to adjacent areas of lawn or planting beds to increase the volume of soil available to trees.

Previous research regarding the establishment of deciduous bare-root trees found that radially trenching the native soil proved to be an effective method of overcoming compacted soil leading to improved tree establishment and growth (Day, Bassuk, and Es 1995). These findings suggest that vertical mulching might be an effective procedure to execute during the planting of trees on sites known to be compacted. This would be considerably less expensive than subsoiling, adding “topsoil”, or replacing soil.

Watson (1990) speculates that if fine, feeder roots concentrate in narrow trenches that have been vertically mulched, then those areas may be ideal for the application of irrigation water or supplemental nutrients. The accumulation of absorbing roots in these areas may be very useful as a management tool (Watson 1990). This strategy would be of value in urban situations where trees are growing in areas with restricted root zones. This becomes more significant considering that urban trees are often forced to tolerate less than ideal growing sites where soils are often compacted. One urban tree researcher has proposed that the best way to help a tree overcome a compacted growing site is to provide that tree with supplemental irrigation (Watson personal communication 1996). The question then becomes how to best supply water to a tree growing on a site

with decreased infiltration due to soil compaction. The vertically mulched trenches may be ideal for drip-irrigation systems and vertical mulching may provide long-term improvements to overall soil structure.

To date, there exists a dearth of information on vertical mulching and its proposed benefits. Meaningful results from this type of investigation may take several years to accumulate. However, some similar studies have been conducted on newly or only recently established plant materials. There have been no replicated studies such as this one on larger, established trees.

Water Relations

Urban trees undoubtedly experience numerous physiological stresses that are due to cultural conditions quite different from their natural environments. These include; restricted root and soil volumes, soils with poor structure and little organic matter which results in reduced soil moisture, unusually high light levels due to reflective surfaces, high winds due to urban canyon effects, increased vapor pressure deficits due to reduced relative humidity, and increased summer temperatures due to numerous factors. It is very difficult to avoid predisposing trees in an urban environment to these types of stresses. It may be practical to use a technique like vertical mulching to moderate these stresses and prevent, or at least ameliorate, some of the inciting factors that lead toward decline (Manion 1981).

Worldwide, the single most important element limiting plant productivity is water. Urban trees undoubtedly experience great variations in available moisture throughout their lifetimes. In fact, a tree species' ability to survive a broad spectrum of soil moisture conditions may be one of the determinant factors in the survivability of that tree in the urban environment. It is probably not insignificant that the most commonly planted street trees of many Midwestern and Southeastern towns are floodplain trees (Ware 1994). Floodplain trees like silver maple (*Acer saccharinum*), green ash (*Fraxinus pennsylvanica*), American elm (*Ulmus americana*), river birch (*Betula nigra*), pin oak (*Quercus palustris*), American sweetgum (*Liquidambar styraciflua*), and red maple (*Acer rubrum*) are well adapted to prolonged flooding in spring and excessively well-drained and dry soils in summer. These types of natural growing conditions have evolutionarily adapted these trees for survival in urban environments where soil moisture extremes are commonplace.

While there have been numerous studies concerning the effect of water stress on the growth and development of forest trees, there has been only limited research on the effects of water stress on trees growing in urban environments (Krizek and Dubik 1987). Due to the numerous differences between cultural circumstances in forests and in urban environments, it is difficult to extrapolate data from forest trees to urban trees (Krizek and Dubik 1987).

Previous research on the effects of surface mulching on the growth of maples has indicated that enhanced growth of mulched trees was probably moisture related (Fraedrich and Ham 1982) and that 80-90% of the variation in tree diameter growth is related to the availability of moisture (Zahner 1968). Soil moisture is also thought to be a key factor in a tree's ability to overcome soil compaction (MacDonald 1994). Vertical mulching by radial trenching may be an effective measure to improve infiltration into the soil by interrupting the crusting action of some soils.

When unrestricted, the root systems of trees are shallow and spread well beyond the dripline (Watson 1988). However, in urban plantings, trees often grow with very limited soil areas and volumes. Trees with poorly developed root systems have a reduced ability to absorb moisture from the soil, especially when it is in limited supply (Watson 1988). During periods of summer drought, water can transpire from leaves faster than it can be replaced by a tree's root system. When this happens, a tree suffers from water stress that can lead to stress-triggered problems with disease or insects (Watson 1990). Periods of drought can also reduce root growth during the current growing season and have affects on tree health during subsequent growing seasons because of their impacts on food reserves (Wargo 1988).

Although this study proposes to investigate treatments that impact the "landscape below ground," the focus of the determinant measurements

will be on manifestations that are above ground. This may appear awkward, but there are at least two good reasons for such an approach. The first being that below ground factors are difficult to measure and quantify. Root research is difficult, tedious, time-consuming, destructive and often, unreliable (Taylor 1986, Craul 1994b). The second is that a tree represents a dynamic interaction and balance between the root and shoot (Wargo 1983). A change instituted below ground in one system must manifest itself in another above ground system due to this functional equilibrium (Neuman 1993). Above ground measurements, in a carefully controlled experiment with multiple replications, should lead to an informed inference on what has and is happening below ground.

II. MATERIALS AND METHODS

Plant Materials

For the purposes of this study, there was a clear preference for using established trees for the testing of radial trenching. However, finding a homogeneous group of large, mature trees growing in similar cultural situations is problematic at best (Dirr and Lindstrom 1989). Also, would a large, mature tree be as responsive as desired in a study that would have to be concluded in only two growing seasons? For these and other reasons, the subjects of this study were a group of 30 red maples (*Acer rubrum* L.) that were established only recently. Trees were planted in March and April of 1991 as balled and burlapped trees with an average caliper of 4 centimeters (1.5 inches) at 61 centimeters (2 feet) above ground level and an average height of 275 centimeters (9 feet). At the beginning of this investigation (April 1996), the trees averaged 4.417 meters (14.561 feet) in height and had an average circumference of 255 millimeters (10.04 inches) at 61 centimeters (2 feet) above ground level. This species is one that is often recommended and used for urban plantings and it often included on lists of plants that are tolerant of urban stress (Flint 1985). It is also considered to be the most widespread forest tree in the eastern United States (Townsend 1983).

Red maple has been shown to be highly variable genetically (Townsend 1983). Fortunately, the study trees are equally divided (15 and 15) between two well-known and popular cultivars, 'October Glory' and 'Franksred' (the tradename is Red Sunset). The former was introduced by Princeton Nurseries, New Jersey and is noted for good fall color even in unfavorable conditions. The latter was introduced in 1966 by Amfac Cole Nurseries but selected by J. Frank Schmidt & Sons, Portland, Oregon (van Gelderen et al. 1994). 'Franksred' was previously selected as the best overall of three red maple clones (Parrish and Wiedenmann 1978) and it is one of the most widely planted red maples in the Southeast (Fare et al. 1990).

Red maple is a commonly planted urban tree. It typically exhibits fast growth and aggressive rooting; which leads to the inference that it would perhaps readily recover from root pruning and would quickly respond favorably to vertical mulching.

Study Area

The trees are growing on the University of Tennessee's Agricultural Experiment Station, Poultry Unit, in Knoxville (Knox County), Tennessee. The site is located in the Ridge and Valley physiographic region. The climate is temperate and continental. The site is somewhat more windy and humid than most local areas due to its location within a mile-wide oxbow of the Tennessee River. Site elevation is approximately 920 feet above sea

level. All of the trees are within 100 meters of US 129 (Alcoa Highway), a major thoroughfare in the Knoxville metropolitan region. The trees are growing on soil classified by the 1942 United States Department of Agriculture, Knox County Tennessee soil survey (Series 1942, No. 10) as Cumberland, silty clay loam, eroded rolling phase. However, during excavation of the trenches, it was evident that all of the trees were probably growing on fill dirt due to soil disturbance from past highway construction activities. The site was not considered to be compacted and the trees were growing well without any supplemental water or nutrients. Despite the multitude of factors that could influence the growth and development of the study trees, this group appeared, at the beginning of the study, to be very uniform and all appeared to be in good health. The site, the species, the clones, the uniformity among the trees, and the site's close proximity to a major urban highway made this group of trees appear to be ideal for this type of investigation.

Tree Culture

The trees were established in an area maintained as utility turfgrass. The dominant turfgrass present is common bermudagrass (*Cynodon dactylon*) with tall fescue (*Festuca arundinacea*) and annual bluegrass (*Poa annua*) being conspicuous during the cooler months of the year. Bermudagrass is recognized as being one of the most severe competitors of all turfgrasses having the greatest suppressing effect on woody plant growth

(Whitcomb 1981). However, it could be that the detrimental effects of bermudagrass on woody plant growth are due to allelopathy (Whitcomb 1981).

The trees had been mulched with a hardwood bark product soon after they were planted and that mulch had been occasionally supplemented over the years. However, the area mulched was minimal, extending only about 50 centimeters from the base of the tree, and probably only served to prevent mower damage to the trees. The trees, prior to the study, had never been artificially watered at the outplant site and the only nutrient added was nitrogen in the form of ammonium nitrate; which was added via two eight ounce applications per tree spread across the surface of the soil over the root zone in May 1991 and again in June 1991 to increase growth rates.

Treatments

Five treatments were selected to test and compare the impact of radial trenching on this group of 30 red maples. Each treatment was represented by six replications: 3 trees of each cultivar. The treatments were distributed across the site in a randomized, split-block design.

Treatment A, Radial Trenches

Using the American Standard for Nursery Stock (American Association of Nurserymen, 1980) as a guide, it was determined that the study trees could safely tolerate significant root injury and removal up to 36

inches (91.5 centimeters) within the base of the trunk. This calculation allowed mechanical trenching close enough to the tree to assure pruning of some roots without harming the tree. Watson believes that there are many similarities between trenching and transplanting and that a vigorous, young tree has a good chance of recovery from moderate root loss if the site is repaired after trenching (Watson 1998).

Once the minimum distance was calculated the maximum distance was figured by evaluating tree canopy spread. We predicted that 427 centimeters (14 feet) of circumference would allow for tree growth by extending beyond the dripline of the trees at the end of the main portion of the study (Fall 1997). The goal was to install mulch treatments that would be immediately effective and that would remain effective even as tree size increased over the course of at least two years of study. The trenches were 15.25 centimeters (6 inches) wide, 46 centimeters (18 inches) deep, and 168 centimeters (66 inches) long. The trenches began at 91.5 centimeters (36 inches) from the tree's base and extended to 213 centimeters (7 feet) from the tree's base.

Eight trenches were dug around the tree approximately every 45 degrees with a mechanical trenching machine. The trenches were dug on May 20 and May 21, 1996. At this time, leaves were fully expanded, but not yet fully hardened off. Sudden root loss at this physiological juncture is thought to result in the severe stress (Watson 1998). It was estimated that

the trenching resulted in the removal and replacement of .94 cubic meter (33 cubic feet) of soil per tree.

The trenches were filled within a week's time with a hardwood bark type mulch and the excavated soil was moved off-site. During the installation the mulch in the trenches was periodically compacted by boot and with a nine-pound sledge hammer used as a battering device in an attempt to reduce voids and increase the bulk density of the mulch to match the bulk density of the soil.

All weeds and turfgrasses were eliminated to approximately 56 centimeters (22 inches) out from the tree's base by using a two percent solution of glyphosate (RoundUp ULTRA) to reduce damage from power mowing equipment.

Treatment B, Radial Trenches with Supplemental Irrigation

This treatment was installed exactly as Treatment A except that a drip irrigation system was installed in the trenches at a depth of approximately 15 centimeters (6 inches). The irrigation system was constructed of Rain Bird, Xeri-Tube-PC, pressure compensating, in-line emitter tubing. Emitters were factory spaced down the length of each trench every 46 centimeters (18 inches). A total of 5 emitters per trench resulted in 40 emitters per tree. Each pressure compensating emitter was capable of supplying 1 gallon of water per hour.

All weeds and turfgrasses were eliminated to approximately 56 centimeters (22 inches) out from the tree's base by using a two percent solution of glyphosate (RoundUp ULTRA) to reduce damage from power mowing equipment.

Treatment C, Control

This group was essentially left as it was found growing. Mulch had previously been placed around each tree but it extended no more than 1 meter from the base. This mulch was left in place but no mulch was added to it. By the end of the 1997 growing season, all of the mulch had decomposed. All weeds and turfgrasses were eliminated to approximately 56 centimeters (22 inches) out from the tree's base by using a two percent solution of glyphosate (RoundUp ULTRA) to reduce damage from power mowing equipment.

Treatment D, Surface Mulch

In order to best compare the possible benefits of radial trenching with other alternatives, the area to be altered with a surface mulch was similar to the area altered with the trenching. Surface mulch was installed at an average depth of 6.6 centimeters (2.6 inches) across the surface of the soil in a circle extending to 213 centimeters (7 feet) from the base of the tree. Prior to the installation of the surface mulch, the area to be mulched was scalped with a rotary mower to eliminate preexisting weeds and turfgrasses. All subsequent weeds and turfgrasses were periodically eliminated from the

area that was covered by the surface mulch by using a two percent solution of glyphosate (RoundUp ULTRA).

Treatment E, Surface Mulch with Supplemental Irrigation

This treatment was installed exactly as Treatment D except that a drip irrigation system was installed on grade (below the mulch but above the soil). This system was an exact duplicate of that used for Treatment B except that instead of the emitters being below grade in the trenches, the 40 emitters per tree were on grade beneath the mulch. This is in accordance with the manufactures recommendation and it also prevented soil and root disturbance on these trees.

All weeds and turfgrasses were periodically eliminated from the area that was covered by the surface mulch by using a two percent solution of glyphosate (RoundUp ULTRA).

Treatment Summary

The mulch product selected for use in this study was a shredded hardwood bark product supplied by a local lumber company. The product was dark in color but had not been composted. The two treatments of surface mulching required the installation of 1.7 cubic meters (59.5 cubic feet) of mulch per tree and the two treatments of radial trenching required approximately 1.7 cubic meters (59.5 cubic feet) of mulch per tree. The amounts used for the radial trenching were somewhat more than the calculated soil removed value (0.94 cubic meter or 33 cubic feet) because of

the subsequent compaction of the mulch in the trench and variations in actual soil removed. So, all four of the treatments requiring the use of mulch received approximately the same quantity of mulch. This will aid with a direct cost and effectiveness comparison among treatments.

Irrigation

The drip irrigation system was utilized on a weekly basis throughout two growing seasons. It was hoped that the supplemental irrigation would expedite the proliferation of small, feeder roots in the trenches and make treatment differences more pronounced in a reduced period of observation. Current recommendations for trees call for irrigation water to wet the soil to the depth of the rooting zone, usually about 46 to 61 centimeters (18 to 24 inches) (Tipton 1996). For this reason, the irrigation system was turned on only once each week but left on long enough to water deeply. Research has indicated that about 6.35 centimeters (2.5 inches) of irrigation water is required to thoroughly wet the upper 12 inches of a dry, silty clay loam soil (Williams 1997). Assuming that the research site is never completely devoid of soil moisture and considering that local growing conditions are generally good (prior to this study, these trees have never received any supplemental irrigation at this site), it was determined that the irrigation should provide only about 3.8 centimeters (1.5 inches) of water per week. Four hours of irrigation would supply 160 gallons (or 21.3 cubic feet or a little more than 1.5 inches) of water to each tree. Irrigation began each growing season

when it was estimated that soil moisture had become limiting (irrigation was initiated on June 25 in 1996 and on July 14 in 1997). Once initiated, weekly irrigation continued despite local moisture conditions. However, an occasional wet week was followed by irrigation for less than the pre-determined maximum of four hours. Irrigation continued until November of each year (to promote root growth) when cold temperatures necessitated the winterizing and shut down of the system. To minimize the immediate effects of irrigation upon water status evaluations, no water relations data were collected within 48 hours of a weekly irrigation episode.

Tree Growth

Plant growth is especially sensitive to water stress and yields can be noticeably decreased even with only moderate drought. So, tree growth was measured by three methods to determine possible treatment impacts. Leaf area was taken near the end of each growing season (September) to determine if treatments had any impact upon fully expanded leaf size. A portable area meter (Li-Cor, model LI-3000A, Lincoln, Nebraska) was used to determine leaf area in square centimeters. Eight fully expanded, unshaded leaves were removed from each tree canopy at approximately 2 meters from the ground. The leaves were collected from around the circumference of the tree at approximately every 45 degrees. The leaves were then immediately measured in the field to minimize desiccation.

Tree height was measured on three occasions (just prior to the trees leafing out in the spring) with a Lietz Digital Reading Measure Pole. To maximize accuracy, one observer climbed a ladder away from the tree to best determine when the extension of the instrument matched the terminus of the tree.

Tree circumference was measured multiple times during and after each growing season to determine treatment impact. Previous research has shown that annual increases in tree girth is a good indication of available moisture during the growing season (Levitt 1972). In fact, tree girth is so responsive to water stresses that diurnal shrinking and swelling of boles has been documented and associated with mid-day water demands (Zahner 1968). Each tree was marked with paint approximately 61 centimeters (2 feet) above ground level and circumference measurements were made in millimeters with a flexible metal tape. Circumference measurements were preferred over diameter for two reasons; first, young red maples typically exhibit asymmetrical trunk growth, and second, diameter does not give a true picture of trunk development (van de Werken 1984). For instance, if a tree's diameter increases 50%, it's circumference will have increased 125%.

Phenological Analysis

A tree's ability to produce and store food is vital. One way of gauging this process is to determine and compare the length of the growing season

(Close et al. 1996). While most trees of the same species will leaf out at approximately the same time, there can be significant differences in when they initiate fall coloration and leaf drop. This is thought to be a reflection of plant stress (Close et al. 1996). In this experiment, Julian calendar days were recorded near the end of the growing seasons (1996 and 1997) on each tree documenting the onset of fall color, peak fall color, and 100% leaf drop. 'October Glory' is noted by some to maintain its leaves longer than most other red maple cultivars (van Gelderen et al. 1994).

Evaluating Water Status

Due to the poor correlation that exists between soil moisture and plant water status, the most reliable way to estimate a plant's water status is to measure the plant itself (Roberts 1987). During a given growing day, a plant's water status may change dramatically. Standard techniques were employed for measuring seasonal foliar water relations, to characterize tree stress and, treatment effects.

Shoot Water Potential

Of all the techniques currently available for measuring plant water status, perhaps one of the most reliable in the field is the estimate of leaf or shoot water potential (Ψ) using the pressure equilibration or pressure bomb technique (Kramer and Boyer 1995). This procedure requires that a leaf or shoot be excised and placed into a pressure chamber with only the cut

petiole or stem surface being exposed. The chamber is then brought under pressure by the controlled release of nitrogen gas. When cut, the previously transpiring stem is under tension and the xylem water retracts into the stem. Pressurizing the chamber forces the xylem water back to the surface of the wound. The pressure required to just moisten the cut petiole or stem surface is shown on a pressure gauge on the device. This pressure is considered to be a reliable estimate of the tension acting on xylem water at the time of excision. This tension, quantified in MPa, is an estimate of leaf water potential (Ψ), assuming local equilibrium between stem xylem water and bulk leaf blade water. It is thought that if consistent sampling and measuring procedures are followed that this technique should be useful in the investigation of the water status of urban trees (Roberts 1987).

Previous experience from University of Tennessee (Department of OHLD) research with maples indicated that individual red maple leaves cannot be reliably sampled with a pressure bomb, due to spurious and unpredictable bubbling of sap from cut petiole ends before true balance pressures are reached (Augé and Stodola, personal communication). However, shoots with multiple leaves can be sampled more accurately and precisely. In fact, the larger size of the shoot wound as compared to the leaf petiole wound makes for easier viewing of cut xylem vessel ends and increased accuracy. For purposes of this study, terminal shoots averaging

20 centimeters in overall length were sampled. Each of these shoots had a minimum of 4 leaves and a maximum of 8. Shoots were removed with a sharp pair of anvil-type hand pruners and placed in the pressure bomb within a minute of removal.

