DISSERTATION

IMPACT OF IRRIGATION REGIME ON TREES AND TURFGRASS IN A LANDSCAPE SETTING

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY DOUGLAS ALAN FINDLEY ENTITLED IMPACT OF IRRIGATION REGIME ON TREES AND TURFGRASS IN A LANDSCAPE SETTING BE ACCEPTED AS FULFILLING IN PART THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

IMPACT OF IRRIGATION REGIME ON TREES AND TURFGRASS IN A LANDSCAPE SETTING

The response of *Gleditsia tricanthos inermis* 'Skyline', *Fraxinus pennsylvannica* 'Patmore', and *Poa pratensis* 'Livingston' grown in a landscape setting to three irrigation regimes was evaluated. Irrigation regimes were based on evapotranspiration (ET) and consisted of deficit, (40% ET), replacement, (80% ET), or excessive, (160% ET) amounts of water applied throughout the growing season. These irrigation regimes had no affect on leaf weight, area, percent moisture, height, caliper, or cold hardiness low temperature exotherms (LTE). Leaf water potential of the trees, a measure of plant water stress, was lower with decreasing application of water. Fall color development was affected only for *Fraxinus pennsylvannica* 'Patmore'. Deficit irrigated trees initiated fall color two weeks earlier and reached maximum fall color one week prior to trees under excessive irrigation.

Turfgrass clipping weight and percent moisture was reduced in both studies with decreasing irrigation levels. Turfgrass irrigated at 160% ET remained dark green, and continued growing throughout the summer, producing large quantities of clippings. Replacement irrigated turfgrass maintained a dark green color, highly desired by landscape

managers and homeowners, but clipping quantities were significantly reduced compared to excessively irrigated turfgrass. When *Poa pratensis* was maintained at 40% ET, it entered drought induced dormancy three to six weeks after treatment initiation. The turfgrass was light green, and bare soil was visible through the canopy in some portions of the plots providing an ideal location for weed seeds to germinate.

Results from these studies indicate that irrigation regime has a limited affect on tree growth and development after one growing season, however the long term impact after several years of similar irrigation regimes may be more important for disease and insect outbreaks. Turfgrass growth is affected by irrigation regime in such a way that landscape managers can reduce clippings by reducing irrigation levels and still maintain acceptable quality turfgrass.

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CHAPTER 1.

INTRODUCTION AND LITERATURE REVIEW

Americans place great importance on having healthy lawns and landscapes, so much so that sales of environmental horticulture products (sod, nursery plants, trees, shrubs, bulbs and fruit/nut plants) reached $24.1 billion in 1993 and are expected to top $26 billion in 1994 (Anonymous, 1995). In 1997 consumers spent $14.6 billion on professional landscape, lawn and tree care services indicating a strong desire in maintaining the landscapes they invested money in previously (Saarela, 1998). Landscaping improvements can increase the value of a house by 8 to 10% depending on the size of the lot. In Colorado real estate professionals estimate 20 to 30% of the value of an average home can be attributed to landscaping (Knox, 1989b).

Throughout the country urban landscapes are continuing to expand onto former farms or pastures. A building boom along the Front Range of Colorado consumes 90,000 acres of farmland and pastureland per year (Long, 1996). Beyond such initial impact, urban landscapes have additional costs; most require large quantities of water to remain green during dry periods when rainfall is insufficient to meet plant demands.

Nearly all of this population growth is centered in urban areas causing urban water needs to increase much more rapidly than supply (Vaux, 1990). Furthermore, a large percentage of population growth is occurring in regions where water availability is much less than the demand, such as the Sun Belt of Arizona. Restrictive water management policies are becoming common throughout the country, even in humid areas of the eastern U. S., since only a limited amount of treated water is available for agricultural, industrial, and urban consumption. Developing new sources of fresh water is not a feasible solution, since the easiest to develop sites have already been developed and new sites would be extremely costly (Langbein, 1982).

On average across the United States, industry accounts for 43% of the daily water use, agricultural irrigation 47%, with the remaining 10% for urban uses such as cooking, bathing, sanitation, drinking, landscape irrigation, etc. (Morton, 1976). In many states agriculture is the largest consumer of water, accounting for 87% in Arizona, 82% in California, and in Colorado the total is 94% (Carr et al., 1987; Schwartz, 1988). In these regions a great deal of research has been devoted to developing best management practices (BMP) that improve on farm water-use-efficiency (Jensen 1973, 1975; Jensen et al., 1990; Waskom et al., 1994). These BMPs allow farmers to maximize irrigation efficiency, thus reducing the amount of water needed to produce a crop, and to reduce agricultural contamination of water resources. In addition to western farmland being converted into subdivisions, agricultural water is being diverted to satisfy urban needs, since one acre of houses in the West uses less water than an acre of tomatoes (Schwartz, 1988).

Residential water use accounts for approximately 65% of total treated water in urban or metropolitan areas (Ellinghouse and McCoy, 1982; Martin et al., 1984). In arid regions an estimated 40 to 50% of the water treated annually is applied to urban landscapes during periods of normal rainfall (Linaweaver et al., 1967; Williamson (1975). Landscape irrigation accounts for approximately 50% of total urban water consumption in Denver, Colorado (Anonymous, 1990), and in Logan, Utah it was reported to be 61% (Aurasteh, 1983). During periods of drought or excessive temperatures, this figure can soar to above 70% of treated water (Winje and Flack, 1986). The drought of the late 1970s resulted in 70% of treated water along the Colorado Front Range (Danielson et al., 1979) and 80 to 85% of treated water in Wyoming being applied to urban landscapes (Pochop and Borrelli, 1979). Prior to an extended drought in California (1987 - 1992), residential water usage accounted for 65% of the total urban water used. By 1991 a 14.1% decline in residential water usage was reported primarily due to drought related restrictions on landscape irrigation and low flow devices inside the home (Dixon et al., 1996; Moore et al., 1993).

The large quantity of treated water being applied to landscapes has caused many municipalities to restrict water use during times of drought (Flack, 1982; Rodiek, 1984), often resulting in plant injury and unattractive landscapes (Lohr and Bummer, 1992). Water restrictions can range from a ban on mid-day irrigation to every other day watering during mild to moderate droughts (White et al., 1980). With more severe droughts outdoor watering may be reduced to twice per week or in extreme cases banned altogether to maintain adequate water supplies for domestic consumption (Anderson, 1980; Howe et al., 1990; Nelson, 1979; Riebsame et al., 1991).

Irrigation Requirements of Urban Landscape Plants

Traditional landscape designs have been based on aesthetically pleasing criteria with little emphasis on water requirements of the plants used to implement the design. In 1981 a task force made up of members from the Denver Water Department, Colorado State University, and the Associated Landscape Contractors of Colorado developed the term Xeriscape for water conservation through appropriate and creative landscaping (Ellefson et al., 1992).

Xeriscaping, a term developed after a major drought in 1977, describes landscaping with water conservation as the main objective. One xeriscaping approach is to reduce the amount of irrigated bluegrass and increase the numbers of trees and shrubs (Knox, 1989b; Anonymous, 1990), since the belief is that turfgrasses use more water than trees do. A survey of homeowners in Tucson, Arizona indicated that 20% would be willing to remove front lawns to conserve water (Martin et al., 1984). However, lawn removal would create other problems and be aesthetically detrimental; in addition turfgrass helps provide cooling in urban areas due to evaporative cooling. Huang et al. (1987) used computer models to demonstrate that evapotranspiration from vegetation is more effective than shading in reducing energy consumption.

Turfgrass is used to provide a number of benefits in urban areas, which can be divided into functional, recreational, and aesthetic components (Beard and Green, 1994). Turfgrass is an inexpensive groundcover that protects soil from wind and water erosion, and reduces sediment and pollutant transport from paved areas into bodies of water. Actively growing *Cynodon* turf was found to be 21C cooler than dormant turf and 39C cooler than synthetic turf during the heat of the day (Beard and Johns, 1985). Around properly designed landscapes, turfgrasses can help integrate trees, shrubs, and flowers into a complete aesthetically pleasing package.

Kentucky bluegrass (*Poa pratensis* L., KBG) is the most common turfgrass species used along the front range of Colorado comprising about 90% of the lawns (Borland, 1988; Knox, 1989b). This grass is traffic hardy and tolerates the cold winter temperatures of this area very well, but requires up to 100 cm of water per average year to maintain the desired deep green color. The natural precipitation average for the Front Range is only 35 cm per year, so supplemental irrigation is needed or bluegrass becomes dormant. Replacing bluegrass with grasses that require less water such as *Festuca arundinacea* Schreb. (tall fescue) or *Bouteloua gracillis* (H.B.K.) Lag. ex Griffiths (blue gramma grass) is one option in urban areas; however, overcoming the perceptions these are not suitable grasses may be difficult (Ellefson et al.,1992).