Water potential measurements made in the early morning hours before sunrise are termed pre-dawn and represent an estimate of bulk root system ψ . Pre-dawn xylem Ψ was sampled bi-weekly during the course of the growing seasons with all measurements taken before local sunrise. In 1996, sampling was conducted on 11 occasions between May 7 and September 20. In 1997, sampling was conducted on nine occasions between May 23 to September 20.

Mid-day xylem Ψ measurements are influenced by transpiration and water uptake by the tree's root system. Diurnal measurements were conducted on eight of the study trees prior to treatment installation to best determine when these trees experienced the greatest amount of daily water stress. In accordance with this, mid-day Ψ measurements were made bi-weekly between the hours of 1 PM and 3 PM local time. Sampling occurred only on bright, sunny days. Shoots were collected from the south side of the tree and were oriented so as to have been in full sun for most of the day prior to sampling. In 1996, sampling was conducted on nine occasions

between May 14 and September 14. In 1997, sampling was conducted on eight occasions between June 15 to September 20.

All xylem Ψ sampling was conducted with a Soil Moisture Equipment Corporation Model 3005 Plant Water Status Console (Santa Barbara, California).

Osmotic Potentials and Plant Turgor

Two leaves from each tree were collected bi-weekly during both growing seasons for later analysis of osmotic potential ($\Psi\pi$). Samples were collected in conjunction with mid-day xylem Ψ . Sampled leaves were located in close proximity and in similar orientation as the shoot that was collected for measurement of total ψ in the pressure bomb. This allows for calculation of leaf turgor (Ψ_p) from leaf $\Psi\pi$ and shoot Ψ data ($\Psi = \Psi\pi + \Psi_p$), which assumes that shoot Ψ reliably estimates average leaf Ψ .

After excising a single leaf from the tree (most of the petiole is left behind), the leaf was immediately sealed in a sterile, single-use 3cc medical syringe. The syringe containing the leaf sample was then quickly placed in a dewar flask containing liquid nitrogen. After collection, the samples were transferred to freezer storage (-75°C) until processing with a Wescor 5500 Vapor Pressure Osmometer (Logan, Utah).

Gas Exchange Instrument Measurements

Transpiration, photosynthesis, leaf temperature, and stomatal conductance were measured with a LCA-3 Carbon Dioxide Leaf Chamber Analysis System equipped with a Parkinson Leaf Chamber (PLCB) both manufactured by the Analytical Development Company Limited (Hertfordshire, England). This system utilizes a solid state carbon dioxide analyzer, a light meter, a temperature probe and a humidity sensor to make moisture and composition comparisons between atmospheric conditions and the air circulating around the leaf in the chamber. It is capable of estimating ten parameters (five measured and five calculated).

Diurnal measurements were conducted on the six control trees (Treatment C) after treatment installation to best determine when these trees experienced the greatest amount of daily water stress. In accordance to this, LCA-3 measurements were made bi-weekly between the hours of 1 PM and 4 PM local time. A total of three samples from each tree were taken daily. The trees were sampled once during each hour (beginning at 1 PM, 2 PM, and 3 PM). Leaves that were sampled were those on the south side of each tree that were oriented so as to have been in full sun for most of the day. Measurements were made only on bright, sunny days. In 1996, measurements were made on seven occasions between June 6 and September 13. In 1997, measurements were made on nine occasions between June 6 and October 1.

Root Investigations

Just after the radial trenches were cut, an attempt was made to quantify root damage that occurred due to roots being severed by the mechanical trenching machine. An electronic caliper (Mitutoyo Corporation Digimatic Caliper) was used to measure the largest root, in each of the 8 trenches per tree in Treatments A and B, that was severed.

Statistical Analysis

It was assumed that this study probably has application for all red maple genotypes and perhaps for even several tree species. However, the design of the experiment allows for separate statistical analysis of each cultivar. Data was analyzed using Statistical Analytical Services' (SAS) Analysis-of-Variance (ANOVA) procedure.

III. RESULTS

Growing Season

Any experiment that involves trees growing out-of-doors will obviously be influenced by local climatic conditions. The following meteorological data was taken at the University of Tennessee's Plant Sciences Farm located approximately 2.4 kilometers (1.5 miles) south of the study plot. It is assumed that data from this weather station accurately portrays what occurred at the study site.

The monthly precipitation for 1996 and 1997 averaged 12 and 10.5 centimeters (4.68 and 4.10 inches), respectively (Figures 1 and 2). The 1996 total was 144 centimeters (56.20 inches), while the 1997 total was 126 centimeters (49.14 inches). The 1996 growing season was marked by average or above average rainfall except for the month of June when only 6.78 centimeters (2.67 inches) was recorded. However, June was preceded and followed by months with more than 12.70 centimeters (five inches) each. The months of August and September had monthly totals of 9.80 and 9.19 centimeters (3.86 and 3.62 inches).

The first six months of 1997 were extremely wet. From January to July, the monthly rainfall averaged 13.97 centimeters (5.5 inches). However, the abundance of rain came to an abrupt end in August when only 2.67 centimeters (1.05 inches) was recorded at the Plant Sciences Farm.

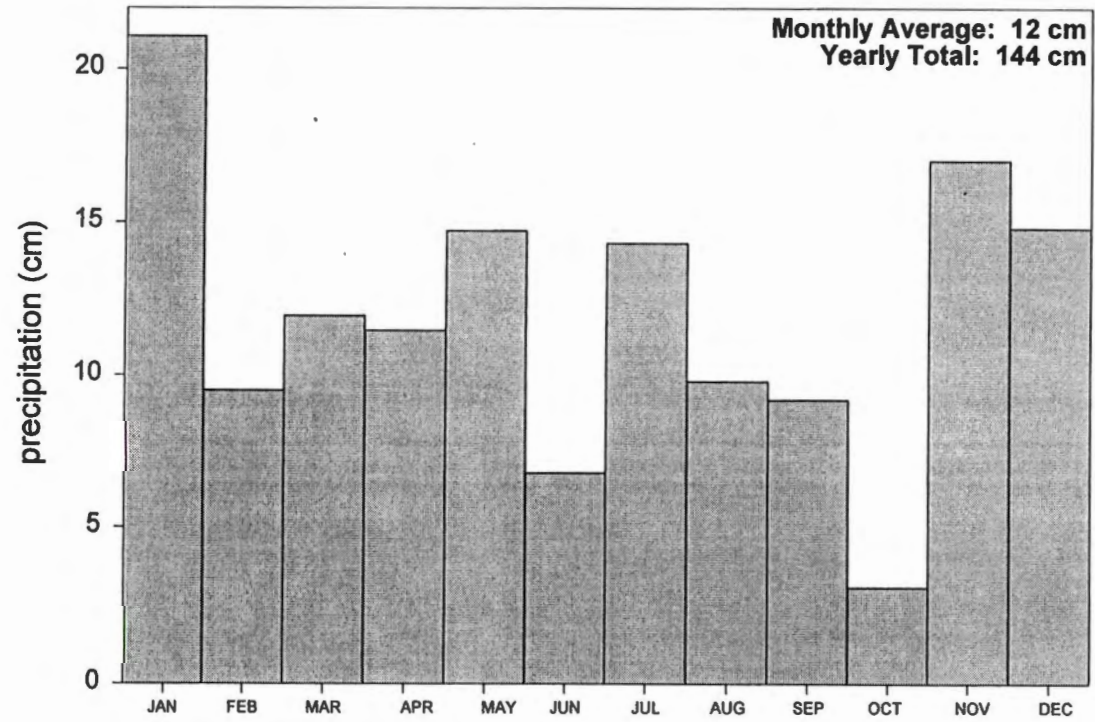


Figure 1. 1996 monthly precipitation. UTK Plant Sciences Farm.

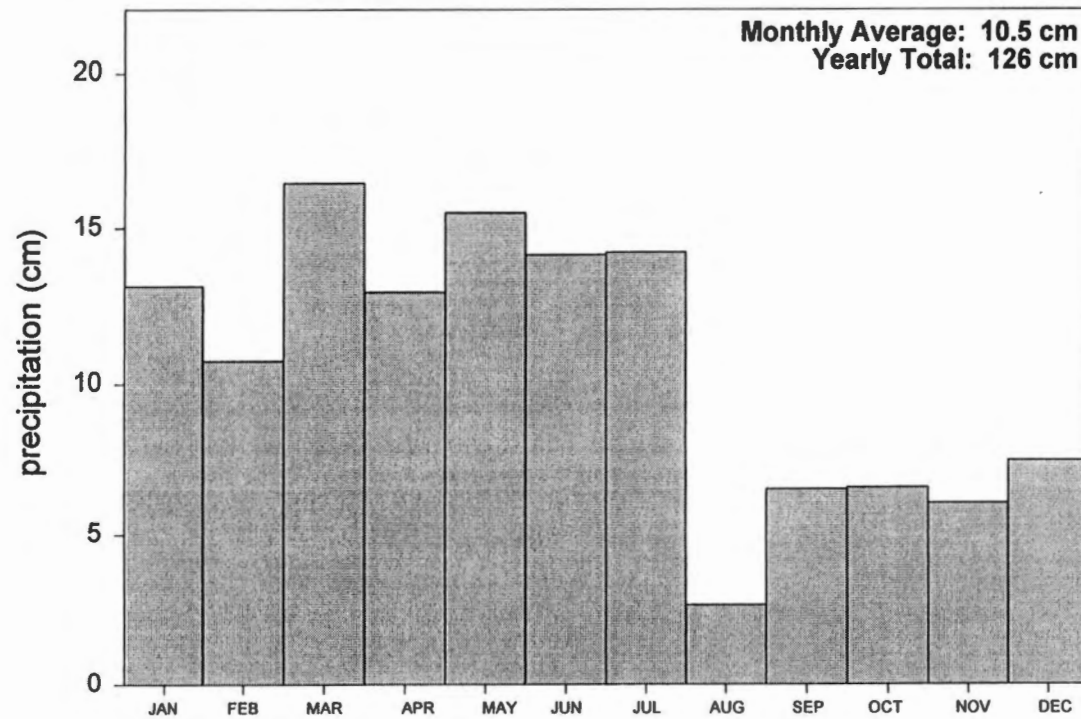


Figure 2. 1997 monthly precipitation. UTK Plant Sciences Farm.

September was also below average with only 6.50 centimeters (2.56 inches). Due to the occurrence of this period of dry, hot weather near the end of the experiment (when treatments were expected to have optimal impact), this period was singled out for additional statistical analysis.

Summaries of daily maximum temperatures for May through September of 1996 and 1997 are contained in Figures 3 and 4.

Pre-treatment Analysis

Prior to treatment installation, data collection was initiated to determine if the design of the experiment contained any detectable pre-existing biases. An analysis of this data by the ANOVA procedure determined that for all parameters of investigation save one (intercellular CO₂) there were no significant differences between treatment block means. This analysis was done on all parameters of investigation except for leaf area and for the phenological study; both of which were impossible to subject to this testing due to the time of the year when this study was initiated.

Tree Growth

There were only minimal differences between treatments in most areas of tree growth. The surface mulching had a positive impact on leaf area, tree height, and tree circumference. Although most of the treatment differences were not statistically significant, it appears that they did result in non-significant enhancements in tree growth.

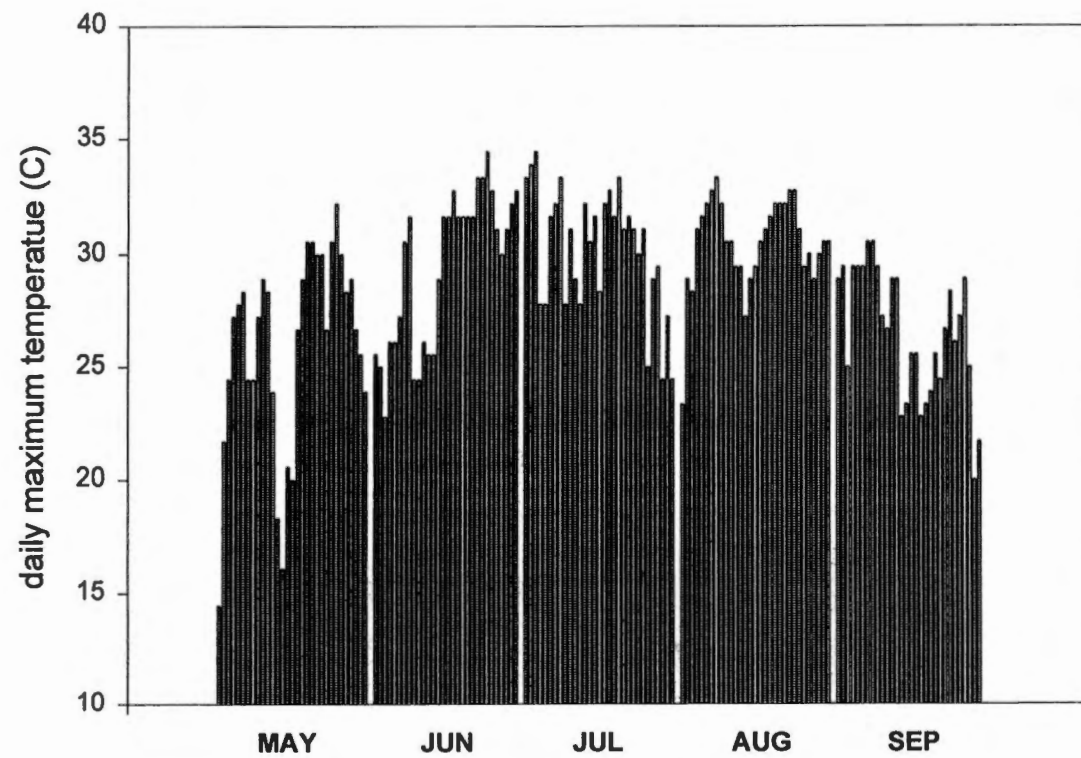


Figure 3. 1996 daily maximum temperature. UTK Plant Sciences Farm.

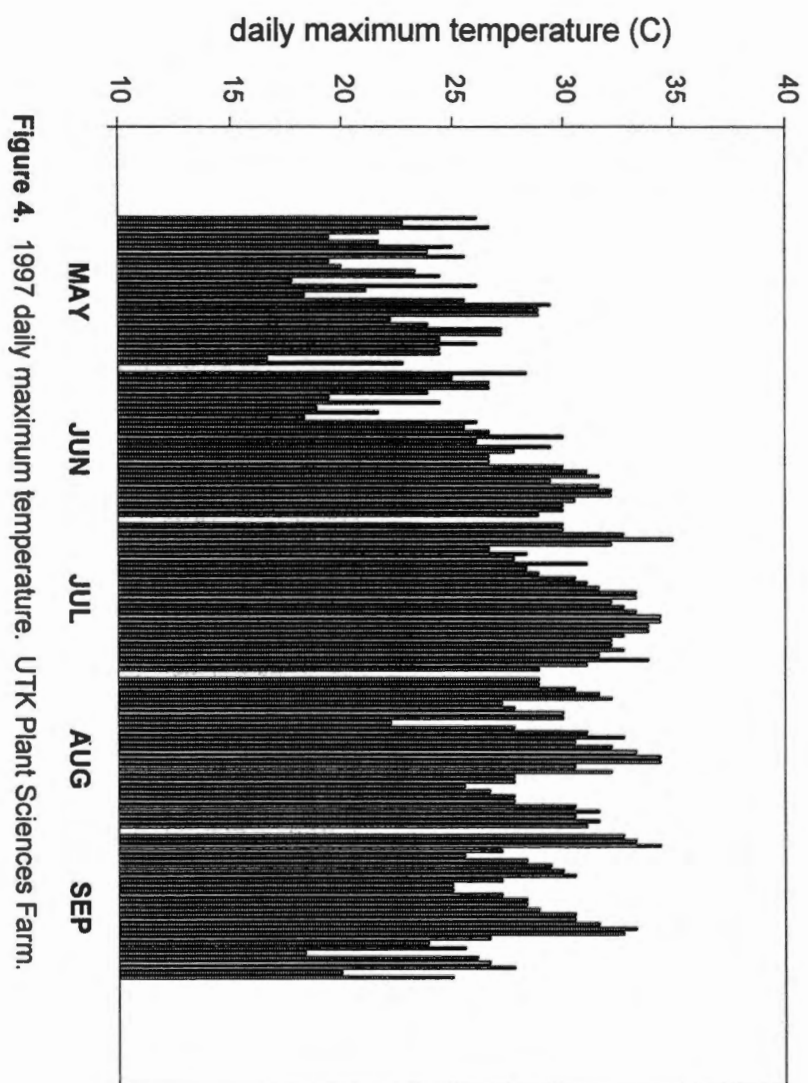


Figure 4. 1997 daily maximum temperature. UTK Plant Sciences Farm.

Leaf Area

The statistical analysis revealed some interesting and significant differences in the leaf areas of the study trees. There is a significant difference in individual leaf area between the two cultivars (data not shown). This is apparently due to physiological functions of each cultivar and not to any treatment effects. The means of each treatment by cultivar show that 'October Glory' trees have larger leaves (the four largest and the sixth largest out of 10) than the 'Franksred'. Since there are equal numbers of each cultivar in each treatment, the remainder of the discussion regarding leaf area will focus on other, more important aspects of this area of investigation.

There was a significant difference between the leaf area means of all trees across all treatments between the two-year analysis (Figure 5). The overall mean for 1996 was 39.85 cm² while the mean for 1997 was 51.50 cm² (an increase of almost 12 cm²). This trend was consistent among all treatments (even the control group increased almost 10 cm² from 38.57 to 48.26). This is almost certainly due to variation in the amount of precipitation prior to and during the early part of the two growing seasons.

As for analysis by treatment effect, there was a significant difference between the two surface mulched treatments compared to the remaining three treatments. Combining 1996 and 1997, the two surface mulched treatments had the greatest leaf area (both having 49+ cm²) compared to

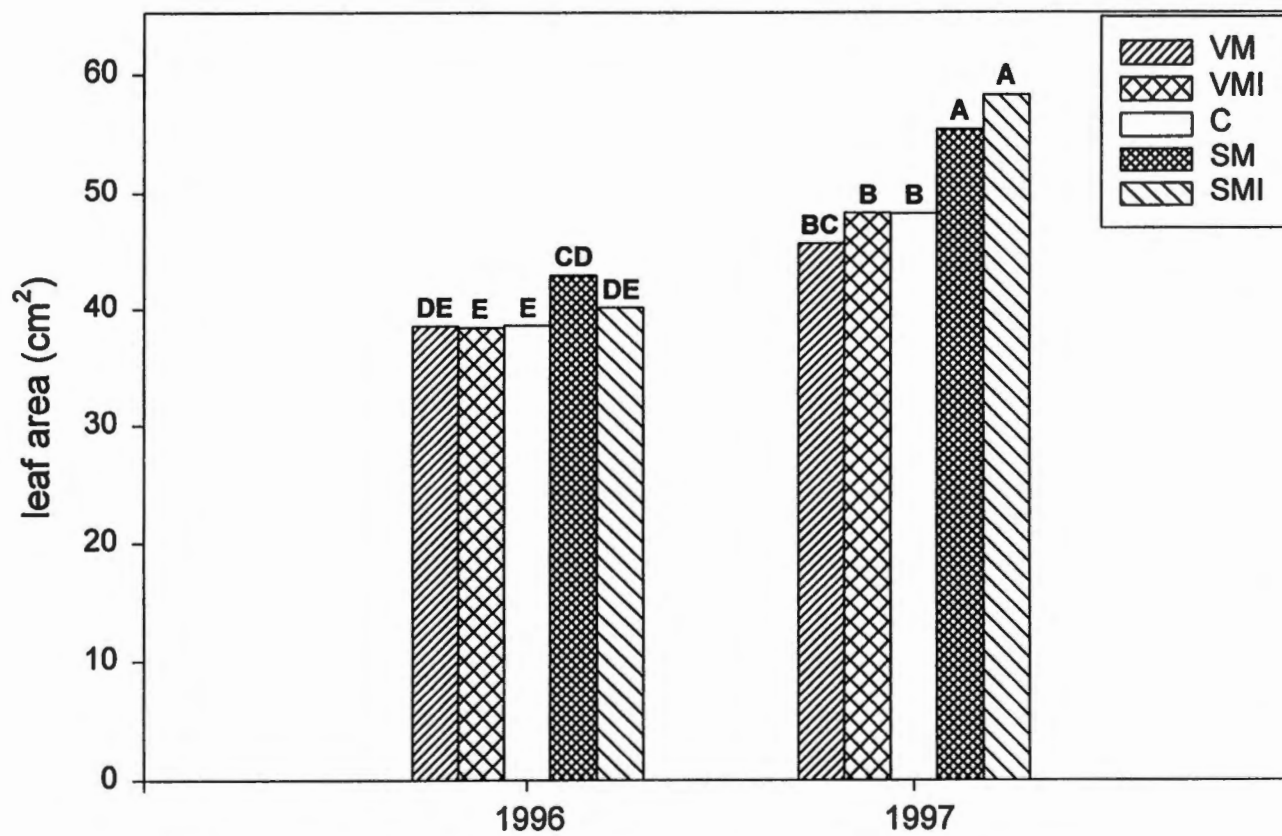


Figure 5. Leaf area by treatment, averaged (n=6) for 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

the remaining three groups which were all in the 43 cm² range (Figure 6). This difference is most pronounced in 1997 when the surface mulched with irrigation treatment was at 58.33 cm² and the surface mulched treatment was at 55.49 cm²; while the remaining treatments were all at 47 or 48 cm².

It is interesting to note that the vertical mulching with irrigation did not provide any significant improvement to leaf area in either year as compared to the control group. In 1996, this treatment was the smallest of the five (perhaps partially due to the May 1996 trenching operations) and in 1997 it improved to third largest but still statistically the same as the control and the vertical mulch without irrigation treatments.

Tree Height

There were no significant differences between cultivars in regard to tree height. There were also no significant differences between treatments (Figure 7). However, it is interesting to note that the two treatments with the smallest means (surface mulch with and without irrigation) at the beginning of the study (1996) grew to be the two largest by the end of the study (1998). It must be noted that accurately measuring trees that are 427 cm (14 feet) or more tall is difficult to do precisely. It may also be problematic to ascertain treatment impacts on tree height because of the multi-leader growth form typically exhibited by this species of *Acer*.

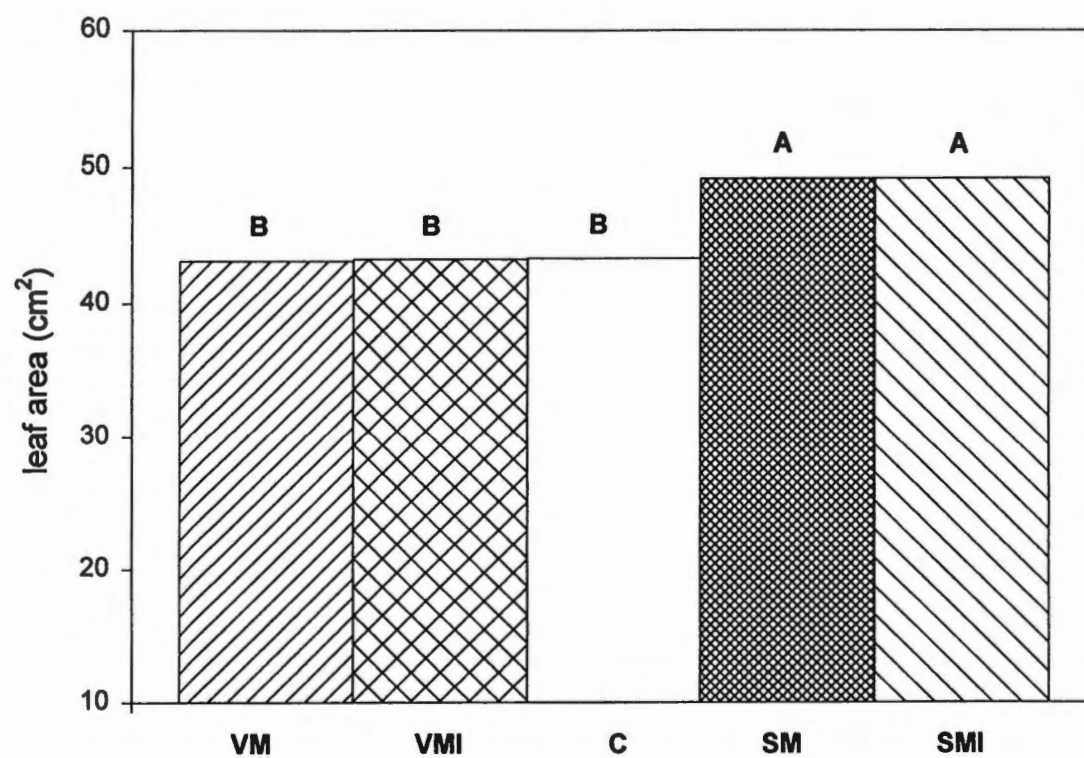


Figure 6. Leaf area by treatment, averaged (n=12) over 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

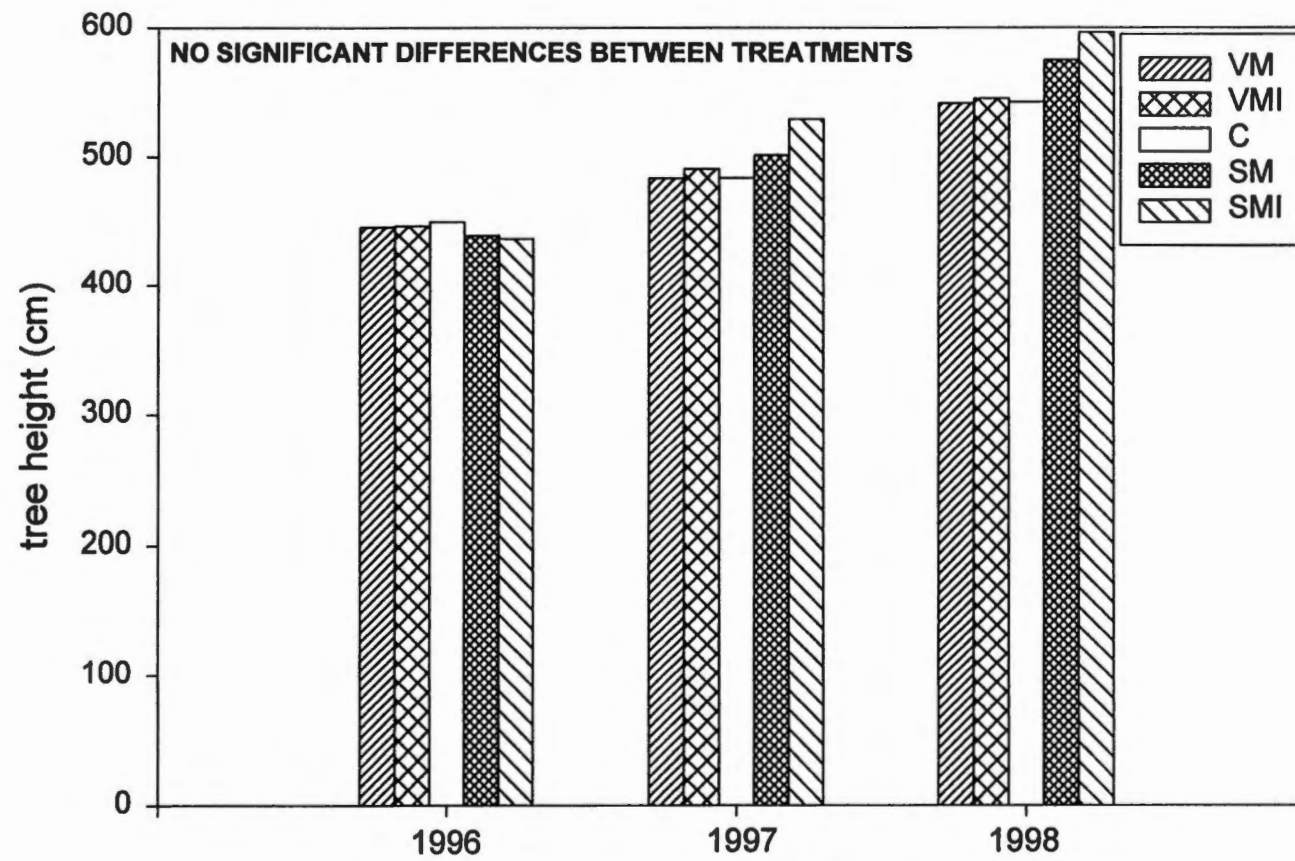


Figure 7. Tree height by treatment, averaged (n=6) for 1996, 1997, and 1998.

Tree Circumference

There were no statistical differences between cultivars in this area of analysis. There were also no statistical differences between any of the treatments (Figure 8) at the end of the study. However, the graph of the treatment means over time (Figure 9) does indicate that the surface mulch treatments exhibited non-significant enhancement in tree circumference.

Phenological Analysis

In this area of investigation there were significant differences between the two cultivars in regards to when they first initiated fall coloration, when they achieved peak fall color, and when 100 percent leaf drop occurred. This was not unexpected for 'October Glory' is known for its propensity to retain leaves later into the growing season than most other red maple cultivars. In this study, 'October Glory' was, on average, about six days behind 'Franksred' in initiating fall coloration, about eight days behind in achieving peak fall color, and about nine days behind in 100 percent leaf drop. Since there are equal numbers of each cultivar represented in each treatment block, the remainder of the phenological discussion will focus on treatment differences.

In each of the two growing seasons, the two surface mulch treatments (with and without irrigation) were best of the five in regards to prolonging leaf retention and delaying dormancy (Figure 10). The surface mulch with irrigation was consistently best followed by surface mulch only.

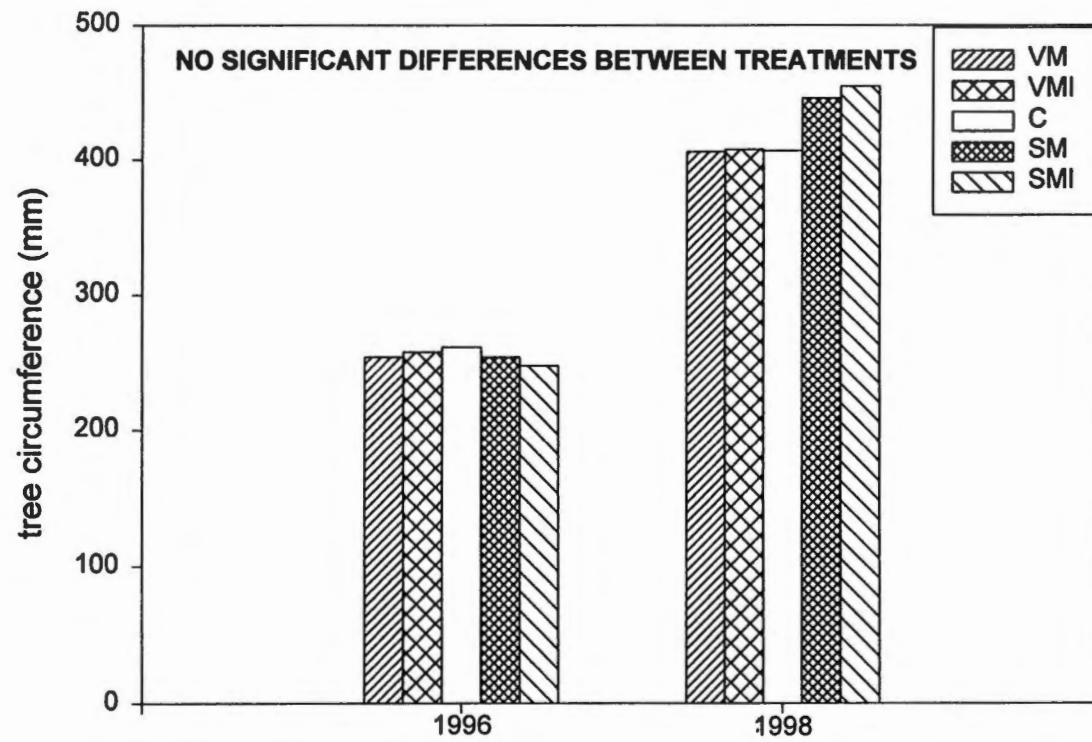


Figure 8. Tree circumference by treatment, averaged (n=6) for 1996 and 1998.

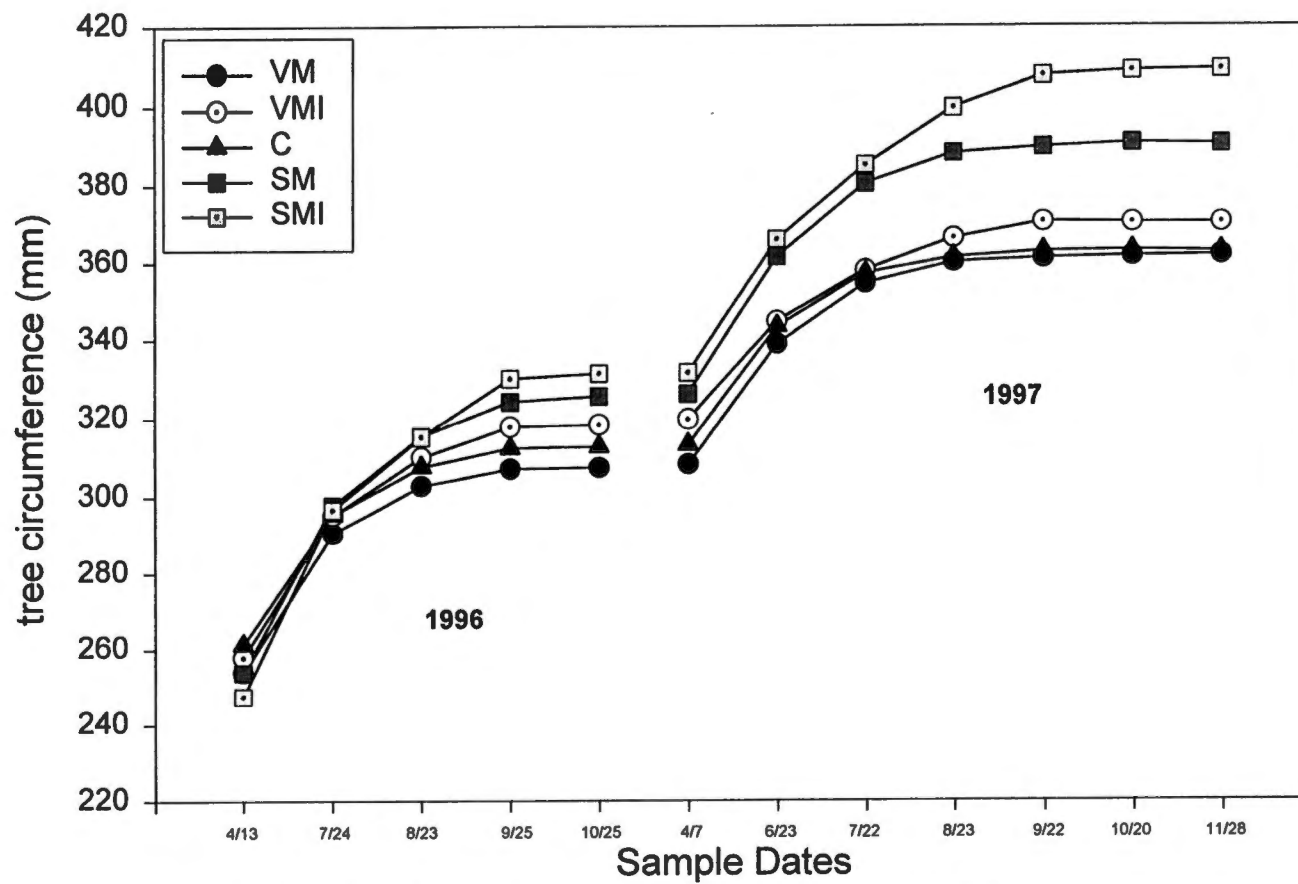


Figure 9. Tree circumference by treatment, over time for 1996 and 1997. Each point is the mean of six replicates.

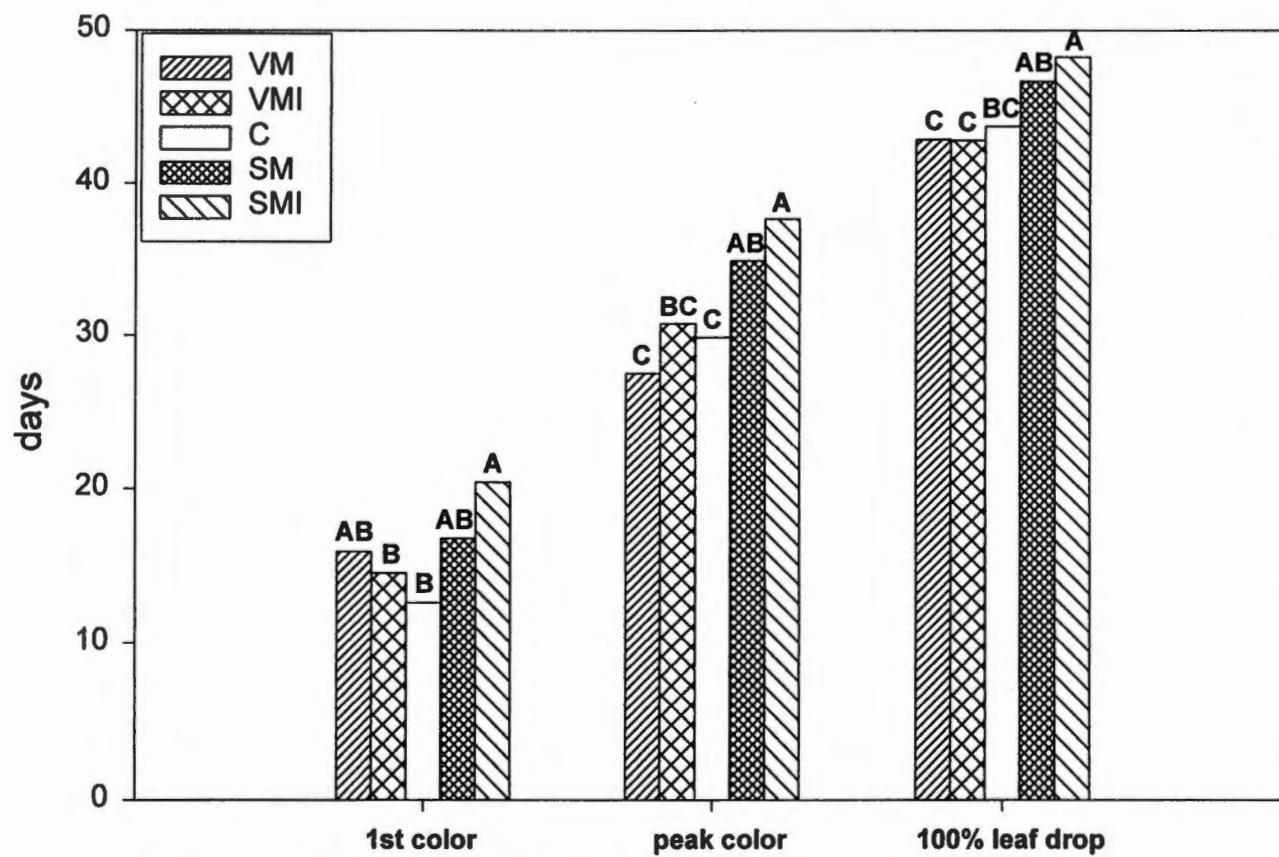


Figure 10. Phenological study averaged (n=12) over 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

Here again, it's surprising to note how poorly the vertical mulch with irrigation treatment performed. In all cases, there was no statistical difference between it and the control group.

Shoot Water Potential

In the analysis of pre-dawn xylem Ψ , the benefits of supplemental irrigation are clearly noted (Figure 11). Surface mulch with irrigation and vertical mulch with irrigation did significantly better than the rest while the control treatment was significantly the driest of the five (Figure 12). There was no significant difference between the two cultivars; in fact, they were remarkably similar with means of -0.3000 MPa for 'Franksred' and -0.2997 MPa for 'October Glory.'