Grasses have survived for centuries in the prairies across the Great Plains of the United States with some areas receiving less than 40 cm of rain per year. In these same regions, trees are found only in low spots or along stream banks where water may be available for most of the year. A major difference between these grasslands and the grasses commonly grown in urban landscapes is in their adaptability. *Buchloe dactyloides* (Nutt.) Engelm., *Bouteloua gracillis*, *Andropogon hallii* Hack., and species of *Muhlenbergia* are commonly found in more arid grasslands (Barbour et al., 1987). The principle lawn grass in Colorado is KBG, which requires more water to remain green than do the native grasses.

There have been very few studies comparing evapotranspiration rates of trees and shrubs to turfgrasses. Devitt et al. (1994, 1995a, 1995b) reported that when trees or shrubs were compared to low fertility *Cynodon dactylon* (L.) Pers., they were found to use greater amounts of water than the grass. However, when compared to high fertility *Cynodon dactylon,* the opposite was true; the grass had higher water-use rates indicating fertility management can play a significant role in altering water-use. These studies indicate that on a per unit land area basis trees and shrubs may be higher water users than turfgrass especially as they mature.

Materials that surround plants can have a large impact on transpiration rates as well. For example, the use of mulch around trees and shrubs is a common practice, intended to conserve soil moisture and reduce weeds. In many regions gravel mulches are becoming popular as a permanent mulching material instead of organic types that need to be replaced periodically. Gravel mulch reflects more longwave radiation than turfgrass or organic mulches do, thus increasing transpiration rates of adjacent plants (Doll et al., 1985). Halvorson and Potts (1981), Kjelgren and Montague (1998), and Miller (1980) determined that isolated trees had greater transpiration rates when surrounded by pavement than in more forested or vegetated settings. In a similar study, Zajieck and Heilman (1991) found transpiration of well watered *Lagerstroemia indica* L. (crape myrtle) was greater for plants surrounded by pine bark mulch than by bare soil, or plants surrounded by *Cynodon dactylon.* These studies indicate materials that surround a plant can have a large impact on transpiration rates.

Water usage of plants in urban landscapes has not received the same amount of attention as agricultural water usage. Limited information is available on water use by landscape plants in general (Devitt et al., 1994, 1995a, b; Fitzpatrick, 1983; Heilman et al., 1989; Holbrook and Sinclair, 1992; Knox, 1989a; Levitt et al., 1995; Martin et al., 1989; Roberts and Schnipke, 1987; Vrecenak and Herrington, 1984; Welsh et al., 1991; Zajicek and Heilman, 1991). Most of the information on low water use plants has come from the recommendations of various organizations (e.g., Arizona Municipal Water Users Association, Arizona Native Plant Society, Colorado State University Cooperative Extension, Xeriscape Colorado) (Feucht, J. R., 1996 a, b, c, d, e; Levitt et al., 1995; Anonymous, 1990). Unfortunately these lists are from empirical observations based on the plants native habitat, and there is a general lack of actual data on plant water use. When water is non-limiting some of these species may be moderate to high water users such as mesquite (*Prosopis* var.) (Levitt et al., 1995), KBG (Danielson et al., 1981), and tall fescue (Younger et al., 1981). The lack of long-term water-use (yearly data) for landscape plants is a problem for landscape architects when designing in arid regions.

Impacts of Drought on Landscape Plants

Water is an integral part of a plant from germination through maturity, until death. Even after death, water is required for fungi to completely decompose woody tissue. Without an adequate supply of water, problems will develop with seed germination, absorption and translocation of minerals or carbohydrates, transpiration, photosynthesis, respiration, and growth (Crafts, 1968). The impact water stress has on these functions varies from species to species, age of the plant, time of year the stress occurs, as well as the duration and severity of water stress.

Drought stress can impact plants in a variety of ways including visual quality, growth rate, evapotranspiration (ET) rate, and recuperative ability following drought-induced dormancy (Beard, 1973). Low leaf water potentials impact many cellular processes including cell expansion, stomatal regulation, photosynthesis, respiration, translocation, and cell wall synthesis (Batten et al., 1994; Hsiao, 1973; Kramer 1983; Vu and Yelenosky, 1988).

Numerous studies have documented the effect of drought on visual quality and growth of crop plants and turfgrass. Reductions in rates of leaf (Boyer, 1968, 1970; Hsiao, 1973; Takami et al., 1981) and shoot (Hoogenboom et al., 1987) expansion of several crop species have been reported as responses to moisture stress. Turfgrass responses to drought are similar for warm and cool season species. Shoot responses include reduced clipping production, and shoot density, while wilt, leaf browning, and canopy temperature tend to increase (Aronson et al., 1987; Carrow, 1996a, b; Huang et al., 1997; Keeley, 1996; Minner and Butler, 1985). Visual quality of turfgrass is very important in urban areas where green lawn color is associated with higher property value (Danielson et al., 1980; Winje and Flack, 1986).

Physiological responses of woody plants to drought conditions are similar to those reported for herbaceous crop plants. Water deficits either directly or indirectly influence many physiological processes (Hsiao, 1973; Kozlowski, 1968a, b, 1972, 1976, 1978). Responses vary from very sensitive (cell elongation) to moderately sensitive (photosynthesis and respiration) to relatively insensitive (irreversible membrane damage) (Hsiao, 1973). Reductions in leaf and shoot growth, changes in dry matter partioning, premature leaf senescence, general decline, and increased susceptibility to insect and pathogen attack have all been reported as tree responses to water stress (Dye, 1996; Halverson and Potts, 1981; Kramer, 1987; Ree 1994; Smitley and Peterson, 1996; Steinberg, et al., 1990).

Foresters have for years used tree height as a measure of potential site productivity because trees located on dry sites grow less per year than those located on moist sites (Brown and Clark, 1981; Ralston, 1964; White, 1958). More recently, researchers have used dendrochronological methods to reconstruct drought histories by examining the growth rings of long lived trees in many parts of the world. Clear correlations between drought and tree decline have been established in European forests for both *Quercus robur* L. and *Quercus petraea* (Mattuschka) Liebl. (Becker and Levy, 1983) and the southern boundary of the boreal forest in central and western Canada (Hogg, 1994).

Power (1994) reconstructed growth histories of healthy and unhealthy *Fagus sylvatica* L. trees in England back to 1960. Healthy trees quickly regained growth rates after a severe drought in 1976, while unhealthy trees failed to recover and still show evidence of reduced growth rates. Peterken and Mountford (1996) examined the impact of the 1976 drought on an unmanaged mixed deciduous woodland in another part of England and reported that mature *Fagus sylvatica* trees were still dying 15 years later from drought-induced damage.

Premature leaf senescence or leaf scorching has been reported as a response to drought stress for many broad-leaved, temperate zone species of trees. The drought of 1913 severely affected street trees in many parts of the country, with many trees almost completely defoliated. *Acer platanoides* L., *Tilia americana* L. and *Ulmus americana* L. were the most severely affected with most of the injury occurring on the south or southwest sides of the crown (Hartly and Merrill, 1915; Pool, 1913). Levy et al. (1978) observed a 29% reduction in canopy growth of grapefruit trees irrigated every 40 days compared to those irrigated every 18 days. Other *Citrus* spp. respond in a similar manner to water stress by shedding leaves in response to drought (Kaufmann, 1977; Marsh, 1973). *Gleditsia tricanthos inermis* L. commonly suffers from premature leaf loss during extended periods of drought in urban environments (Halverson and Potts, 1981; Potts and Herrington, 1982). In addition to leaf senescence, several species of Eucalyptus suffer from bark fissuring and separation of wood from bark indicating severe dehydration (Pook et al., 1966). Premature leaf senescence tends to cause a growth reduction of shade trees (Begg, 1980) and reduced fruit size of citrus trees (Shalhevet et al., 1976).