The two samplings (May 7 and 16, 1996) prior to the installation of the vertical mulch trenches showed the pre-dawn xylem Ψ treatment means to be very consistent among all five treatments. However, this trend was also somewhat apparent at the beginning of the 1997 growing season and may be due to near optimum soil moisture conditions that routinely occur at this particular time of year. There appears to be little long-term impact from the cutting of roots for vertical mulch installation. The two vertically mulched treatments were the two driest treatments on the two samplings immediately following trenching operations. However, the control treatment was

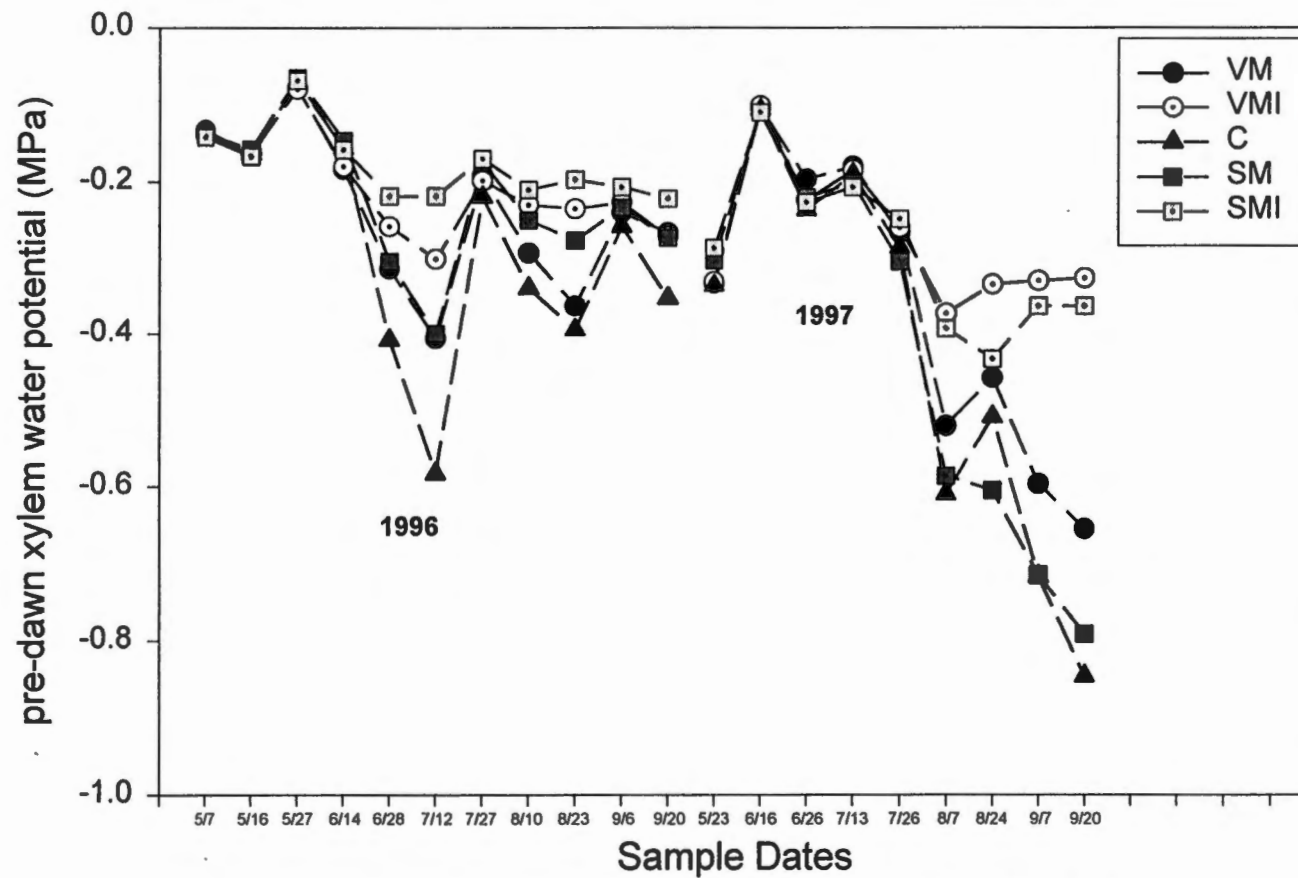


Figure 11. Pre-dawn xylem water potential by treatment, over time for 1996 and 1997. Each point is the mean of six replicates.

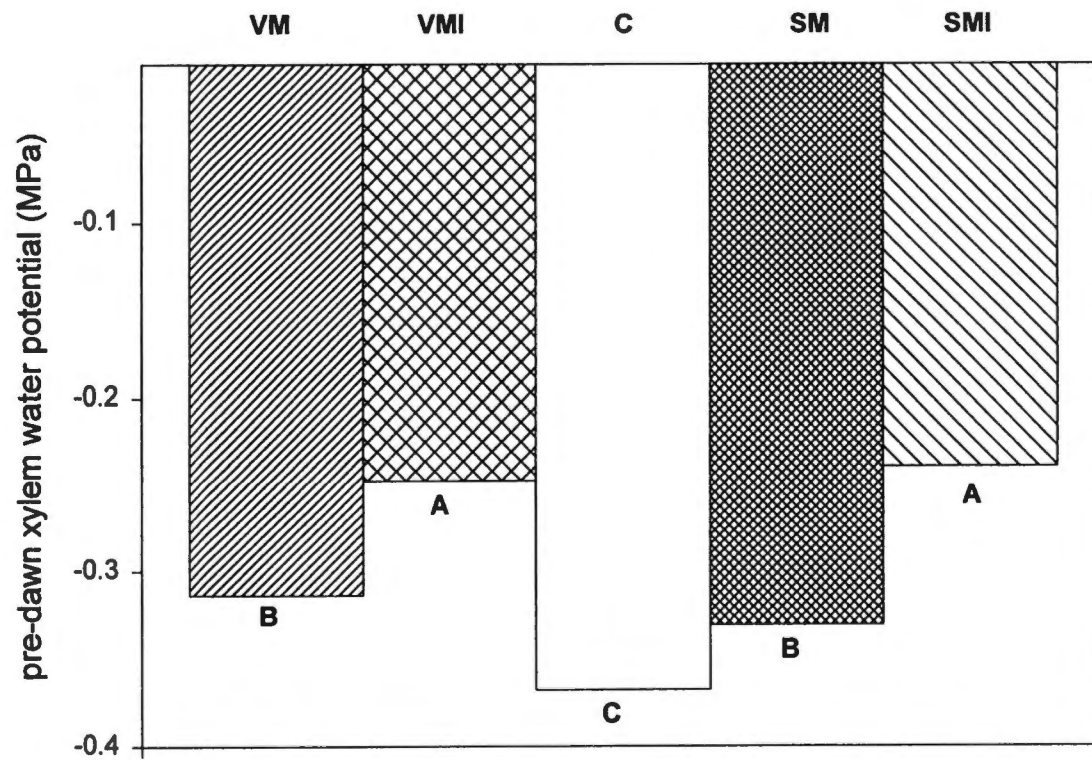


Figure 12. Pre-dawn xylem water potential by treatment, averaged (n=108) over 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

consistently drier (seven of nine samplings throughout the 1996 growing season) than the two vertically mulched treatments.

The control treatment, in regards to pre-dawn Ψ , was the driest of the five with a mean of -0.37 MPa. It was significantly drier than the surface mulch only treatment with a mean of -0.33 MPa. The surface mulch with irrigation and the vertical mulch with irrigation were the wettest and statistically the same with pre-dawn Ψ of -0.24 MPa and -0.25 MPa respectively. Intermediate was the vertical mulch only treatment with a shoot Ψ of - 0.31 MPa.

The analysis of the mid-day shoot Ψ did not provide much in the way of significant trends among the treatments (four of the five treatments are statistically the same). Also, there was a significant difference between the two cultivars; 'October Glory' exhibited less mid-day water stress than the 'Franskred'. The study-wide mean for 'October Glory' was -1.47 MPa, while for 'Franskred' it was -1.60 MPa. When comparing cultivars by treatments, this trend held up consistently with the five 'Franksred' treatments being among the six (of 10) that exhibited the most negative potentials. Since each treatment contained equal numbers of each cultivar (3), this difference should have minimal impact on treatment evaluation.

The two irrigated treatments experienced the least stress in regards to mid-day Ψ . The surface mulch with irrigation mean was -1.48 MPa while

the vertical mulch with irrigation was -1.51 MPa. They were not significantly different from the two mulched but non-irrigated treatments which were intermediate (Figure 13). The control treatment was the driest of the five at -1.66 MPa. The control was not significantly different from the two non-irrigated mulch treatments.

Osmotic Potential and Plant Turgor

Previous research into the osmotic potential ($\Psi\pi$) of numerous tree species at the University of Tennessee has determined that red maple exhibit very little osmotic adjustment (Augé et al 1998). So, it is not surprising that there are only minimal differences between the treatments (Figure 14). The ANOVA did detect a significant difference between the two cultivars: -1.59 MPa for 'Franksred' and -1.63 MPa for 'October Glory'.

There were no significant differences between any of the treatments in regard to leaf turgor pressure (Ψ_p) (Figure 15). There was a significant difference between the two cultivars. However, this was apparently due to genetics and was not related to any treatment effects because the five treatments with highest turgor pressures were all 'October Glory' (mean of 0.21) while the five lowest were all 'Franskred' (mean of .013). It is important to recall that leaf turgor pressure is a calculated value based upon Ψ and $\Psi\pi$.

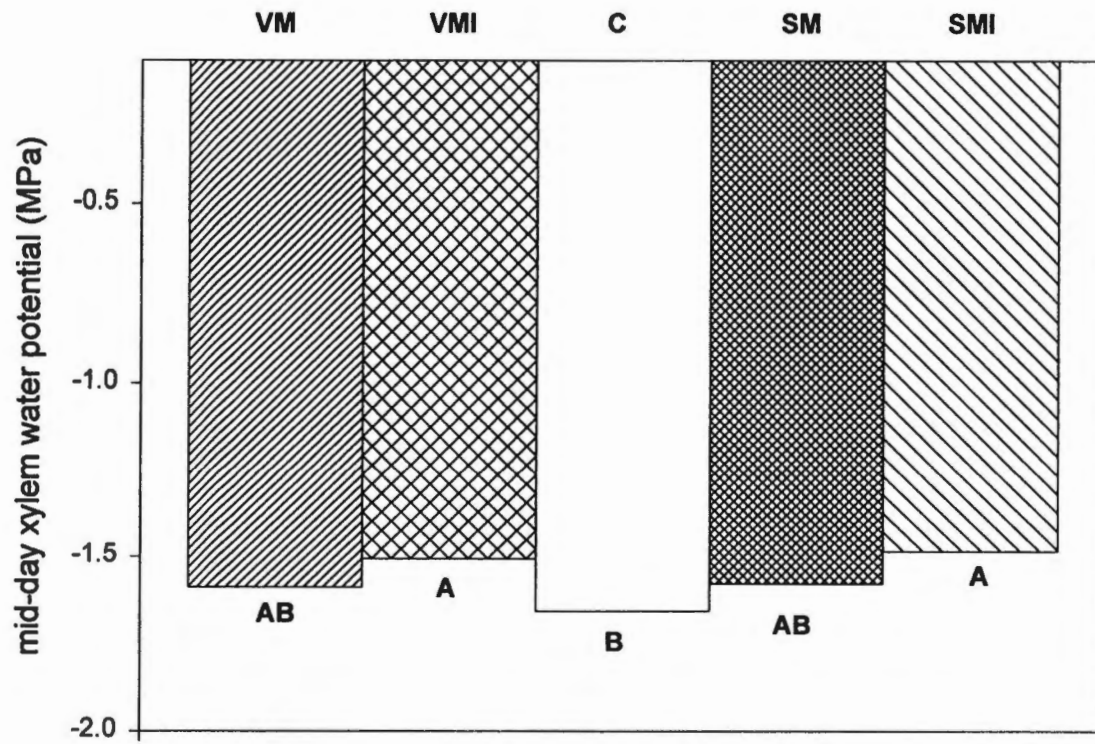


Figure 13. Mid-day xylem water potential by treatment, averaged (n=96) over 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

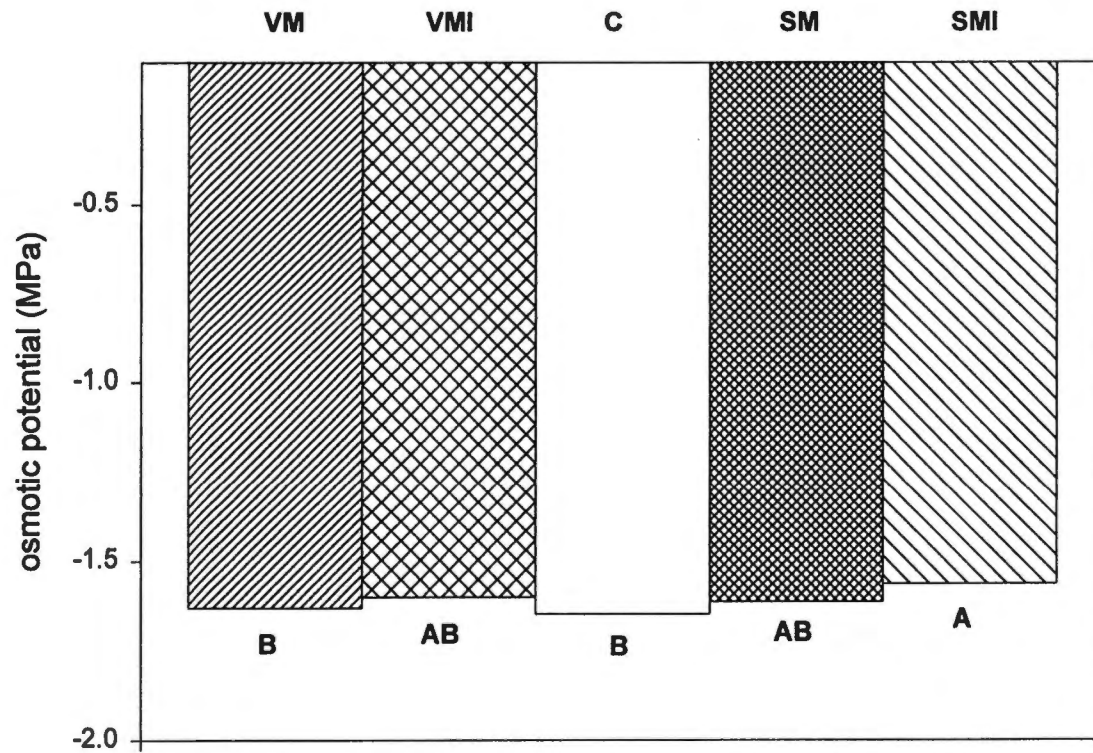


Figure 14. Osmotic potential by treatment, averaged (n=96) over 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

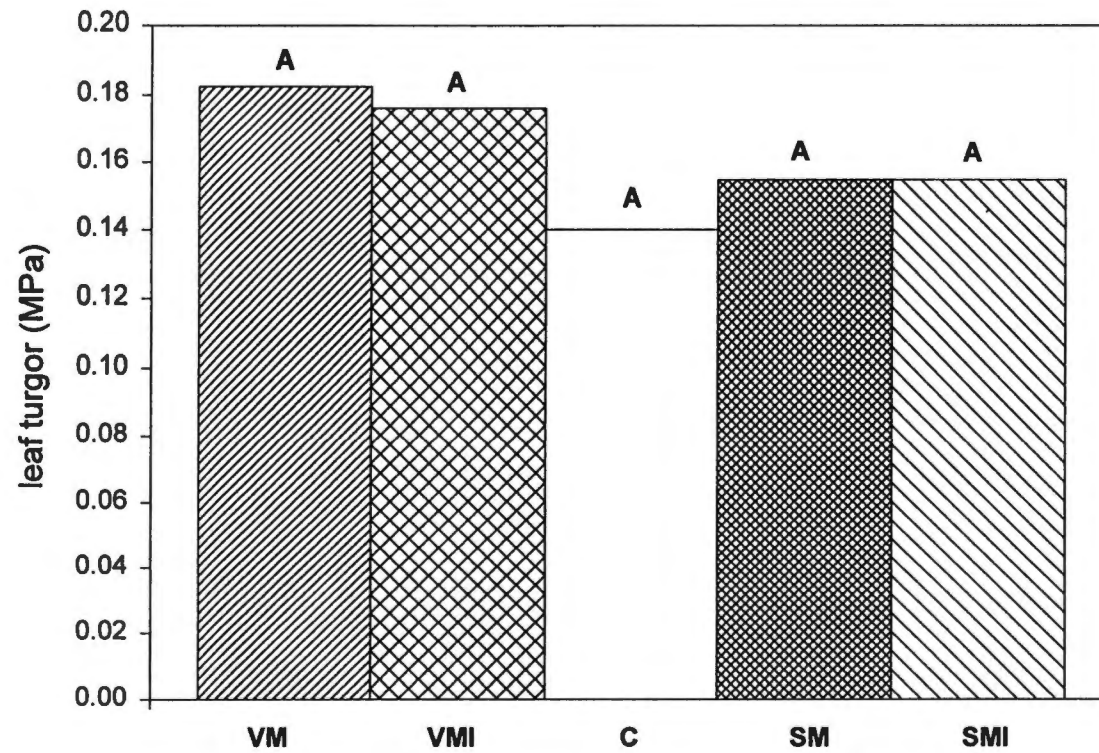


Figure 15. Leaf turgor by treatment, averaged (n=96) over 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

Gas Exchange Instrument Measurements

Five measurements from the bi-weekly LCA3 measurements were selected for statistical analysis; stomatal conductance, photosynthesis, transpiration, leaf temperatures and intercellular CO₂ levels. Of the five, significant differences were evident in all but intercellular CO₂. There were treatment trends among the four parameters showing significant differences. There were no significant differences between the two cultivars in regards to stomatal conductance, transpiration, and leaf temperatures. It seems clear from these data that the treatment of surface mulching with supplemental irrigation performed the best during the experiment in regards to stomatal conductance, photosynthesis, transpiration, and leaf temperature. The other four treatments were at two distinct levels and remained consistent throughout the gas exchange data. The vertical mulch with irrigation treatment and the surface mulch only treatment tended to perform about the same while the vertical mulch only treatment and the control are ranked closely together as the poorest performing of the five.

Stomatal Conductance

In regards to stomatal conductance, the surface mulch with irrigation treatment performed significantly better than all other treatments (Figure 16). The mean conductance for 1996-97 was 235 mmol m⁻² s⁻¹. The other treatments ranged between 196 mmol m⁻² s⁻¹ (surface mulch only) and 156 mmol m⁻² s⁻¹ (vertical mulch only). In 1996, the surface mulch with irrigation

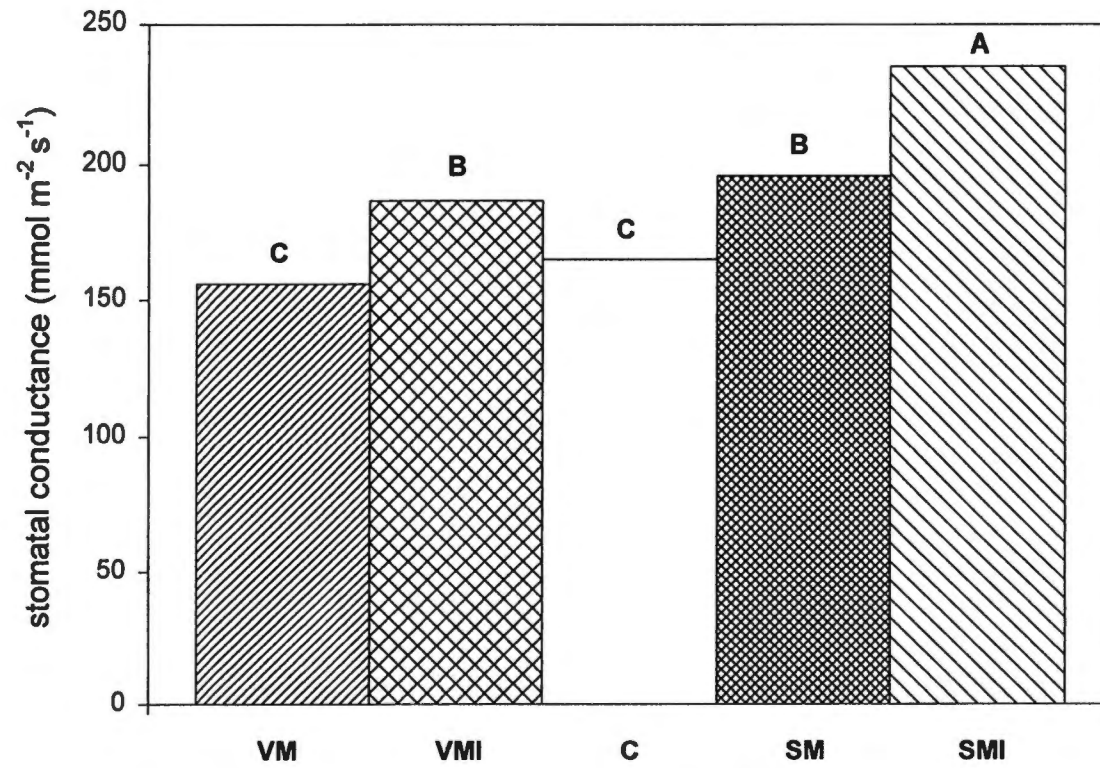


Figure 16. Stomatal conductance by treatment, averaged (n=258) over 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

treatment exhibited the highest level of conductance on six of eight sample days and in 1997 it was highest on eight of nine days (Figure 17).

The May 13, 1996 sampling (which took place prior to the cutting of the vertical mulch trenches on May 20 and 21, 1996) shows all treatments to be very similar in regards to conductance. However, the cutting of the trenches apparently had some short-term negative effects on the two vertically mulched treatments as they both exhibited the lowest levels of conductance on the next two sampling dates (June 6 and 21, 1996). In fact, the vertical mulch only treatment exhibited the lowest average conductance throughout the entire study period and from July 5, 1996 (when the vertical mulch and the control were essentially the same) on, the vertical mulch only treatment was the poorest performer nine out of 13 times.

By the end of both growing seasons, it appeared that the trees receiving supplemental irrigation were clearly benefiting from it. They were able to continue to maintain higher levels of conductance into the months of August and September, while the other trees are quickly entering into winter dormancy.

Photosynthesis

The surface mulch with irrigation treatment proved superior to the others in respect to rates of photosynthesis (Figure 18). It stands alone, significantly better than the other treatments, with a photosynthesis rate of $8.6 \text{ micromol m}^{-2} \text{ s}^{-1}$ while the others ranged from $7.6 \text{ micromol m}^{-2} \text{ s}^{-1}$

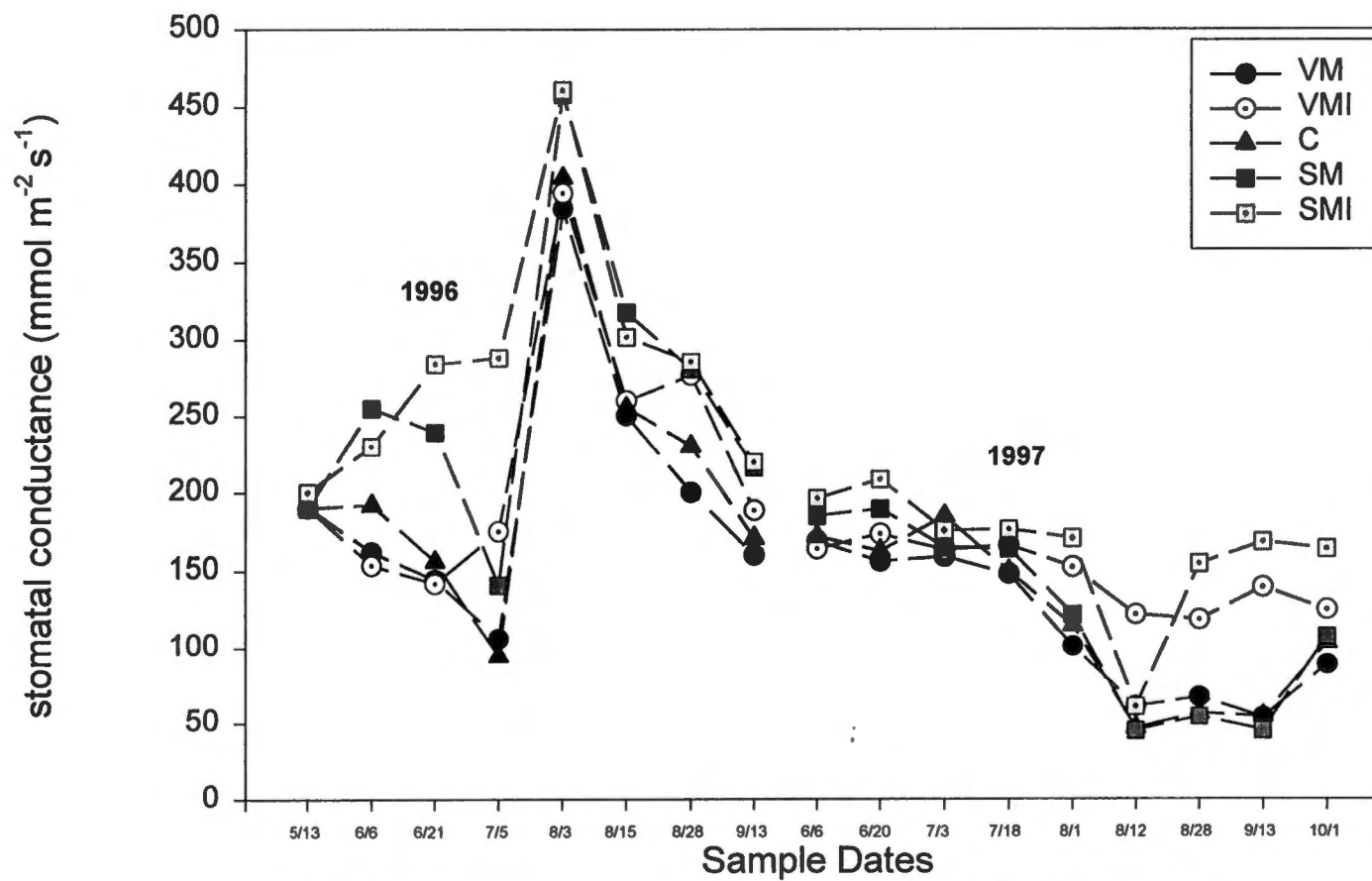


Figure 17. Stomatal conductance by treatment, over time for 1996 and 1997. Each point is the mean of six replicates.

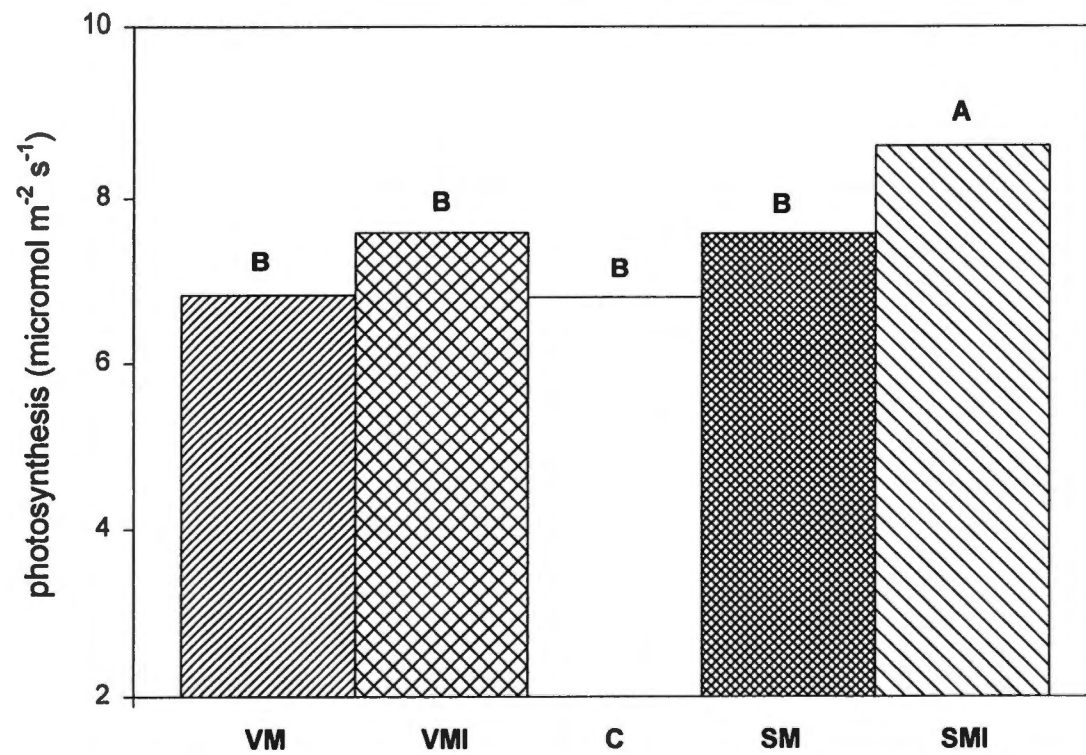


Figure 18. Photosynthesis by treatment, averaged ($n=258$) over 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

(vertical mulch with irrigation) to $6.8 \text{ micromol m}^{-2} \text{ s}^{-1}$ (control). The vertical mulch with irrigation and the surface mulch only treatments were statistically similar to the vertical mulch only and the control treatments which display the lowest rates of photosynthesis.

The effects of irrigation are apparent in the final samplings of 1997 as the two irrigation treatments perform much better than the others (Figure 19). In the last six samplings, the two irrigation treatments displays the highest rates of photosynthesis. Surprisingly, this does not seem to be the case in 1996 when the surface mulch only treatment exhibits the highest rates of photosynthesis three out of the last four sample days. This is probably due to the growing season and the generally good monthly precipitation rates in 1996. There does not appear to be any notable decrease in photosynthesis rates on sample dates immediately subsequent to the installation of the treatments.

Transpiration

The May 13, 1996 sampling (which took place prior to the cutting of the vertical mulch trenches on May 20 and 21, 1996) shows all treatments to be very similar in regards to transpiration (Figure 20). It does appear that the two vertically trenched treatments experienced some decrease in transpiration due to root loss because of trenching operations. The two vertically mulched treatments exhibited the lowest rates of transpiration during the subsequent two samples (June 6 and 21, 1996).

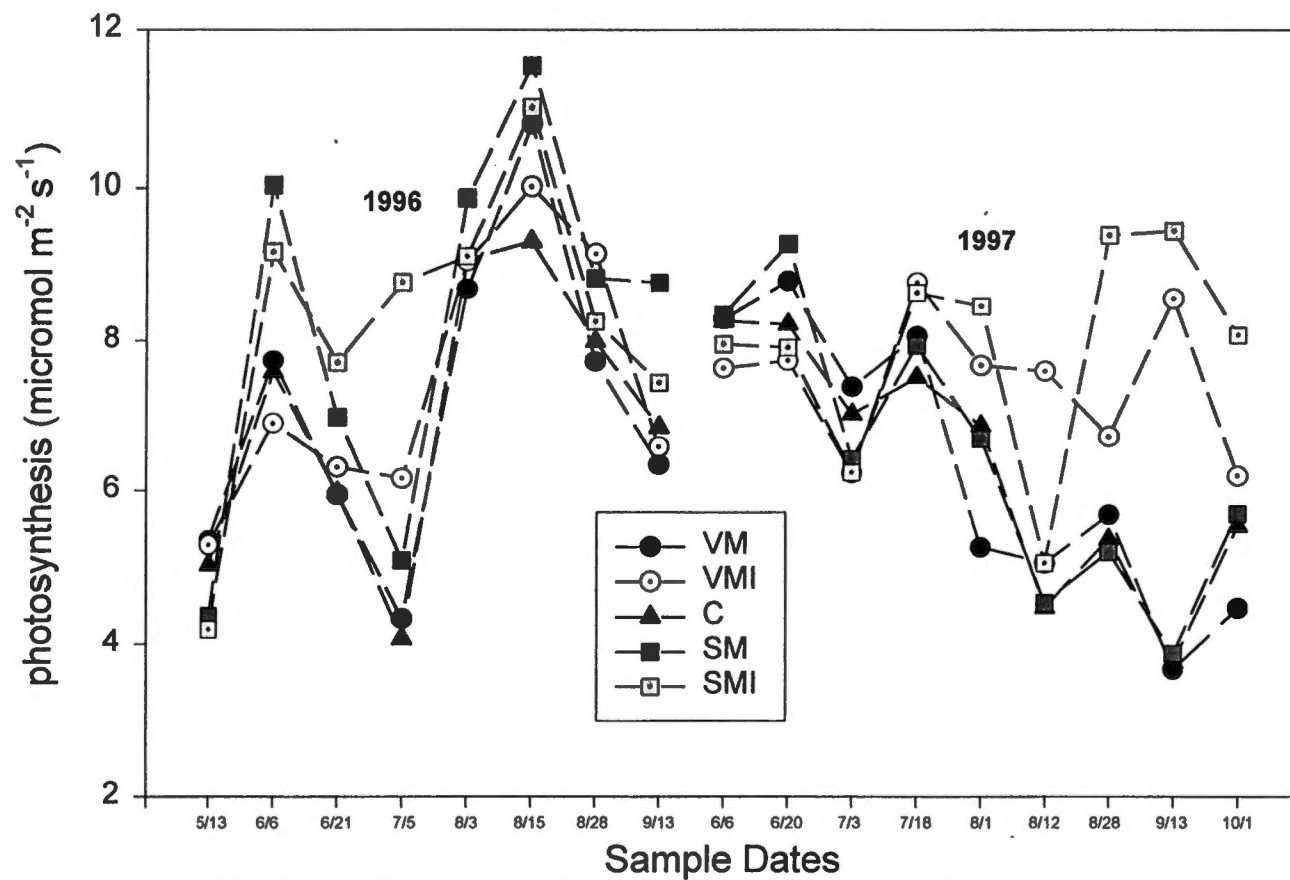


Figure 19. Photosynthesis by treatment, over time for 1996 and 1997. Each point is the mean of six replicates.

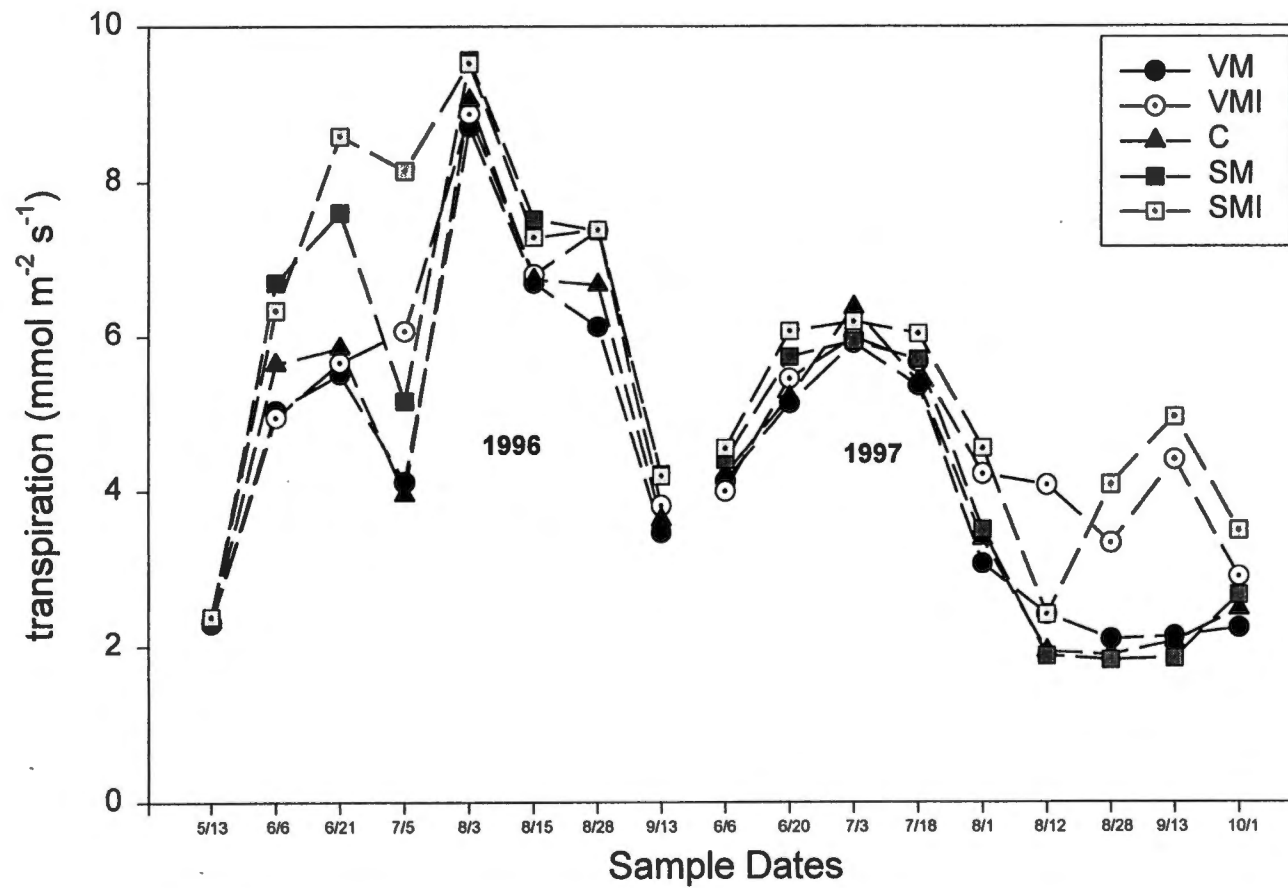


Figure 20. Transpiration by treatment, over time for 1996 and 1997. Each point is the mean of six replicates.

After treatment installation, the surface mulch with irrigation exhibited the highest levels of transpiration on ten of the remaining 16 sample days and ended up being significantly best among the five (Figure 21). In 1997, it had the highest readings on seven of nine sampling days.

The irrigation appeared once again to be of some importance as the two irrigated treatments showed much higher rates of transpiration late into the growing season of 1997. The two irrigated treatments were ranked either first or second on all of the last five samplings of 1997. The irrigation appeared to play less of a role in the status of the treatments during 1996.

Leaf Temperatures

A look at the graph of treatment means by sample day (Figure 22) shows that there was very little variation in treatment impact on leaf temperature. However, there was enough variation for the ANOVA to detect that the surface mulch with irrigation was significantly superior to the others (Figure 23). The overall mean for this treatment was 29.23°C while the remaining treatments ranged from 29.58°C (surface mulch only) to 29.90°C (control). The surface mulch with irrigation exhibited the coolest leaf temperatures on ten of the 16 sample days after treatment installation.