General declines of forests in central Europe and North America were first described in the 1960s. Originally this was attributed to acid rain but upon further study many are now convinced this general tree decline is caused by a combination of many events, including atmospheric pollution, changes in weather patterns, extreme temperatures, and biotic factors (Larcher, 1995). Oak (*Quercus* spp.) and beech (*Fagus* spp.) decline in both Europe and the United States have been attributed to repeated periods of drought that predispose trees to diseases such as *Armillaria* spp., *Cytospora* spp., *Ophiostoma* spp., and *Hypoxylon* spp. (Bassett and Fenn, 1984; Bussotti et al., 1995; Peterken and Mountford, 1996; Vannini and Valentini, 1994).

Water Stress Effects on Cold Hardiness

Cold hardiness is known to be influenced by both water stress and the timing of that stress. Increases in cold hardiness induced by water stress have been reported in some woody plants, such as citrus (*Citrus* spp.) (Yelenosky, 1979), evergreen azaleas (Anisko and Lindstrom, 1995, 1996a, b), red-osier dogwood (Chen et al., 1975,1977; Chen and Li, 1977, 1978), and red spruce (Amundson et al., 1993). No apparent effect on cold hardiness was detected for Douglas-fir seedlings (*Pseudotsuga menziesii* (Mirb.) Franco) (van den Driessche, 1969). The water potential of these plants ranged from -1.2 MPa in Douglas-fir (Timmis and Tanaka, 1976), -1.7 MPa in red-osier dogwood (Chen et al., 1977), -1.5 to -1.8 MPa in evergreen azaleas (Anskio and Lindstrom, 1996a), and -1.3 to -2.3 MPa in red spruce (Amundson et al., 1993).

Changes in cold hardiness appear to be related to changes in tissue water relations (Burke and Stushnoff, 1979; Gross and Koch, 1991; Grossnickle, 1992; Ritchie and Shula, 1984; Tyree et al., 1978). Water loss observed during cold acclimation may actually result from dry matter accumulation (Ritchie and Shula, 1984) or actual water loss (Bray and Parsons, 1981). Drought induced increases in cold hardiness may be caused by the removal of nonessential water, reducing mechanical damage during freezing (Li and Weiser, 1971), or freezing point depression associated by a decrease in osmotic potential (Biddington and Dearman, 1988; Li and Weiser, 1971; Yelenosky, 1979).

The timing of water stress is important in determining if cold hardiness is enhanced. Blake et al. (1979) observed that cold hardiness in Douglas-fir seedlings was increased only when water stress began before photoperiodic induction of dormancy. Timmis and Tanaka (1976) reported that cold hardiness of Douglas-fir seedlings was not immediately affected after eight to nine weeks of reduced irrigation. However, five to eleven weeks after normal watering resumed, plants that had been water stressed were more cold hardy than non-water stressed seedlings. Cold hardiness was enhanced for *Rhododendron* 'Catawbiense Boursault' when drought episodes occurred in late summer, early fall and late fall but not when applied during winter (Anisko and Lindstrom, 1996c).

Reversing drought stress may cause a reversal of induced cold hardiness. Cold hardiness of red-osier dogwood was increased by 8 to 10C after reduced water application for three weeks, but upon rewatering, water stressed plants lost the induced cold hardiness (Parsons and Li, 1979). Amundson et al. (1993), working with red spruce trees, and Anisko and Lindstrom (1996a) with evergreen azaleas found that drought-induced cold hardiness was lost three to six weeks after resuming irrigation.

Increases in cold hardiness due to water stress have been induced by reduced watering for periods ranging from days (Biddington and Dearman, 1988; Yelenosky, 1979 to weeks (Anisko and Lindstrom, 1995, 1996a,b,c; Chen et al., 1975) and months (Utsunomiya, 1988; Nelson et al., 1993; Anisko and Lindstrom 1996a). One season of reduced water increased cold hardiness between 0.5 and 5C in leaves, and from 2 to 5C in stems of container grown *Rhododendron* 'Catawbiense Boursault'. A second season of reduced water during early fall however caused a 2C decrease in stem cold hardiness for these same plants (Anisko and Lindstrom, 1996a). Increases in cold hardiness of water stressed plants range from 0.5 to 5C for evergreen azaleas (Anisko and Lindstrom, 1995, 1996a) to 8 to 10C for red-osier dogwood (Chen et al., 1975, 1977; Chen and Li, 1978).

Water stress does not always cause an increase in cold hardiness, in fact in some instances it may delay or inhibit cold acclimation in sensitive species. Quamme et al. (1972a) observed a lack of cold hardening for highbush blueberries in Minnesota after a fall drought, while the following year, with adequate moisture, virtually no injury occurred. Apple trees closest to sprinklers suffered less winter injury than those located further away, possibly due to increased soil moisture resulting in higher heat capacity, thus insulating the roots from extreme air temperatures (Quamme and Brownlee, 1989).

Water Stress Effects on Other Physiological Processes

Foliar nutrient concentrations of *Picea abies* (L.) Karst. were reduced (Nilsen, 1995), and reductions in size and abundance of starch grains in *Pinus sylvestris* L., *Picea abies* (L.) Karst. (Palomaki et al., 1994), and *Salix* sp. (Vapaavuori and Nurmi, 1982; Vapaavuori et al., 1984) also were attributed to drought. Photosynthesis and stomatal conductance declined with increasing drought stress for *Betula papyrifera* Marsh, *Acer negundo* L., *Ulmus parvifolia* Jacq., *Robinia pseudoacacia* L., *Malus baccata* Borkh (Ranney et al., 1990) and *Quercus petraea* (Matt.) Liebl. and *Quercus robur* L. (Epron and Dreyer, 1993).

Duration of drought stress is an important factor that determines the severity of injury. Short-term water deficits can impact physiological processes such as stomatal opening or closing and photosynthesis within minutes (Passioura, 1982), but short-term efects may only have a minor influence on growth over the life of the plant (Passioura, 1986). Even relatively longer periods of moisture stress, those lasting a few days or weeks, generally do not cause long term changes in plant structure or function, despite effects on cell growth (Fitter and Hay, 1987), leaf surface area (Borghetti et al., 1989; Hennessey et al., 1985), and dry matter production and partitioning (Graves and Wilkins, 1991; Joly et al., 1989).

Fruit growers in many parts of the world use deficit irrigation during part of the growing season to reduce water and fertilizer use and to minimize pesticide leaching (Chalmers, 1989). Vegetative growth is decreased with deficit irrigation, thus reducing pruning costs (Chalmers, 1989; Girona et al., 1993; Irving and Drost, 1987), without adversely impacting fruit quality (Mills et al., 1994). However, depending upon timing, fruit size can be reduced by drought periods or when deficit irrigation is applied at the wrong part of the growing season (Powell, 1976).

Long term drought conditions, i.e. moisture stress lasting more than one growing season, can cause tree growth reductions, growth rate slowing, dieback, and general decline (Delatour, 1983; Kramer, 1987), and it is thought that some pathogens may increase these effects on trees (Delatour, 1990). Comparisons between deep rooted and shallow rooted *Quercus douglasii* H. & A. trees indicated decreased leaf area per leaf, leaf specific mass, chlorophyll per leaf area, incident quantum yield, leaf respiration rate, and irradiance at light compensation for the shallow rooted trees (Callaway and Mahall, 1996). Shallow rooted trees were dependent on shallow soil moisture which is rapidly removed during rainless summers in central California.

Intraspecific differences in drought tolerance of *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir) have been identified in seed sources from Rocky Mountain and southern Oregon compared to coastal environments (Ferrell and Woodard, 1966; Heiner and Lavender, 1972; Pharis and Ferrel, 1966). Xeric *Pseudotsuga menziesii* seedlings had slower growth rates, earlier budbreak and budset compared to mesic seedlings grown under similar irrigation levels indicating a strong genetic link to drought susceptibility (Joly et al., 1989).

Impacts of Excessive Irrigation on Plants

Urban landscapes face environmental challenges other than drought injury. Typically, homeowners or landscape managers do not accurately measure the amount of water being applied with a sprinkler system, and this can lead to excessive irrigation. Excessive irrigation is not only wasteful since extra water either runs off the soil surface or percolates beyond the plant root zone where it is unavailable, but can also cause flood-like conditions without standing surface water.

During times of no water restrictions it has been estimated that most urban landscapes receive excess amounts of water. The high demand for water during these times has been attributed to homeowners' preference for green lawns (Martin et al., 1984). In California, it is estimated that as much as 20% of applied irrigation water may represent overwatering (Flack, 1982). There was little correspondence between lysimeter determinations of plant water needs and the amount applied in research conducted in Utah (Aurasteh, 1983) or Wyoming (Pochop and Borrelli, 1979). Urban landscapes in Las Cruces, New Mexico used 50% more water than was needed to meet consumptive use

(Flack, 1982). In Fort Collins, Colorado water applications of 135% of potential ET were applied by homeowners (Danielson, et al., 1980), much greater than the 80% of potential ET requirements of cool season turfgrasses for this area (Ervin, 1995).