It is interesting to note how similar leaf temperatures were on all treatments at the beginning of each growing season. And, once again, the stress of the trench installation did seem to manifest itself in the data; the

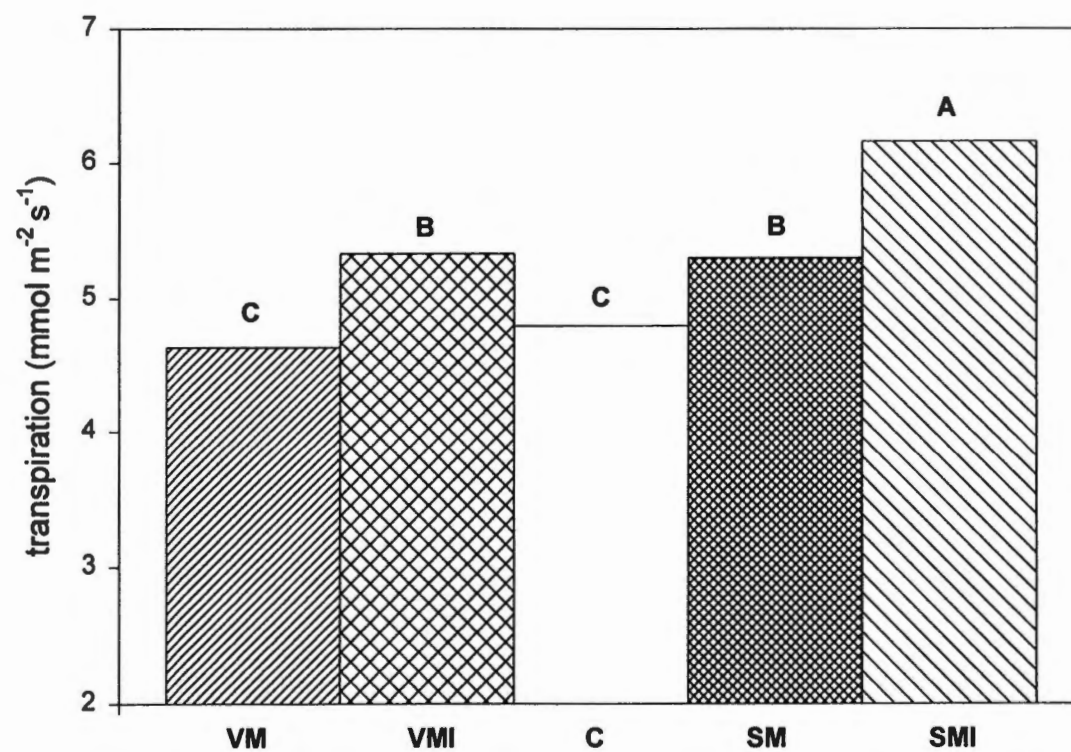


Figure 21. Transpiration by treatment, averaged (n=258) over 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

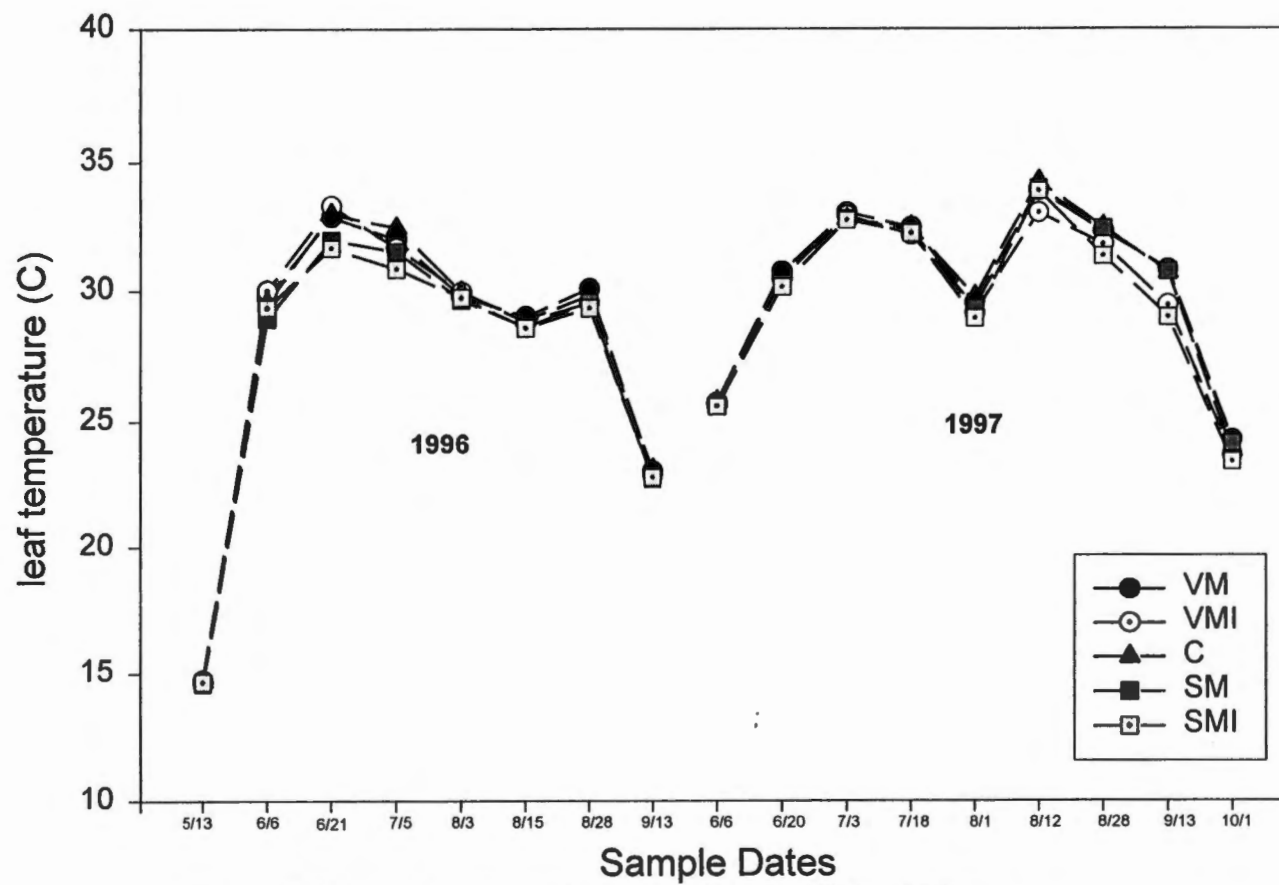


Figure 22. Leaf temperature by treatment, over time for 1996 and 1997. Each point is the mean of six replicates.

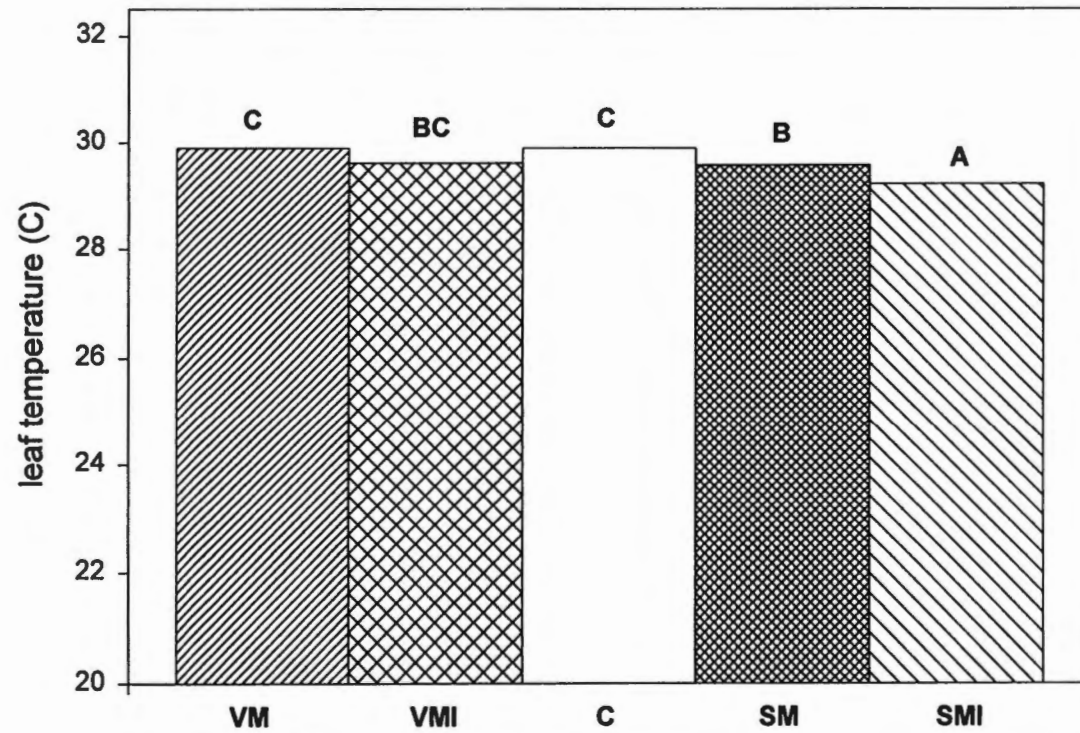


Figure 23. Leaf temperature by treatment, averaged (n=258) over 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

two vertically mulched treatments exhibited the warmest leaf temperatures on June 6, 1996. The vertical mulch with irrigation was warmer than the vertical mulch on four of the first five samplings. However, from August 15, 1996 on, the irrigation apparently began having an impact and the vertical mulch with irrigation was always cooler than the vertical mulch only.

Intercellular CO₂

While there was no statistical difference between any of the treatments in regard to intercellular CO₂ rates, the surface mulch with irrigation did exhibit the highest overall mean (270.44 microbar/bar) among the treatments (Figure 24). The range among the others was 265.77 (vertical mulch with irrigation) to 260.56 (vertical mulch only).

Analysis of Water Status Data from August 1997

The drought event that occurred near the end of the growing season of 1997 allowed for a good opportunity to see how the treatments (which had then been in place for well over a year) would perform during a time when temperatures were high and soil moisture was low. Fortunately, during a five-week span from August to the first week of September, all seven water status parameters were sampled on three separate occasions. This data was separated from the rest, and then analyzed using the ANOVA procedure.

The results were largely the same. But, there does seem to be a slight improvement in the performance of both vertically mulched

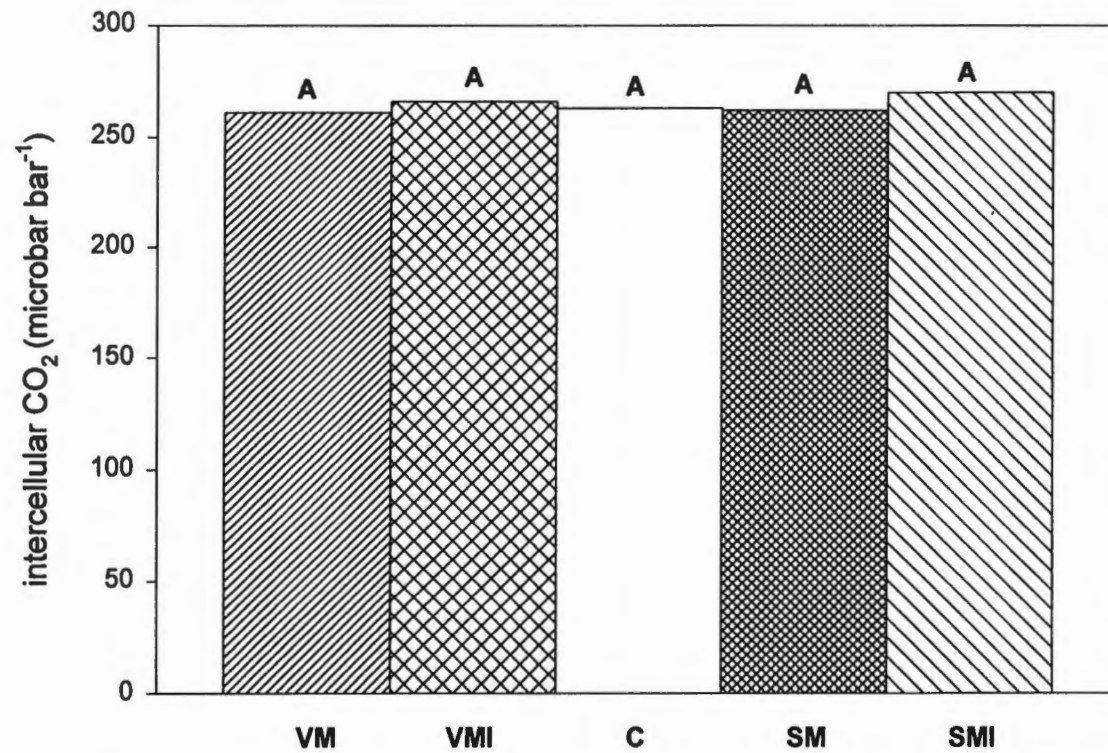


Figure 24. Intercellular CO₂ by treatment, averaged (n=258) over 1996 and 1997. Bars having different letters are significant at $P \leq 0.05$.

treatments. At this point, the irrigation treatments were clearly superior to the other three. There was also an improvement of the performance of the vertical mulch with irrigation treatment over what the previous analysis had shown. Also, the vertical mulch only treatment did as well or better than the surface mulch only treatment in all seven parameters. However, there was little or no statistical difference between any of the three non-irrigated treatments.

A summary of the shoot Ψ and Ψ_{π} data from this time period can be found in Figure 25. The gas exchange data from this time period (transpiration, stomatal conductance, leaf temperature and photosynthesis) is summarized in Figure 26.

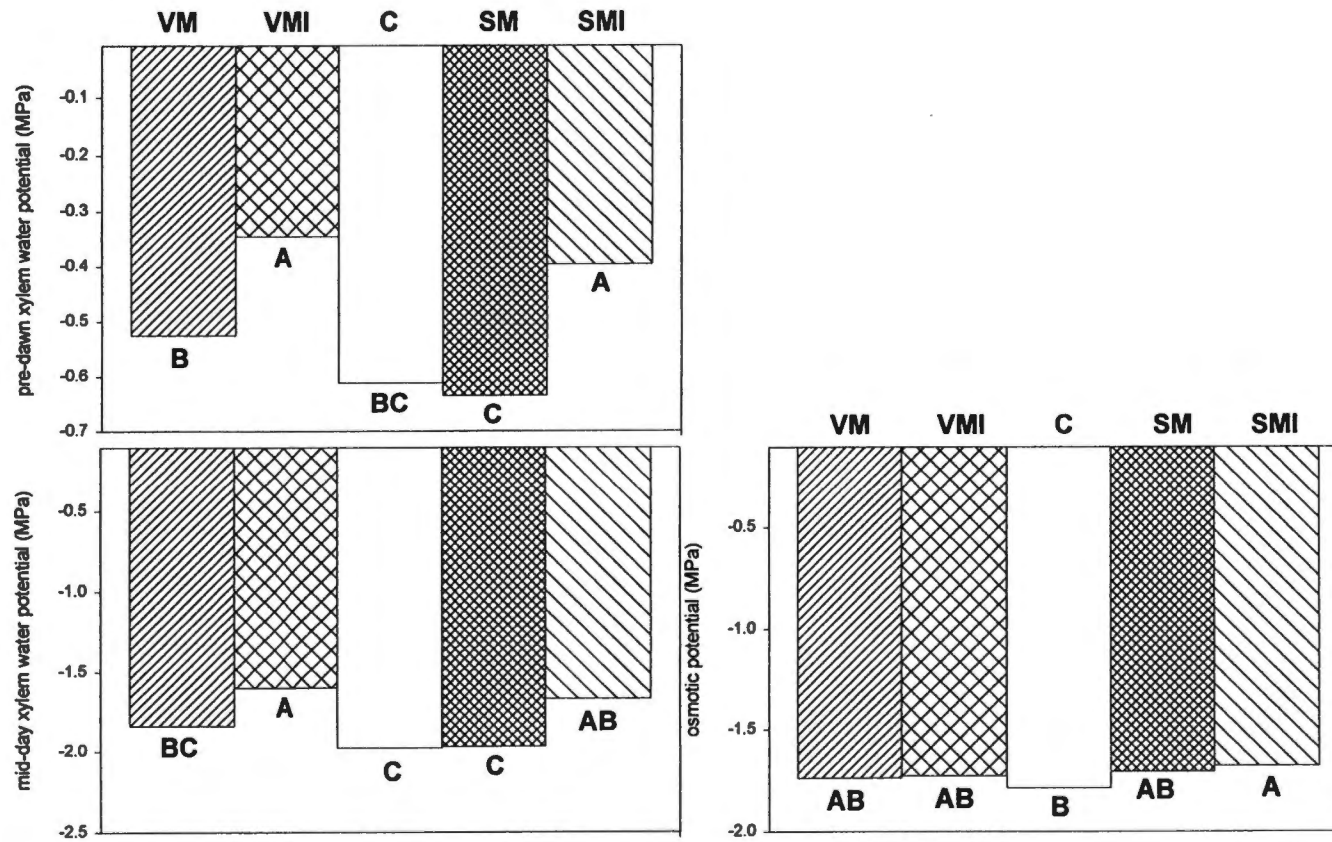


Figure 25. Pre-dawn and mid-day xylem water potential, and osmotic potential by treatment, for Aug 7 & 24 and Sep 7, 1997. Each bar represents the mean of each treatment (n=18). Bars having different letters are significant at $P \leq 0.05$.

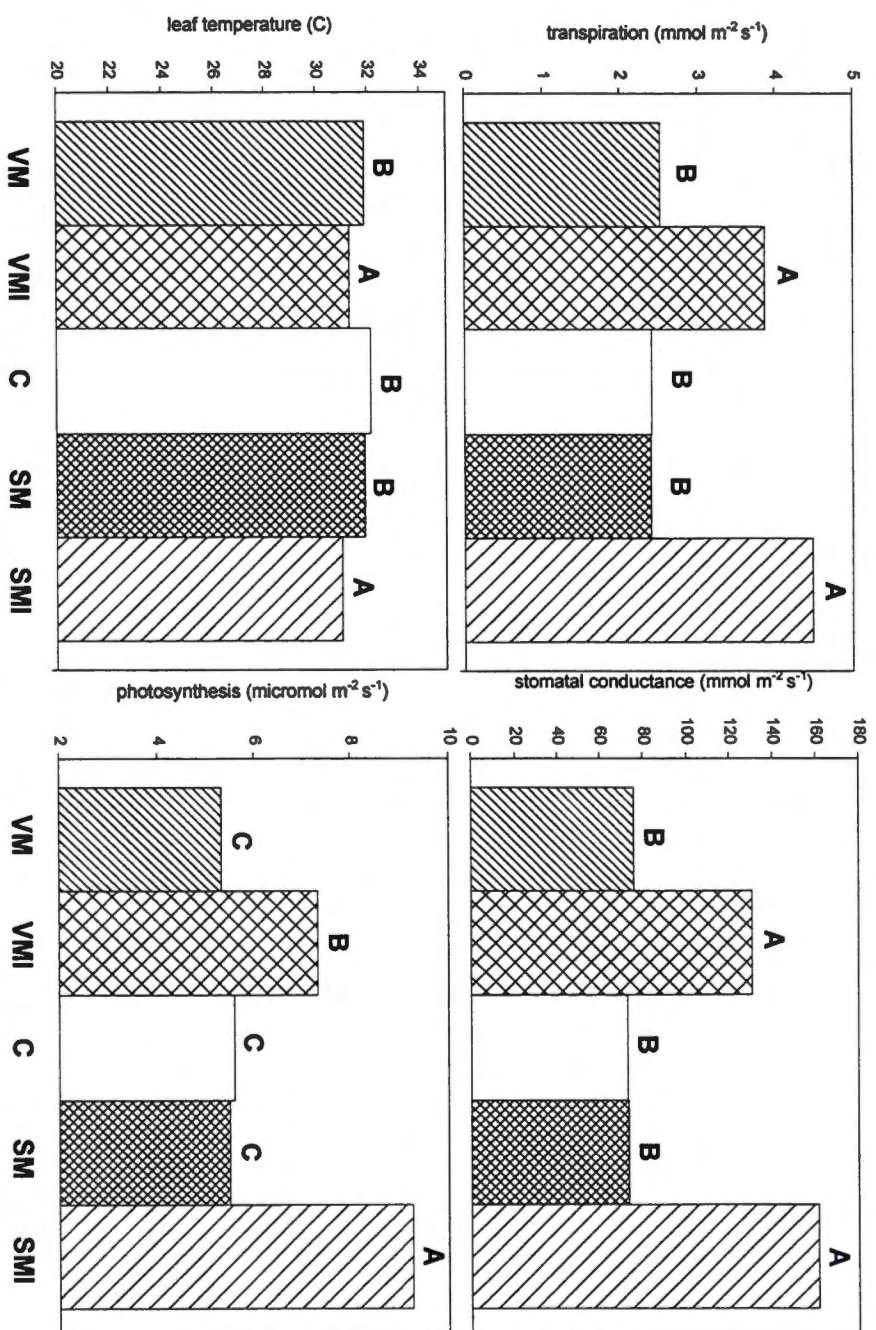


Figure 26. Transpiration, stomatal conductance, leaf temperature and photosynthesis by treatment, for Aug 1, 12 & 28, 1997. Each bar represents the mean of each treatment ($n=54$). Bars having different letters are significant at $P \leq 0.05$.

IV. DISCUSSION

It is important to remember that the practice of vertical mulching has only recently come to the attention of those involved with urban trees and that the ultimate reason for considering it is the potential that it may have for ameliorating difficult cultural situations. It has been proposed that vertical mulching might be a viable tool to use in the remediation of soil compaction (Craul 1994). Although there is little evidence directly linking soil compaction to reduced vigor and increased mortality of urban trees, there has accumulated a significant amount of circumstantial evidence which supports this supposition (Craul 1994).

This study sought to test vertical mulching alone and in combination with drip irrigation. It has been suggested that using supplemental irrigation and fertilizer to maintain a tree in vigorous condition are fine as long as those practices can be maintained. However, once stopped, the treated tree, now larger and more consumptive, will suffer because it cannot be supplied with the water and nutrients it needs (Santamour 1990). In many urban situations, bigger is not going to equate to better. But trees are obligated by their genetic codes to grow bigger and produce a new tree, completely enveloping their former selves, each year (Shigo 1982).

The results of this study indicate that the practice of vertical mulching had very little positive impact on the water status of the study trees. In most

parameters of inquiry, the control trees performed as well as the vertical mulch only treatments while the vertical mulch with irrigation treatments performed no better than the surface mulch only treatments.

While this study did not take place on a site that suffers from soil compaction, (in fact, the soil would probably be considered to be good for an urban area), it seems reasonable to think that these trees would have received some benefit from the vertical mulching.

It should not be too surprising that the surface mulch treatments performed best in this experiment. Surface mulching can contribute to both physical and chemical improvements in the soil (Himelick and Watson 1990). Also, the installation of the surface mulch did not involve the trauma of severing roots for soil removal. In addition, the vertical mulch treatments had to compete with turfgrass while the surface mulch treatments were essentially free from all other plant competition. The improvements caused by the addition of the surface mulch probably led to increased development of fine roots. Research with white oaks showed that fine root densities were nearly twice as high under mulched soils versus turf areas (Himelick and Watson 1990). A more developed fine root system can increase a tree's ability to exploit available water (Himelick and Watson 1990).

It is assumed that water stresses result in the lowering of both total leaf Ψ and $\Psi\pi$ due to turgor loss and/or an increase in solutes. However,

previous research at this university has determined that *Acer rubrum* does not exhibit a wide range of osmotic adjustment (Augé et al. 1998). It is unfortunate red maples exhibit only a minimal amount of adjustment in regards to $\Psi\pi$. And, due to the problem with reliably ascertaining $\Psi\pi$ in this species, the study's Ψ_p data must be viewed with suspicion. There were essentially no significant differences between treatments for either of these parameters.

The shoot Ψ data showed that the any type of mulching was beneficial when compared with the control. In the pre-dawn hours, the two irrigated treatments were clearly superior while the mulched but non-irrigated treatments were intermediate. At mid-day, the treatment effects were less evident (however, there were at least non-significant enhancements apparent that are in agreement with the pre-dawn data). This was perhaps due to the daily water stresses that are usually maximized during the hours when this sampling was conducted which could have reduced the variability among the five treatments. And, as leaf Ψ is known to be influenced before stomatal conductance can be much affected, this would partially explain the occurrence of trends that were evident in the gas exchange data but absent in the mid-day water potential data.

The gas exchange instrument data are perhaps the most telling in regards to water stresses. Plant water deficits cause reductions in stomatal

aperture either progressively or when a threshold level is reached (Kramer and Boyer 1995). The data clearly showed that the stomatal conductance of the vertical mulch with irrigation treatments was equal to or less than the surface mulch only treatments. The same trend was apparent in regards to leaf area and tree circumference. This is quite surprising when you consider that the weekly irrigation episodes (16 from July to November of each study year) supplied, on average, 537 liters (142 gallons) of water per tree, each week. It could be that this amount of water was either insignificant (which seems unlikely due to the fact that the surface mulch with irrigation treatments received exactly the same amounts, delivered at the same times, and were significantly better than all the rest), or that the vertically mulched trees were stressed by the trenching operations and were unable to recover during the course of this short-term study. Perhaps the most reasonable explanations for the poor showing of the vertical mulch with irrigation treatments are: that the trees were unable to exploit the irrigation water because of a dearth of roots in the immediate area (the mulched trenches) where it was supplied or, that the elimination of competing turfgrasses played a major role in the superiority of the surface mulch treatments.

The same trend is apparent in the other areas of the gas exchange data; the vertically mulched treatments with irrigation did no better than the surface mulch only treatments in regards to photosynthesis, transpiration, or

leaf temperature. It is interesting to note that the vertical mulch only treatments did no better than the controls. Perhaps this would not have been the case if the soil at the study site had been compacted so that the vertically mulched trenches could have played a more critical role by serving as break out zones for the roots.

The analysis of the August 1997 data showed some improvements in the performance of the vertically mulched treatments. One might reasonably expect that the benefits of mulching vertically might require a greater amount of time before they manifest themselves.

Despite the results of this study, there is some recent research which has determined that the effects of using surface mulches might be mixed. Zajicek and Heilman (1991) looked at the impact of surface mulching on the micro-environment of *Lagerstroemia indica* and determined that the dark color of mulches resulted in higher surface temperatures which resulted in greater fluxes of longwave radiation. Also, because of the greater energy load, plants on mulched surfaces had increased stomatal conductances, higher leaf temperatures, and higher leaf-air vapor pressure deficits (Zajicek and Heilman 1991). This is not at all insignificant when you consider that root-zone temperatures are generally higher to begin with at tree planting sites in urban areas, especially for trees planted near streets and roadways (Wilkins et al. 1995).

Zajicek and Heilman believe that under well-watered conditions mulches do increase transpiration. This certainly coincides with this study's findings. They conclude by speculating (but calling for further research) that, in cases where water is limiting, the increase in transpiration due to mulching may be offset by reductions in evaporation. The results of this study support, and perhaps prove, this speculation. For, in almost all parameters of this investigation, the surface mulch only treatment outperformed the control and the vertical mulch only treatments.

Mulching for the benefit of deciduous trees might be best understood by comparing it with the long-time practice of amending soils in the planting hole at the time of planting. The practice of vertical mulching, much like amending soil at the time of planting, allows for a one-time only opportunity to impact what eventually becomes a small percentage of the tree's rooting zone. Surface mulching allows for repeated applications of mulch over an area that can grow as the tree does. As the mulch breaks down and is incorporated into the soil profile, additional mulch could be added; which would be necessary if high levels of soil organic matter are to be maintained. The process of surface mulching certainly follows a more natural progression; much like the falling of leaves in a forested situation. However, many of the places where we want trees to grow and thrive are far-moved and culturally much different from the conditions of the natural forest, and trees growing here may require more than a simple mimicry of

what was once adequate. A future area of inquiry might be to research the potential benefits of using vertical **and** surface mulching in combination.

There are still many unanswered questions about vertical mulching. In this study, we have paid particular attention to water status parameters that are measured above-ground. What has been neglected here are numerous below-ground parameters. Root growth and development, soil physics, and micro and macro soil fauna populations are all potential areas of future investigation. Also of some probable importance is the time frame of investigation. This short-term study was able to look closely at the impacts of the installation of the treatments and the two subsequent growing seasons, but may not have been able to capture the long-term effects of the vertical mulching on the trees.

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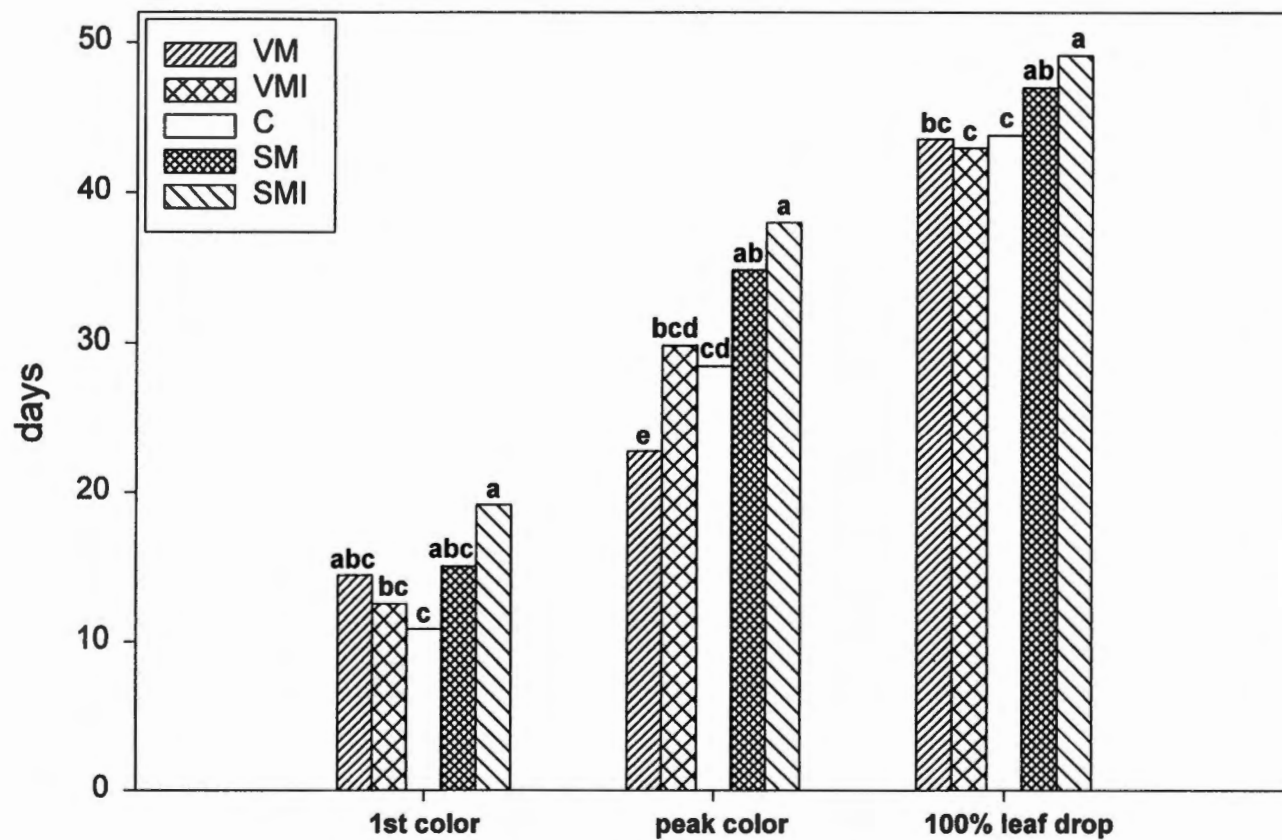
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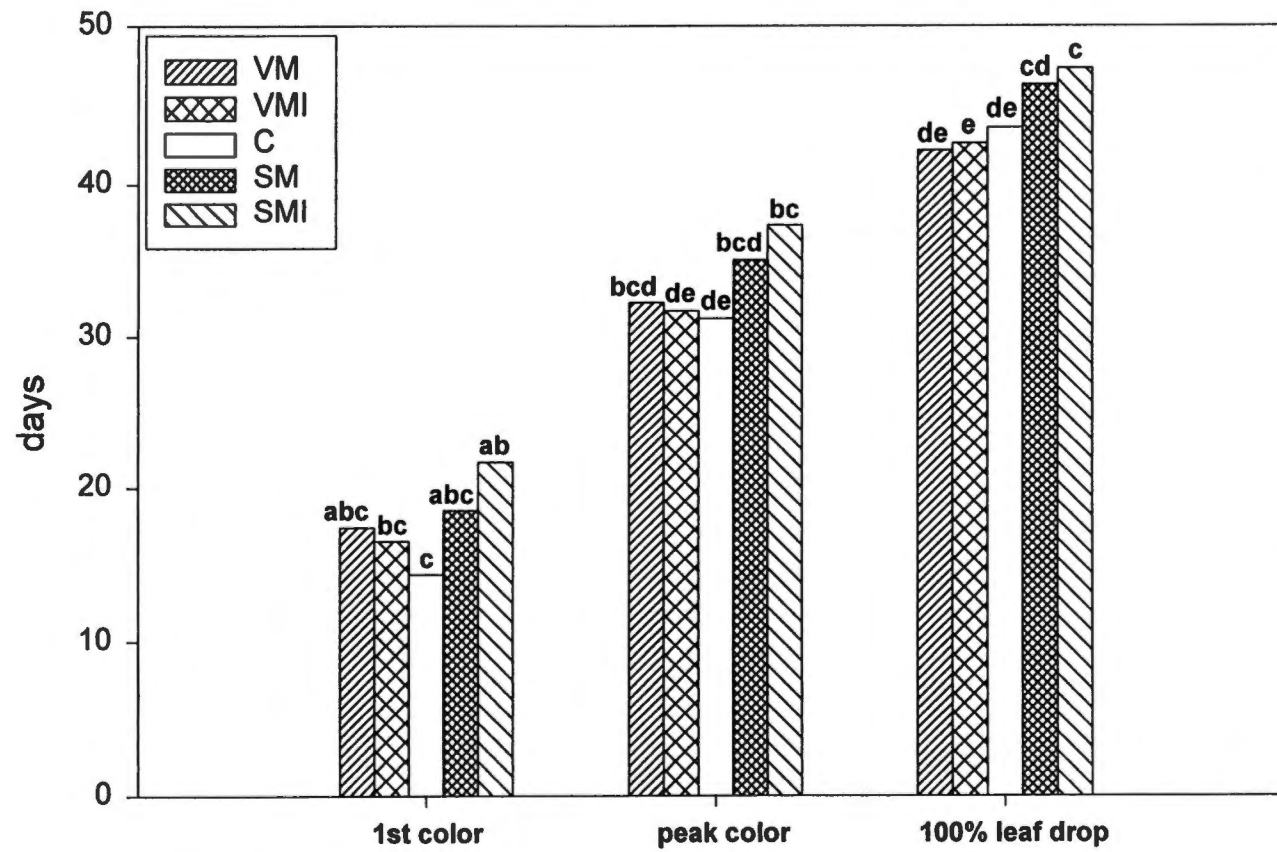
APPENDIX

Largest Root (greater than 5 mm) Severed During Trenching Prior to Verical Mulching
Figure is Root Diameter in Millimeters
Data Collected with a Mitutoyo Corporation Digimatic Caliper (0.01-150mm) on May 21, 1996

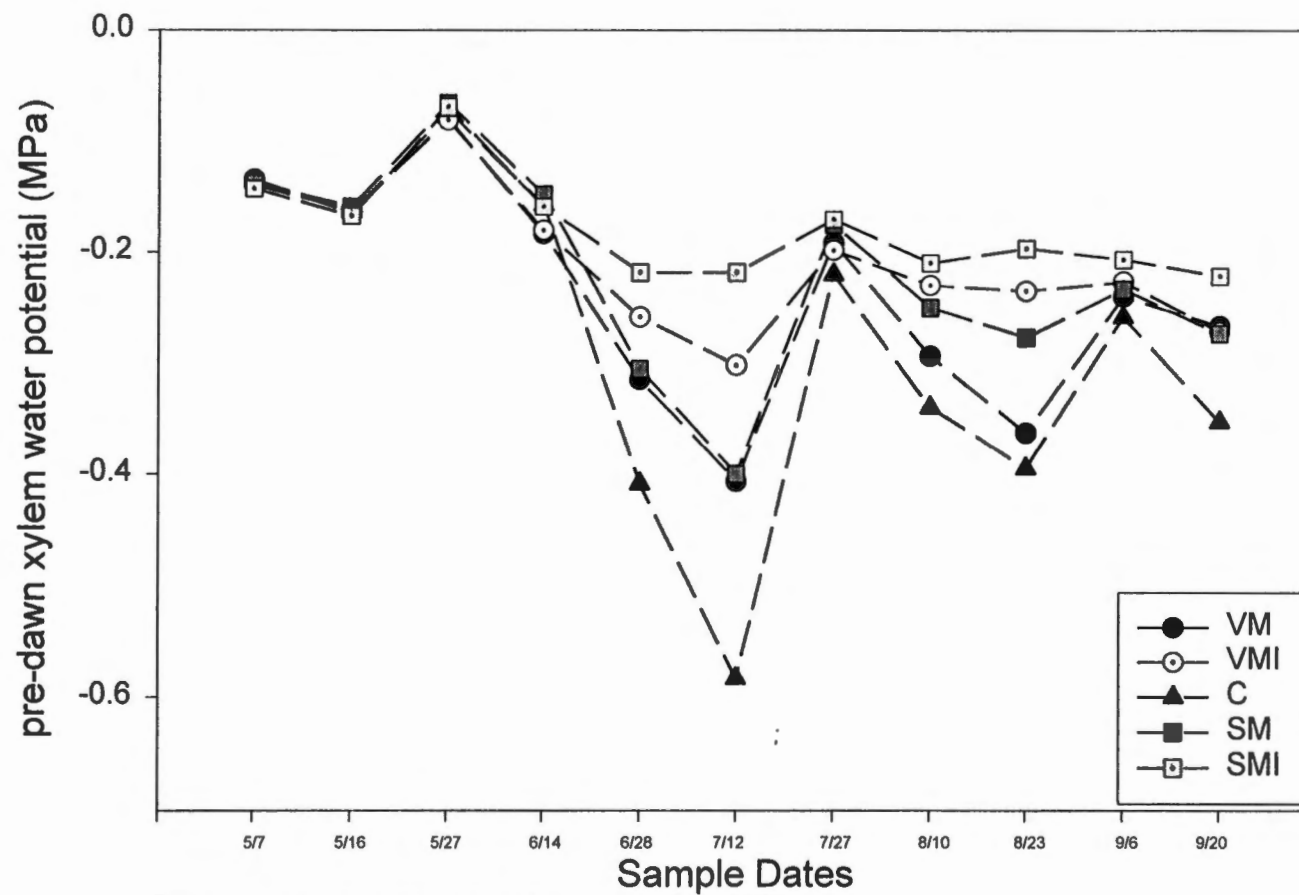
Tree #	Treat.	Cultivar	Trench Orientation							
			N	NE	E	SE	S	SW	W	NW
5	VM	FR	12.99	9.68	15.55	*	23.63	12.5	16.54	*
9	VM	FR	10.25	30.87	41.53	*	14.73	*	16.88	10.13
13	VM	FR	18.2	23.7	19.28	9.53	19.28	17.01	22.08	22.87
19	VM	OG	10.93	12.84	15.46	10.22	13.75	5.78	*	5.22
23	VM	OG	7.55	*	25.56	8.45	9.08	8.67	*	19.33
29	VM	OG	10.74	14.82	9.98	*	15.08	8.79	6.67	10.53
1	VMI	FR	9.47	12.07	12.05	19.39	8.57	13.56	13.09	*
7	VMI	FR	37.69	6.41	*	17.83	*	4.96	5.8	5.84
11	VMI	FR	8.65	*	9.28	20.34	20.98	19.82	*	19.77
16	VMI	OG	13.53	15.31	5.99	8.74	18.97	7.35	12.19	15.52
22	VMI	OG	15.37	11.81	13.15	*	10.02	16.34	11.51	*
26	VMI	OG	12.96	11.07	14.21	*	13.49	*	21.48	*
Per Trench			* Indicates there was no significant root encountered.							
Means		11.58	14.03	12.38	15.17	7.88	13.97	9.57	10.52	9.10
Rank			2	4	1	8	3	6	5	7
Franksred Means		13.18	16.21	13.79	16.28	11.18	14.53	11.31	12.40	9.77
Rank			2	4	1	7	3	6	5	8
Oct. Glory Means		9.97	11.85	10.98	14.06	4.57	13.40	7.82	8.64	8.43
Rank			3	4	1	8	2	7	5	6