Inefficient irrigation systems contribute to the problem of excessive water application (Vinchesi and Lynch, 1990). Hoag et al. (1981) estimates a 20% reduction in water use could be realized with proper maintenance and adjustment of automatic sprinkler systems. A New Mexico study determined that by using efficient watering techniques, water requirements could be reduced by as much as 47% (Flack, 1982).

Physiological effects of excess water applications may create plants less able to tolerate subsequent periods of low water availability, and that use greater amounts of water than is needed. Devitt et al. (1994, 1995a), has reported that when plants are overwatered, many will increase water usage as a response to increased water availability.

Excessive soil moisture for extended periods of time causes a number of physiological problems in plants. The earliest responses to flooding are reduced water uptake and increased leaf water deficits caused by root death (Kozlowski, 1976, 1982). Reduced mineral uptake, stem hypertrophy, leaf senescence and abscission, chlorosis, wilting, and epinasty, have all been attributed to soil flooding (Kawase, 1981; Kozlowski, 1985). Turfgrass responses to excessive water include shallower rooting (O'Neil and Carrow, 1983; Agnew and Carrow, 1985), higher disease potential (Fry, 1982; Schumann and Wilkinson, 1992; Zadoks and Schein, 1979), increased weed pressures (Watschke and Schmidt, 1992), and soil is more easily compacted (Carrow and Petrovic, 1992). The extent of injury for both trees and turfgrass varies by species, soil factors, timing and duration; flooding during the growing season is more damaging than that occurring when plants are dormant (Gill, 1970; Rowe and Beardsell, 1973).

Tree age is important in determining the severity of injury for many trees. Generally older trees are able to tolerate flooding better that seedlings or young trees of the same species. Popescu and Necsulescu (1967) reported when various ages of *Populus* x *canadensis* Moench trees were flooded for 150 days all trees were injured, but injury was greatest for the youngest trees. *Taxodium distichum* (L.) L. C. Rich. naturally grows in swamps and marshes throughout the southeastern U.S. with mature trees able to withstand extremely long periods in standing water (Krinard and Johnson, 1976). Seedlings of this species died after two weeks of complete submergence indicating a need for a dry site to become established (Demaree, 1932).

Compacted soil layers can be found in many urban areas, often resulting from building construction. These compacted layers are difficult for roots to penetrate, leading to small, shallow root systems (Alberty et al., 1984). Elevated water tables can develop above these layers with excessive irrigation or rainfall events, and subsequent flooding can cause root death. Shallow, fluctuating water tables result in shallow-rooted unstable trees (Whitehead and Jarvis, 1981). The primary cause of root death are the metabolic changes induced by anaerobic conditions associated with decreased soil aeration. The respiration of roots and microorganisms rapidly consume soil oxygen during flooded conditions (Hook and Scholtens, 1978). Tree species vary considerably in their ability to tolerate flooded conditions; for example, *Gleditsia triacanthos* is only moderately able to survive flooding, while *Fraxinus pennsylvanica* Marsh. roots continue to grow under flooded conditions (Dickson et al., 1965; Hook and Brown, 1973; Hook et al., 1970; Yelenosky, 1963).

Methods for Studying Water Stress on Plants

Plant Moisture Status

Water potential is the (moisture) measurement relevant to growth and water movement within plants and soil. It has been defined as the difference between the chemical potential of pure, free water and the water within the soil-plant system at atmospheric pressure and at the same temperature; its value has been arbitrarily set at zero (Salisbury and Ross, 1992). The following equation describes total water potential:

$$\psi = \psi_g + \psi_m + \psi_o + \psi_p$$

where the subscripts are for gravitational, matric, osmotic, and pressure potentials, respectively (Campbell, 1990). Gravitational potential is generally not considered in plant water measurements unless one is working with very tall trees.

The driving force for water movement from soil into and through the plant, and into the atmosphere is negative water potential. A typical soil-plant-atmosphere system has a gradient from highest water potential (soil) to lowest water potential (air) as seen below (Wilkens, 1987):

	Water Potential (Mpa)
Soil	-0.10
Root	-1.00
Stem	-1.50
Leaf	-1.50
Air (20C, 50% RH)	-100.00

The movement of water from the soil into the root system is a passive process, driven by leaf transpiration induced water potential gradients (Kozlowski, 1981).

Direct measurements of water potential in either soils or plants is not possible at this time, but several indirect techniques based on comparison between the sample and a known reference have been developed over the years. A common method to measure leaf water potential is use of a pressure chamber. The petiole is placed through a rubber stopper, into a metal chamber with the cut end of the leaf remaining outside the chamber. Pressure is applied gradually until water is first observed at the cut end of the sample. The pressure applied to the tissue at this point in time is equal to the negative leaf water potential.

Most errors associated with using this instrument can be attributed to improper sealing of the gasket to the petiole (Simonelli and Spomer, 1980), relative amount of tissue inside vs. outside the chamber (Kaufmann, 1968), rate of chamber pressurization (Ritchie and Hinckley, 1971), and moisture loss from the sample prior to pressurization (Ritchie and Hinckley, 1975). With proper procedures these sources of error can be minimized, allowing the pressure equilibration method to be the simplest and quickest technique for estimating leaf water potential (Bennett, 1990; Spomer, 1985).

Soil Moisture Status

Measurement of soil water is important in understanding plant moisture relations. Water is first removed from a soil where it is most available, usually the upper soil layers where the majority of roots are located (Woods and O'Neal, 1965). Only as the profile continues to dry will soil moisture be removed from deeper layers (Nnyamah and Black, 1977). One common method of measuring soil moisture within root zones is with a neutron probe. To measure soil moisture, fast neutrons are emitted from a radioactive source. When they collide with hydrogen they are slowed or thermalized; a counting device records the number of thermalized neutrons, which is proportional to soil water content. These instruments are relatively quick, accurate, and allow for repeated sampling at the same location (Carijo and Cuenca, 1992).

Evapotranspiration

Many methods have been investigated and used for scheduling irrigation. These are based on some measure of plant water status, soil moisture status, or atmospheric demand. In the semi-arid regions of the western United States, the 1982 Kimberly-Penman method of estimating reference evaporation (atmospheric demand) is widely used (Wright, 1982; Jensen et al., 1990). This method is an improvement of the original 1948 Penman equation based on an empirical formula integrating the primary meteorological variables of temperature, radiation, humidity, and wind run (Penman, 1948; Jensen et al., 1990). The 1982 Kimberly-Penman method works so well in semi-arid regions partly because the method incorporates a region specific wind function (Wright, 1982).

In Colorado, a network of agricultural weather stations, COAGMET (Colorado Agricultural Meteorological Network), use the 1982 Kimberly-Penman combination equation to calculate ET_r, which is then made available by mail, telephone, or internet. Irrigators then use these alfalfa ET estimates and appropriate crop coefficients (K_c) for irrigation scheduling.

The general form of the Penman equation is:

$$\lambda ET_r = [\Delta/(\Delta+\gamma)]\ [R_n - G] + [\gamma/(\Delta+\gamma)]\ [6.43]\ [W_f]\ [e_z^o - e_z]$$

λET_r	= reference evapotransporation
Δ	= slope of the saturation vapor pressure-temperature curve
γ	= psychometric constant
R_n	= net radiation
G	= heat flux density to the ground
W_f	= wind function
e_z^o	= saturation vapor pressure at height z
e_z	= vapor pressure of air at height z

The 1982 Kimberly-Penman modification is to the wind function (W_f) as below:

$$W_f = a_w + b_w u_2$$

$a_w = 0.4 + 1.4 \exp\{-[(D - 173)/58]^2\}$
$b_w = 0.007 + 0.004 \exp\{-[(D - 243)/80]^2\}$
u_2 = wind speed at 2 m reference height (km d^{-1})
D = calender day for northern latitudes

Weather data for these calculations is collected on an hourly basis, allowing for a high degree of accuracy with the 1982 Kimberly-Penman equation, even on a short time interval (Brown, 1990; Jensen et al., 1990).

Various municipalities provide ET estimates for one, three, and seven day periods during the growing season as a guide for turf irrigation. This allows irrigation managers to make decisions on a daily basis on whether irrigation will be required or not. A K_c of 0.80 is used along the Front Range for scheduling irrigation of cool-season turfgrasses (Ervin, 1995).

Cold hardiness

The distribution of plant species is based not only on moisture availability and distribution patterns but also temperature. Many tree species of the eastern deciduous forest cannot survive midwinter minimum temperatures below -40C (George et al., 1974b; Sakai and Weiser, 1973). Boreal forest tree species, such as *Betula papyrifera* and *Cornus stolonifera*, can tolerate immersion in liquid nitrogen (-196C) when fully acclimated (Burke et al., 1976). Cold hardiness of plants is influenced by a number of factors including temperature, day length, plant maturity, physiological age, water content, nutritional status, and dormancy status (Stushnoff, 1972).

Intraspecific differences in cold hardiness have been reported for a number of tree and shrub species, with these differences related to latitude of the parent plant material. Trees of northern origin generally sustain less injury than trees of southern origin during both controlled freezing test (laboratory) and provenance plantings. Differences have been reported for *Acer negundo* L. (Demos et al., 1973), *Cornus stolonifera* Michx. (Smithberg and Weiser, 1968), *Quercus rubra* L. (Flint, 1972), *Fraxinus americana* L. (Wright, 1944a; Alexander et al., 1984), *Fraxinus pennsylvanica* (Wright, 1944b), *Juglans nigra* L. (Bey, 1979) , and *Pinus strobus* L. (Mergen, 1963; Maronek and Flint, 1974), all commonly used in urban landscapes.

Knowledge of plant cold hardiness can help determine the potential of injury caused by low winter temperatures, and also when to take protective measures to reduce injury from late spring or early fall frosts. Several methods are available to determine cold hardiness of plants, including whole plant freeze tests, freeze-induced electrolyte leakage, and differential thermal analysis (DTA) (Burr et al., 1990). Whole plant freeze tests require destructive sampling, results are subjective, are not practical for large plants due to space limitations, and require seven to fourteen days until results are ready.

When plant tissue is injured, either from temperature stress, or mechanical injury, membranes are damaged and electrolytes leak out. More injury causes greater amounts of electrolytes to leak out. Electrolyte leakage tests allow for many more samples to be run at one time, but requires two twenty hour incubation periods. The first incubation period is used to determine a base line reading for the tissue sample prior to a freezing period, since some amount of electrolyte leakage will occur from mechanical injury to cells during sampling. The second incubation period occurs after the freeze test, this period allows the electrolytes from freeze damaged tissue to enter the solution and reach equilibrium.

Some plants have the ability to avoid ice formation within certain tissues even when subjected to temperatures below 0C by deep supercooling or undercooling the water within them. Deep supercooled water in plants is in a metastable state and will rapidly freeze intra-cellularly when a heterogeneous nucleating agent such as dust particle or ice nucleating bacteria is present, or spontaneously when homogenous nucleation temperature of pure water is reached (-38C) causing cell damage (Burke et al., 1976; Rajashekar and Burke, 1978; Rasmussen and Mackenzie, 1972). The additional compounds found within cell sap may depress the freezing point by several more degrees (Burke et al., 1976).

Tissues and organs that deep supercool include xylem ray parenchyma in deciduous hardwoods (Arora et al., 1992; Ashworth et al., 1983; George et al., 1974b; Quamme et al., 1972b; Ketchie and Kammereck, 1987; Lindstrom et al., 1995), flower buds (Andrews and Proebsting, 1987; Flinn and Ashworth, 1995; George and Burke, 1977; Kang et al., 1997; Quamme, 1974), vegetative buds (Dami et al., 1996; Hamman et al., 1996; Quamme, 1995), and hydrated seeds (Stushnoff and Junttila, 1978). A large number of fruit and forest tree and shrub species have been evaluated in the past 25+ years for the ability to deep supercool in an effort to identify species that could be used in breeding programs to extend the useful range of agricultural fruit trees and other crops northward.

The freezing of deep supercooled water within plant tissues releases heat of fusion which is observed as a low temperature exotherm (LTE) that can be detected by thermal analysis (Quamme, 1991). Differential thermal analysis (DTA) is commonly used to detect the occurrence of a LTE using dormant buds or stem sections. Sample temperatures are compared to a reference sample (dried tissue of similar size) undergoing the same rate of cooling. When the water within the sample undergoes a phase change a difference in temperature between the sample and reference results, producing a peak on a thermogram. This peak represents an exotherm during freezing or an endotherm during melting (Burke et al., 1976).

The DTA profile of tissue that deep supercools typically displays two exothermic peaks; the first or high temperature exotherm (HTE), is relatively large and generally occurs between -5 and -10C, and is associated with extracellular or bulk water freezing (Colman, 1985; George et al., 1974b; Quamme, 1995). Plants that are cold acclimated can survive this freezing temperature. The peak(s) that follow are called low temperature exotherm(s) (LTE), and have been observed at temperatures between that of the HTE and -41 to -47C depending on the plant species and tissue being evaluated (George et al., 1974a; Quamme, 1995; Quamme et al., 1972b; Weiser, 1970). This LTE results from intracellular water freezing and has been correlated with tissue injury as observed by the visual browning of the tissue (Quamme, 1995; Sakai, 1978).

Seasonal variation in LTEs have been reported for xylem ray and pith parenchyma of *Malus* sp. (Quamme et al., 1972b, 1973; Ketchie and Kammereck, 1987), and *Acer rubrum* L., *Fraxinus americana*, and *Zelkova serrata* (Thunb.) Mak. (Lindstrom et al., 1995), for flower buds of *Forsythia* sp. (Flinn and Ashworth, 1995), and *Prunus* sp. (Quamme, 1974), and mixed buds of *Diospyros khaki* Thunb. (Kang et al., 1997), and *Vitis vinifera* L. (Dami et al., 1996; Hamman et al., 1996). These seasonal differences in LTE are a result of growth cycles that are synchronized with seasonal environmental changes. As temperate plant species are exposed to low, but non-freezing temperatures and/or short day length, they become tolerant to extreme sub-freezing temperatures. This process of going from cold tender to cold hardy is termed cold acclimation, and primarily involves two stages (Levitt, 1980; Sakai and Larcher, 1987). The first stage of cold acclimation in many woody plant species is induced by short days occurring in late summer and early fall prior (Fuchigami et al., 1971; Howell and Weiser, 1970; Irving and Lanphear, 1967). The second stage of cold acclimation is induced by temperatures between 5C to below 0C. Cold hardiness will rapidly increase after exposure to these temperatures, and generally coincides with the first frost of the fall (Howell and Weiser, 1970).

Once the chilling requirement of the plant has been fully satisfied, dormant buds will rapidly grow when exposed to favorable conditions. The period from the fulfilment of chilling requirements to the resumption of growth is know as deacclimation and refers to a natural loss of cold hardiness (Fuchigami et al., 1982). Deacclimation in spring is largely dependent on exposure to warm temperatures, however subsequent exposure to low temperatures may reverse the process but not to similar levels of maximum midwinter cold hardiness (Fuchigami et al., 1982).

Lethal temperatures can not always be estimated using LTEs detected by DTA. For some species bark or vegetative buds may be more sensitive to cold injury than xylem tissue, and these tissues do not always exhibit LTEs. Blueberry is one species in which the bark, which has no LTE, is injured at a much higher temperature than xylem tissue which does have a LTE (Cappiello and Dunham, 1994; Hiirsalmi and Hietaranta, 1989; Quamme et al, 1972a). Kaku and Iwaya (1978) evaluating trees indigenous to Japan, and George et al. (1974b) evaluating trees of eastern North America both found that xylem injury for some trees did not coincided with the LTE, thus care must be taken during plant evaluation to determine if a LTE correlates to tissue injury.

Summary

Urban landscapes are entering a period of change due to an increasing human population. We can not much longer justify large inputs of treated water to maintain most current landscapes in an aesthetically pleasing condition. Accordingly, additional information is needed on the impact that limited water availabilities will have on the health and longevity of landscape plants. In addition, there is a need to investigate the impacts of excessive irrigation on plant growth and development since numerous studies have demonstrated the average homeowner applies more water than is required. This research project was designed to investigate both short and long term impacts that the irrigation regime has on the growth and development of an urban landscape using two of the more popular shade trees and the most popular turfgrass for the Front Range of Colorado.

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CHAPTER 2.