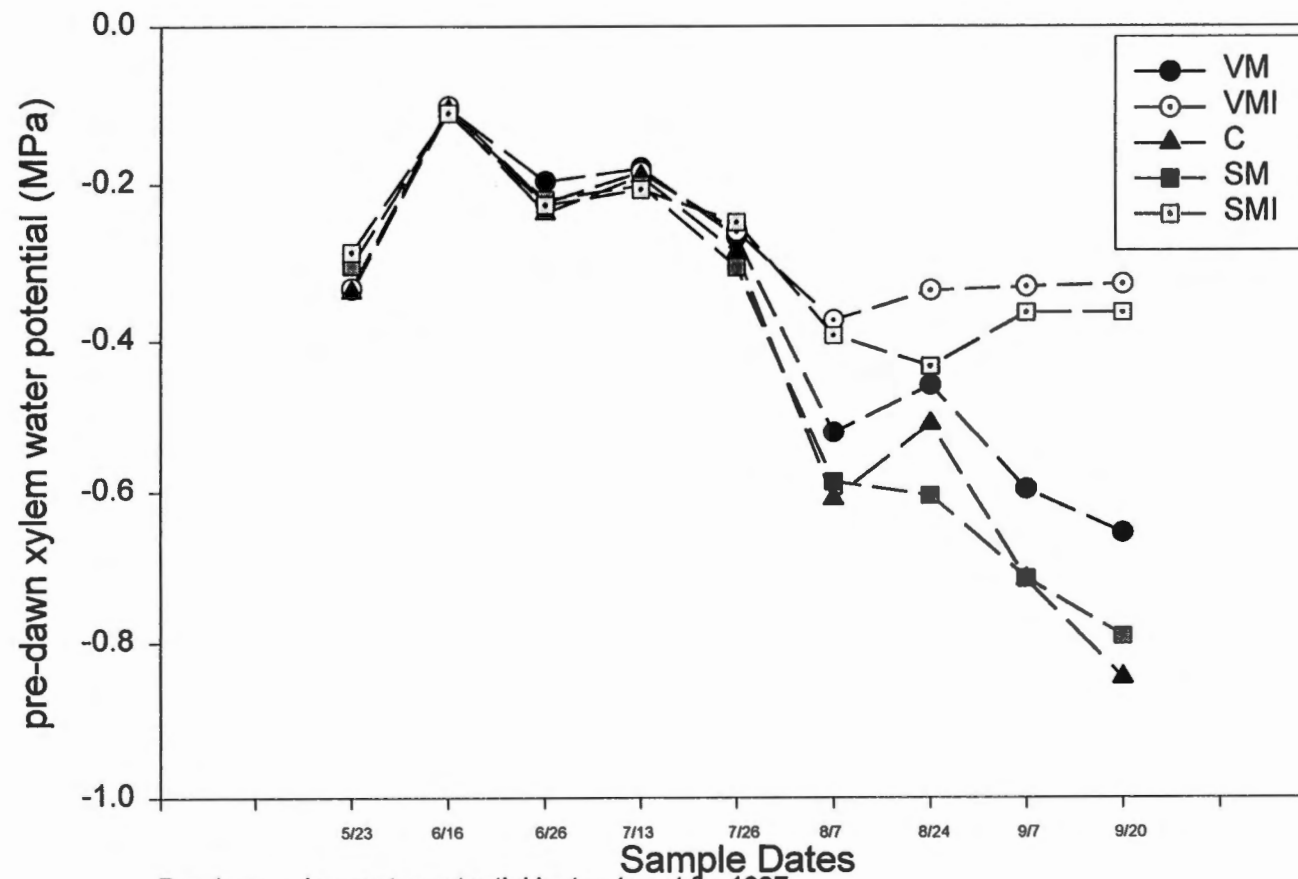
Phenological study averaged (n=6) for 1996. Bars having different letters are significant at $P \leq 0.05$.



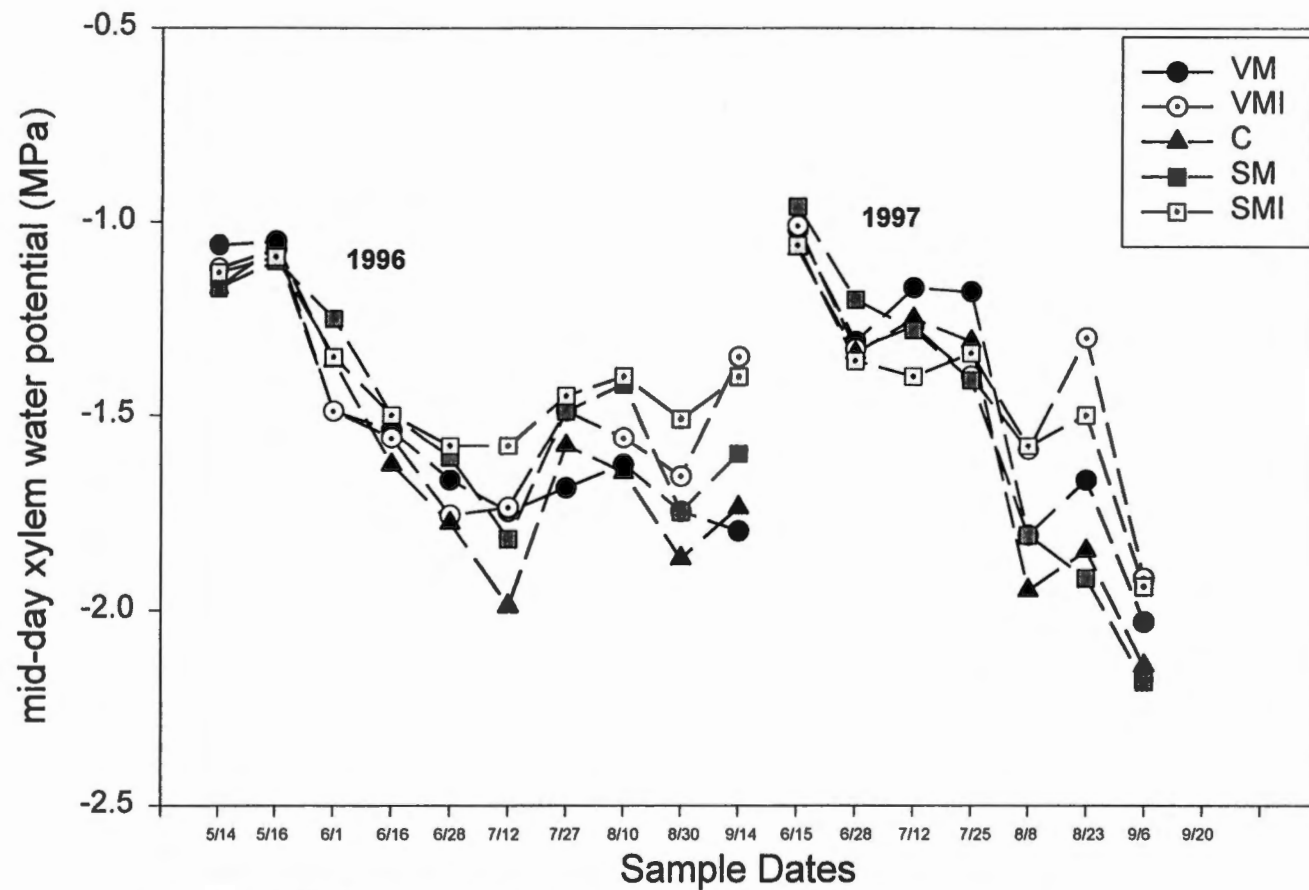
Phenological study averaged (n=6) for 1997. Bars having different letters are significant at $P \leq 0.05$.



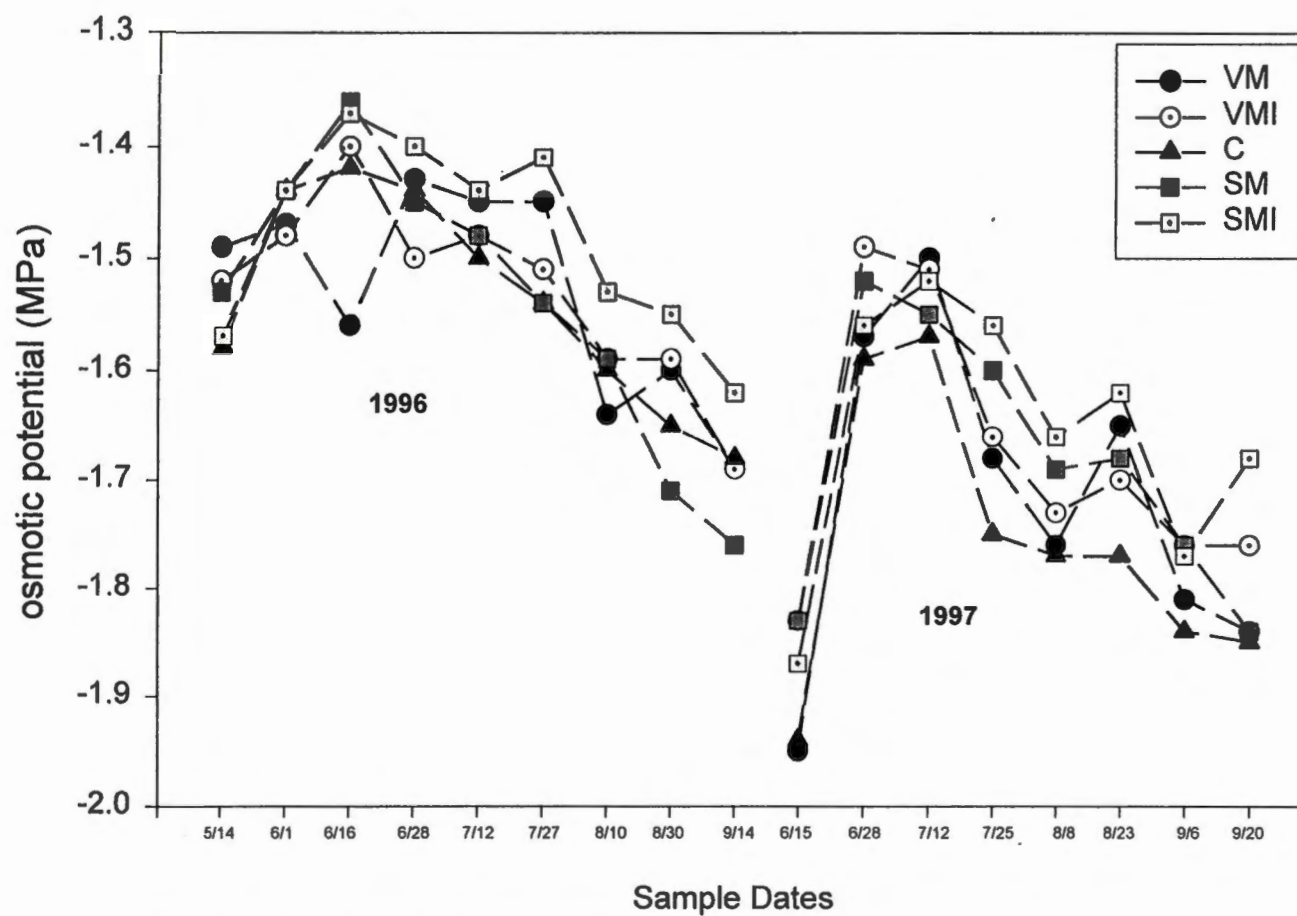
Pre-dawn xylem water potential by treatment for 1996.
Each point is the mean of six replicates.



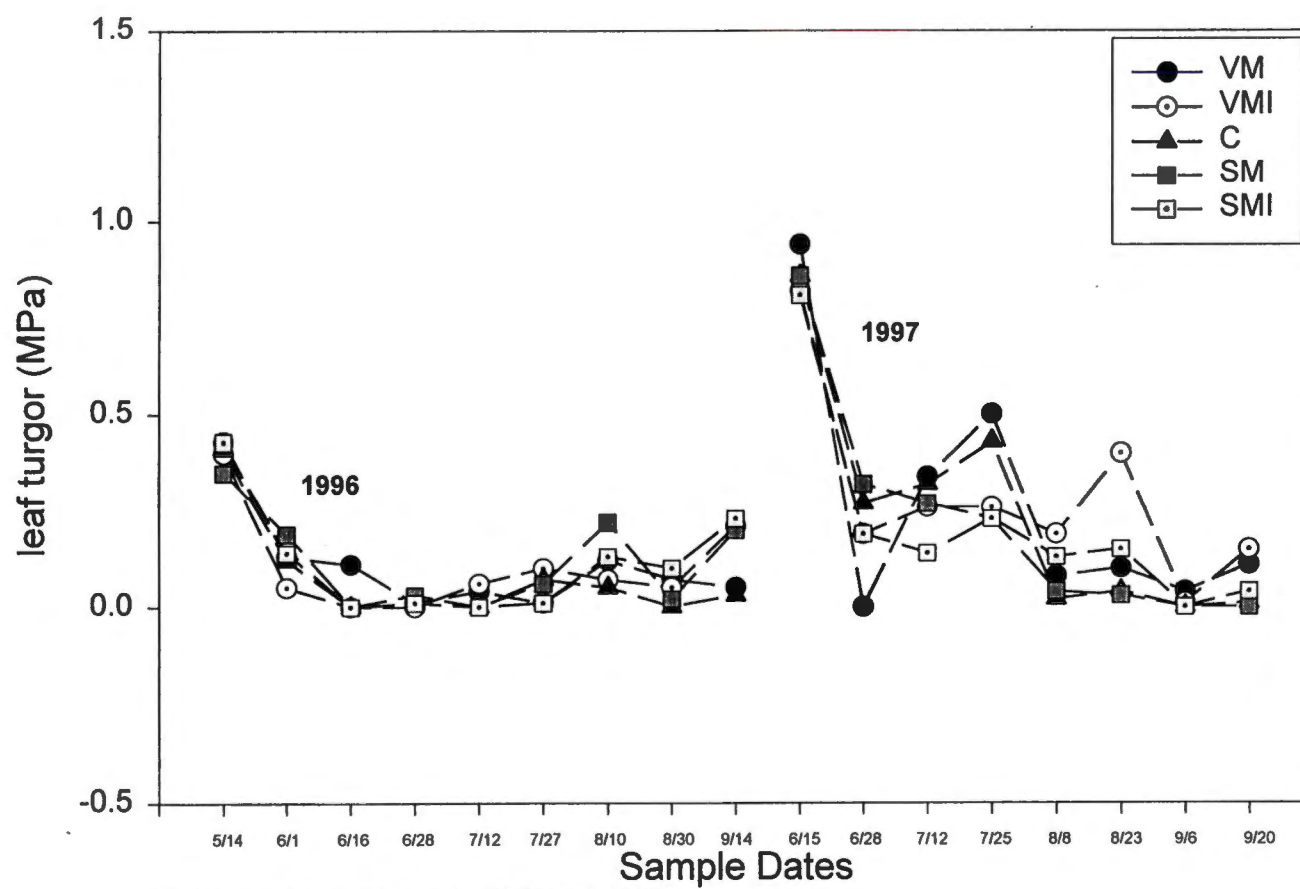
Pre-dawn xylem water potential by treatment for 1997.
Each point is the mean of six replicates.



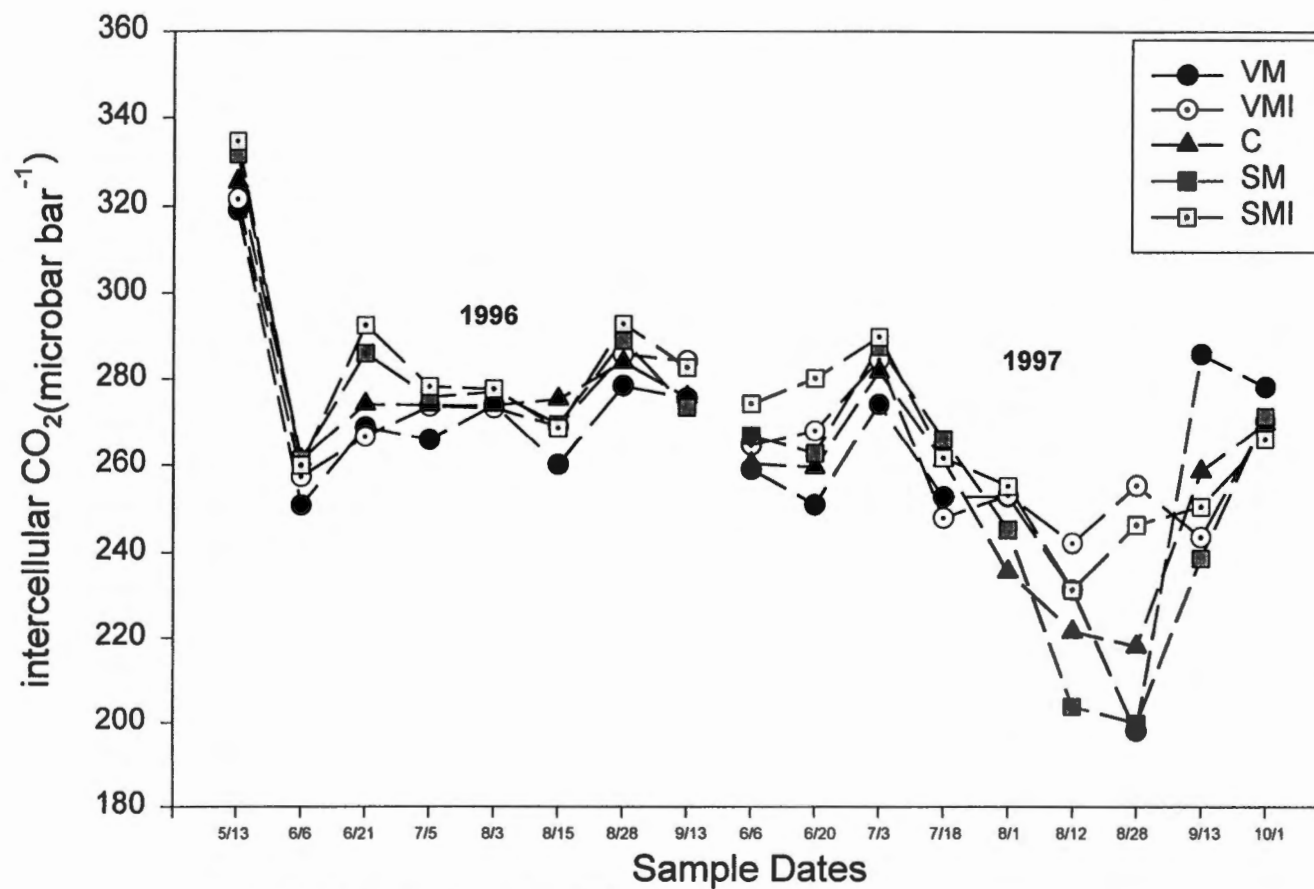
Mid-day xylem water potential by treatment for 1996 and 1997.
Each point is the mean of six replicates.



Osmotic potential by treatment for 1996 and 1997.
Each point is the mean of six replicates.



Leaf turgor by treatment for 1996 and 1997.
Each point is the mean of six replicates.



Intercellular CO₂ by treatment for 1996 and 1997.
Each point is the mean of six replicates.

VITA

Joel Franklin Keebler was born in Knoxville, Tennessee on May 11, 1966. He later moved to Morgan County, Tennessee where he graduated from Central High School in Wartburg in 1984. He earned an Associate of Arts degree from Roane State Community College in Harriman, Tennessee in 1986. In 1987, Keebler entered the University of Tennessee at Knoxville. He studied history and earned the B.A. in 1988. In 1989, he accepted a position with the U.S. Office of Personnel Management. In 1994, Keebler began work on a second undergraduate degree from the University of Tennessee. In 1995, he earned the B.S. with a major in Ornamental Horticulture and Landscape Design. After an internship at the Arboretum at Flagstaff in northern Arizona, he began graduate studies at the University of Tennessee. While working towards the M.S. degree, Keebler was employed by the Department of OHLD as a Graduate Teaching Assistant and a Graduate Research Assistant. Also, from 1997-98, he worked as a Graduate Research Assistant with the University's Energy and Environment Research Center on a landscape ecology project with the Saturn Corporation in Spring Hill, Tennessee.

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