DESIGN AND INSTALLATION OF A LARGE SCALE TREE AND TURF SITE FOR LONG TERM IRRIGATION STUDIES

INTRODUCTION

Throughout the United States the demand for clean water is increasing as population growth continues. In arid regions of the country water management is becoming more important since only a limited amount of water is available for agricultural, industrial, and urban consumption. New reservoirs or well fields are not often viable because they can have serious environmental and economic costs that are difficult to assess and address prior to construction.

Agriculture is the largest consumer of water in many states, 94% of the state-wide total in Colorado (Carr et al., 1987), and a great deal of research has been devoted to developing best management practices that improve on farm water-use-efficiency (Jensen 1973, 1975; Jensen et al., 1990). However, urban landscapes have not received the same amount of attention. Limited information on water use by landscape plants (Devitt et al., 1994, 1995 a; Martin et al., 1989; Vrecenak and Herrington, 1984; Welsh et al., 1991) is available. The lack of long-term (yearly) water-use information for landscape plants is a problem for landscape architects, especially when designing in arid regions.

In the Denver, Colorado area, the use of water on landscapes has been reported to be as high as 50% of total urban water consumption (Anonymous, 1990), and in Logan, Utah it was reported to be as high as 61% (Aurasteh, 1983). During times of drought, landscape irrigation is often one of the first water uses restricted (Rodiek, 1984), resulting in unattractive landscapes and plant injury (Lohr and Bummer, 1992). Water deficits of even relatively short duration can reduce cell growth (Fitter and Hay, 1987), decrease leaf surface area (Borghetti et al., 1989; Hennessey et al., 1985), and alter dry matter production and partitioning (Graves and Wilkins, 1991; Joly et al., 1989; Zwack et al., 1998).

The long term effects of drought on forest trees has been investigated and include reduction of growth rate and total growth, dieback, and general decline (Delatour, 1983; Kramer, 1987). In addition it is thought that some pathogens may interact to increase these effects on trees (Delatour, 1990). Long term drought stress was also reported to decrease leaf area, leaf specific mass, chlorophyll per unit leaf area, and leaf respiration rate in *Quercus douglasii* trees (Callaway and Mahall, 1996). Changes in leaf specific mass (Nobel, 1980), quantum yield (Bjorkman and Powles, 1984; Ben et al. 1987), respiration rate (Gaff 1980; Dougherty and Hinckley, 1981), and light compensation point (Tenhunen et al. 1984, 1985) have also been observed as water stress responses in other species.

During times of no water restrictions, it has been estimated that most urban landscapes receive excess amounts of water, which is thus wasted. In California, it is estimated that as much as 20% of applied irrigation water may represent overwatering

(Flack, 1982). In a New Mexico study it was determined that by using efficient watering techniques, water requirements could be reduced by as much as 47% (Flack, 1982). In addition, most overwatering occurs with inefficient irrigation systems, which compounds the problem (Vinchesi and Lynch, 1990). With this excess water homeowners may be creating plants that are less able to tolerate periods of low water availability, and that use greater amounts of water than is needed. Devitt et al. (1994, 1995a), has reported that over watered plants will increase water usage beyond amounts needed to sustain acceptable growth and appearance. In addition, for many taxa, excessive soil moisture retards leaf development, induces stem hypertrophy, and causes chlorosis, wilting, epinasty, and leaf senescence (Kawase, 1981; Kozlowski, 1985).

Current thinking is that turfgrasses use more water than trees so typical recommendations are to reduce the amount of turf in a landscape and increase the numbers of trees (Anonymous, 1990). However Devitt et al. (1994, 1995a, 1995b) reported that trees and shrubs used greater amounts of water than low fertility bermudagrass. When compared to high fertility bermudagrass, though, the opposite was true; grass had higher waster-use rates than the woody plants, indicating fertility management can play a significant role in altering water-use. Grasses have survived for centuries in the prairies across the Great Plains of the United States with some areas receiving less than 40 cm of rain per year. In these same regions, trees are found only in low spots or stream banks where water may be available for most of the year. A major difference between these native grasslands and the managed urban landscapes is the type of grass grown. Buffalo grass, blue grama, sand bluestem, and species of *Muhlenbergia* are commonly found in more arid grasslands (Barbour et al., 1987), while the principle lawn grass in Colorado is Kentucky bluegrass which requires more water to remain green than do the native grasses.

With the increased demand for water in arid regions the need to manage available water resources is becoming more critical. With increased emphasis on management, and decreased amounts of water available for landscape usage, landscape professionals need information on how the growth and development of landscape plants is affected by reduced water availability. Studies have demonstrated significant inter- and intra- specific differences in drought sensitivity among turfgrass cultivars. Similar differences have been reported in agronomic crops as well. However no studies have been conducted using simulated landscape settings in which both trees and turf are evaluated for water use efficiency under controlled conditions.

In May 1996, a seven year field study was initiated to evaluate the long term impact of a defined irrigation regime on tree and turf health. This study involved setting up a 1.3 ha (3.2 ac) research platform comprised of two commonly used shade trees, 'Patmore' green ash (*Fraxinus pennsylvanica* Marshall 'Patmore'), and 'Skyline' honeylocust (*Gleditsia triacanthos inermis* L. 'Skyline') underplanted with 'Livingston' Kentucky bluegrass (*Poa pratensis* L. 'Livingston'). Three irrigation treatments will be applied each growing season after establishment, representing deficit (40% ET), replacement (80% ET) and excessive (160% ET) amounts of water, relative to evapotranspiration (ET). Plants will be evaluated for changes in growth, disease or insect feeding preference, and long term survival.

The experimental site described here was designed to investigate the difference in water use between trees and turfgrass as they mature over several years. In addition, plant health studies will be conducted to investigate the influence irrigation rates may have on long term plant survival.

MATERIALS AND METHODS

In May 1996 a long term tree and turf research project was established at the Agricultural Research Development and Education Center (ARDEC) located approximately 14.8 km northeast of Ft. Collins, CO (lat. 40° 39' 08" N, long. 104° 59' 46" W lat., elevation 1550 m). The climate is semi-arid with average annual maximum temperatures of 16.8C, minimum of 1.2C, and average annual precipitation of 365 mm. The maximum temperature recorded in Ft. Collins was 38.9C, minimum temperature -40.5C, maximum precipitation 701 mm, minimum precipitation 142 mm. The soil is a Ft. Collins clay (fine, mixed, mesic Ustollic Haplargid) with a pH of 8.0.

Nine plots 32.9 m x 43.9 m were established at the research site (Figure 2.1). Each whole plot was divided into three sub-plots containing either trees and turfgrass or turfgrass only. Tree and turfgrass sub-plots were planted with 27 bareroot *Gleditsia triacanthos inermis* L. 'Skyline' ('Skyline' honeylocust) or *Fraxinus pennsylvanica* Marshall 'Patmore' ('Patmore' green ash) trees spaced 4.9 m apart within rows and 3.7 m apart between rows (Figure 2.2). Organix Outdoor mix (Organix, Inc., Plattville, CO) was incorporated into each planting hole at a 9:1, v:v, soil to amendment at planting.

During the first year, trees were irrigated biweekly using furrow irrigation. *Gleditsia* trees measured 2.8 cm and *Fraxinus* trees measured 2.4 cm in caliper measured 15 cm from the soil line, tree height was 3.6 m for *Gleditsia* and 2.7 m for *Fraxinus* one year after planting. In fall 1996 all trees were mulched with 5-7 cm aged bark. *Poa pratensis* L. 'Livingston' ('Livingston' Kentucky bluegrass) was seeded in late fall, 1996 at 195.3 kg seed ha^{-1} in both the turfgrass only and tree and turfgrass sub-plots (Figure 2.3). Due to poor winter survival turfgrass was reseeded May 4, 1997 at 195.3 kg seed ha^{-1}.

Soil tests indicated additional N and P were needed for bluegrass turf (Table 2.1). Nitrogen was applied at 45 kg ha^{-1} in the form of diammonium phosphate 18N-20.1P-0K (Jirdon Agri Chemicals, Inc., Morrill, NE) in June, July, and October 1997 to supply the needed nutrients. After establishment, turf was maintained at home lawn conditions with weekly mowing at 7.6 cm height using a rotary mower, and clippings were returned (Figure 2.4).

Irrigation at the site was provided with a standard home pop-up irrigation system. Toro Super 700 Commercial Low Angle (The Toro Company, Riverside CA) sprinklers with matched precipitation rates spaced 11 m apart were used. Each plot was individually controlled using a Hardie model TC-2400 LX II multi-station irrigation controller (James Hardie, Inc., Laguna Niguel, CA) allowing multiple start and run times for irrigation treatments. During 1997, all plots were irrigated uniformly as needed to promote full establishment of both turf and trees. Irrigation treatments, initiated in 1998, were based on estimated evapotranspiration (ET) and include 40%, 80%, and 160% of ET to represent deficit, replacement, and excessive water applications based on turf requirements. ET was calculated from data obtained at a Colorado Agricultural Meteorological Weather Station (COAGMET) 0.8 km south of the research site. ET estimates were calculated using the modified Penman equation, described by Buchleiter et al. (1988). Irrigation treatments after turf establishment occurred twice per week based on ET, corrected for any rainfall occurring since the last irrigation.

Aluminum access tubes 5.08 cm in diameter and 1.8 m long were installed during July 1997 for use with a Troxler Model 4302 Depth Moisture Gauge (Troxler Electronic Laboratories, Inc., Research Triangle Park, NC) to monitor soil moisture status. Three tubes per sub-plot were installed for a total of 81 locations across the research site. Tubes in tree and turf sub-plots were located equidistant from four trees.

Initial measurements were taken in May 1997 to determine tree and site uniformity prior to initiating irrigation treatments. These included height, caliper, and date of spring budbreak of the trees, subsample of soil moisture across the site, and soil test for nutrient levels. Tree height was measured to the nearest cm, tree caliper was measured to the nearest mm at 15 cm above soil line per American Association of Nurserymen standards (Anonymous, 1997). Trees were monitored three times per week for evidence of budbreak, the date buds had swelled to 0.635 cm in diameter was classified as budbreak. All 27 trees of each species within a plot were used for height, caliper, and budbreak measurements. Soil moisture was sampled at 30, 60, 90, 120, and 150 cm depths below the soil surface using a Troxler model 4302 neutron probe that used a 10μCu Am^{241}/Be neutron source. Soil samples from the upper 20 cm of the profile were taken from ten locations within a plot. These samples were combined and a subsample for each plot was then sent to the Colorado State University soil testing lab for nutrient analysis. All tree related data were subjected to analysis of variance. Mean separations were determined by Duncan's Multiple Range Test, P = 0.05.

RESULTS AND DISCUSSION

Site uniformity. Initial tree height, trunk diameter, and budbreak measurements taken one year after trees were planted indicated uniformity across all nine plots (Table 2.2). A soil survey conducted during the installation of neutron probe tubes identified a buried pond located in a small portion of plot six, under the 'turf only' sub-plot. This soil feature was located approximately 0.9 m below the soil surface and was between 0.3 m and 0.9 m thick. Volumetric soil moisture readings had to be recalibrated for measurements taken within this layer. Growth of trees and turf above this soil may be impacted as they mature and roots reach this layer; however, at this time there is no indication of an effect on growth. A trend in decreasing volumetric soil moisture was detected from north to south across the research site. This created the need to block for this variation when assigning irrigation treatments for the 1998 growing season and beyond.

FUTURE OBJECTIVES OF THIS RESEARCH SITE

The objective of this project is to investigate the relationship between trees and turfgrasses in the landscape as affected by water resources. Specifically landscape settings and experimental treatment were assigned to assess the impact of limited water availability over several years on plant growth, development, disease and insect susceptibility. Questions that might be answered by this project include those asking:

1) if increased water application leads to increased water use by both trees and turfgrass.

2) if turfgrass growth is affected when grown in a landscape setting with trees under various irrigation regimes.

3) if tree leaf expansion is affected by irrigation regime.

4) if spring bud break, leaf size, fall color, and shoot elongation of trees are affected by irrigation regime.

5) if tree disease or insect damages are affected by irrigation regime.

SIGNIFICANCE TO THE INDUSTRY

The development of this large scale research facility will allow researchers the opportunity to investigate several aspects of tree and turf health in a landscape setting. Information gained can be used by industry professionals and homeowners in developing cost effective maintenance plans that reduce insect and disease pressures and still provide aesthetically pleasing landscapes. The long term nature of this site will allow scientists to determine how irrigation regimes applied over several years will affect the health and vigor of plants in the landscape.

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Figure 2.1 Aerial view of research site at the Agricultural Research Development and Education Center (ARDEC) from south (left) to north (right).

Figure 2.2. Research site after bare root trees were planted on May 25, 1996. Orange tube supplies water to furrows for irrigating trees until sprinkler system is completed.

Figure 2.3. Research plots September 10, 1996 after seeding 'Livingston' Kentucky bluegrass at 195.3 kg ha^{-1}.

Table 2.1. **Soil analysis of upper 30 cm of soil prior to 'Livingston' Kentucky bluegrass establishment [z].**

Variable	pH	E. C. (mmhos/cm)	Percent O. M.	NO_3-N	P	K	Zn	Fe	Mn	Cu
Plot 1	7.7	0.7	1.7	27	1.5	323	15.6	8.3	1.2	4.5
Plot 2	8.0	0.7	1.5	22	2.8	255	8.7	6.6	0.9	3.2
Plot 3	8.1	0.7	1.5	24	3.4	300	5.9	7.1	0.9	3.3
Plot 4	8.0	0.7	1.4	20	3.1	203	6.2	7.9	0.8	4.5
Plot 5	8.1	0.7	1.7	20	2.8	241	3.4	6.6	0.7	3.2
Plot 6	8.1	0.6	1.9	22	4.3	285	4.8	6.7	0.8	2.8
Plot 7	8.1	0.6	1.3	17	1.5	182	1.8	6.9	0.7	3.0
Plot 8	8.2	0.6	1.5	18	1.2	208	4.9	5.4	0.8	2.7
Plot 9	8.0	0.7	1.8	23	2.1	238	6.3	7.6	1.0	3.6

[z] All nutrient results reported in ppm using ammonium bicarbonate-DTPA extract methods of the Colorado State University Soil, Water, and Plant Testing Laboratory, Fort Collins, Colorado. Results are based on ten samples of the upper 30 cm of soil per plot mixed together and one subsample per plot submitted for testing.

Figure 2.4. Research site August 16, 1997 after turfgrass is established.

Table 2.2. Height, caliper ^{Z}, and date of budbreak of 'Patmore' green ash and 'Skyline' honeylocust May 1997.

	'Patmore' green ash			'Skyline' honeylocust		
Variable	Height (m)	Caliper (cm)	Budbreak ^{Y}	Height (m)	Caliper (cm)	Budbreak
Plot 1	2.68	2.5	126	3.60	3.0	126
Plot 2	2.63	2.4	125	3.60	3.1	126
Plot 3	2.74	2.4	125	3.72	3.1	126
Plot 4	2.77	2.5	126	3.66	3.1	126
Plot 5	2.78	2.5	125	3.70	3.0	126
Plot 6	2.67	2.4	126	3.64	3.1	126
Plot 7	2.67	2.4	125	3.66	3.1	126
Plot 8	2.64	2.4	125	3.70	3.1	126
Plot 9	2.72	2.4	126	3.66	3.1	126
Significance ^{X}						
Block	NS	NS	NS	NS	NS	NS
Plot	NS	NS	NS	NS	NS	NS

^{Z} Height measured to the nearest cm and caliper measured to the nearest mm in May 1997, one year after tree planting. Caliper measurements were taken 15 cm above soil line. All measurements based on 27 trees per species per whole plot.

^{Y} Year day of budbreak based on buds swelling to 0.635 cm in diameter.

^{X} NS: non significant at $P \leq 0.05$ based on ANOVA.

CHAPTER 3.

TURFGRASS GROWTH AS IMPACTED BY IRRIGATION REGIME AND TREES IN THE LANDSCAPE

Introduction

Turfgrass provides many functional, recreational and aesthetic benefits for urban dwellers including heat dissipation, noise abatement, increased property values, and complements other landscape elements (Beard and Green, 1994). An estimated 18.8 million hectares of land in the United States is devoted to turfgrass (Grounds Maintenance, 1996), representing the single largest 'crop' produced (Bormann et al., 1993). The economic impact of professional turfgrass maintenance has been estimated at $14.6 billion (Saarela, 1998). The most widely used perennial turfgrass species in temperate and subarctic regions is Poa pratensis L. (Kentucky bluegrass KBG) (Turgeon, 1991). Along the front range of Colorado, KBG is used in over 90% of the lawns (Borland, 1990; Knox, 1989).

Urban landscape management in semi-arid regions requires careful water management strategies that maintain aesthetically pleasing plants. With increasing population pressures in these same regions, the need to conserve a finite resource is increasing. Estimated annual irrigation requirements for urban landscapes in Fort Collins, CO is about 61 cm, however most consumers are applying 90 cm, or 31% more than required to adequately maintain the landscape (Staats, 1993). During periods of drought, landscape irrigation is one of the first water restrictions used to reduce demand (Lohr and Bummer, 1992). A California study estimated that in periods of no water restrictions, consumers apply at least 20% more water than is required for maintaining turfgrass (Flack, 1982).

Short term responses of turfgrass to drought stress include decline in visual appearance, reduced growth rate, and ability to recover from stress (Beard, 1973). Many turfgrass species stop growing, become dormant , and turn brown with drought stress, but are able to recover once rainfall resumes (Sifers et al., 1990; Keeley, 1996).

Excessive water applications to turfgrass can result in increased plant water use (Devitt et al., 1993; Kopec et al., 1991), and increases in vegetative growth for some warm-season turfgrasses (Qian and Engelke, 1999). Disease pressure on turfgrass varies with increased water application. Jiang et al. (1998) reported *Rhizoctonia solani* Kuhn (brown patch) injury was reduced however *Sclerotinia homoecarpa* F. T. Bennett (dollar spot) injury was twice as great on perennial ryegrass (*Lolium perenne* L.) with increasing water application. Irrigation levels > 80% of Class A pan evaporation (Ep) greatly increased *R. solani* outbreaks on 'Nortam' St. Augustinegrass [Stenotaphrum secundatum (Walt.) Kuntze]and *S. homocarpa* on 'Tifway' bermudagrass [*Cynodon dactylon* (L.) Pers] compared to lower irrigation levels (Qian and Engelke, 1999).

A negative impact of trees on turfgrass growth has been reported by a number of researchers (Barrios et al., 1986; Beard 1973; Whitcomb and Roberts, 1973), but most of these studies have used artificial shade in their evaluations. Therefore this research was conducted to determine both short- and long-term effects of different irrigation regimes on Kentucky bluegrass when grown with or without trees in a landscape setting.

Materials and Methods

In June 1997 a landscape field research plot was established at the Agricultural Research Development and Education Center (ARDEC) located 14.8 km northeast of Ft. Collins, CO for the study of the interactions between trees and turfgrass under three irrigation regimes. Two initial studies were conducted during 1998, the first from 1 June 1998 to 23 July 1998, the second from 3 Aug. 1998 to 3 Sept 1998. Each of the studies included three irrigation regimes designed on the basis of evapotranspiration (ET). These three treatments were excessive (160% ET), replacement (80% ET), and deficit (40% ET) irrigation based on the requirements of *Poa pratensis* L. (Kentucky bluegrass) turf compared to alfalfa as the reference crop. Ervin (1995) and Mecham and Crookston (1994) determined that a crop coefficient (K_c) of 0.80 in conjunction with estimates of ET is effective for cool-season turfgrass irrigation scheduling in Colorado. ET was calculated using data obtained from a Colorado Agricultural Meteorological (COAGMET) weather station located 0.8 km south of the research site. The modified Penman equation, described by Buchleiter et al.(1988) was used to calculate daily ET requirements. Irrigation treatments were applied twice per week between 2000h and 0600h (8:00 pm and 6:00 am) to minimize the effects of wind on water distribution, and were corrected for any rainfall occurring since the last irrigation.

A split-plot statistical design using a randomized complete block (RCB) with three replications was used. Each whole plot measured 32.9 m x 43.9 m divided into three sub-plots containing either trees and turfgrass or turfgrass only. Tree and turfgrass sub-plots contained 27 *Gleditsia tricanthos inermis* L. 'Skyline', (HL), or *Fraxinus pennsylvanica*

Marshall 'Patmore', (GA), trees spaced 4.9 m within rows and 3.7 m between rows. An aged mulch ring 1 m in diameter was placed around each tree to reduce grass encroachment to tree bases. *Poa pratensis* 'Livingston', (KBG), had been seeded in both tree and turfgrass and turfgrass only sub-plots in May 1997 at 195 kg ha^{-1}. 'Livingston' KBG was selected based on consistently displaying good performance during water stress when evaluated for visual quality and leaf-firing (Keeley, 1996). In May and June 1998, 49 kg ha^{-1} N in the form of diammonium phosphate (18 N-20.1 P-0 K) (Jirdon Agri Chemicals, Inc., Morrill, NE) fertilizer was applied across all plots.

Weekly clipping samples were collected from 1.5 m x 1.5 m plots centered over neutron probe tubes using a rear bagging rotary mower. Clipping samples were weighed after collection to the nearest 0.5 g using an A & D model EP-40 KB electronic balance (A & D Company, Ltd., Tokyo, Japan), and placed into a 70C drying oven for 72h. After drying samples were reweighed and moisture percentage was calculated by the formula (fresh wt. - dry weight)/(fresh weight). Three samples per sub-plot were collected for a total of nine samples per treatment per sub-plot. The KBG was mowed weekly, after samples had been taken, to a height of 7.6 cm; clippings were not collected during maintenance mowing.

Volumetric soil moisture measurements were measured weekly prior to an irrigation application. Measurement were made 30, 60, 90, 120, and 150 cm below the soil surface using a Troxler model 4302 neutron probe (Troxler Electronic Laboratories, Inc., Research Triangle Park, NC) that used a 10 μCu Am^{241}/Be fast neutron source. The neutron source was maintained at the same position within a nominal 5.08 cm diameter aluminum access tube at each sampling depth and a 15 s count was used.

Data analysis. Plots were arranged in a completely randomized block with a split-plot factor. There were three treatments with three replications each. Data for fresh and dry clipping weight and moisture percentage were analyzed over all dates in a study using Statistical Analysis System's repeated measures analysis PROC GLM (SAS Institute, 1989). Percentage data were first arcsin transformed to satisfy normality assumptions. When a significant F statistic occurred, means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

Results and Discussion

Irrigation treatments Weekly irrigation applications in study 1 averaged 19.8 mm for 40% ET treatment, 39.6 mm for 80% ET treatment, and 79.2 mm for 160% ET treatments. In study 2, weekly irrigation treatments averaged 14.6 mm, 34.1 mm, and 77.5 mm for the 40% ET, 80% ET, and 160% ET treatments, respectively.

Growth The main effects of sampling date and irrigation regime were significant in both studies, while sub-plot (species) was only significant in study 1 (Table 3.1). Turfgrass only sub-plots (KBG) produced significantly more clippings per m^2 (fresh weight) than tree and turfgrass sub-plots, 23.9% more than turfgrass grown with green ash (GA) trees, and 32.1% more than turfgrass grown with honeylocust (HL) trees (Figure 3.1). Clipping dry weight responded similarly, with more clippings per m^2 produced in turfgrass only sub-plots compared to tree and turfgrass sub-plots (Figure 3.2). This growth reduction may be a result of root competition for water and nutrients or allelopathy between the two species. Whitcomb (1972) and Whitcomb and Roberts

(1973) reported that KBG was more sensitive to tree roots than red fescue, rough bluegrass, or perennial ryegrass, and KBG rooting was severely restricted by trees having shallow feeder roots. Allelopathic effects on KBG rooting when seeded around established honeylocust trees was hypothesized by Whitcomb and Roberts (1973). Since species sub-plot was significant only in the first study, additional investigations are warranted for this area.

In both studies clipping fresh weight decreased over time across irrigation treatments. In study 1 there were 4.5 times as many clippings collected (132 g m^{-2}) at the first sampling date versus the last sampling date (29 g m^{-2}) (Figure 3.3). In the second study a similar trend was evident, with 4.3 times as many clippings at the first sampling (86 g m^{-2}) versus the last sampling (20 g m^{-2}) (Figure 3.4). Clipping dry weights per m^2 decreased 400% between June 16 (41 g m^{-2}) and July 14 (10 g m^{-2}) in study 1 (Figure 3.5). In study 2 a 350% reduction in clipping dry weight per m^2 occurred between August 3 (26 g m^{-2}) and August 24 (7 g m^{-2}) (Figure 3.6). These reductions in clipping may be related to temperatures above what is optimal for KBG growth. Optimal shoot growth for cool-season turfgrass species occurs between 15 to 24C (Beard, 1973; Turgeon 1991).

Between treatment initiation (1 DAT) and the first sampling date (16 DAT) three days had maximum temperatures above this range (Study 1), however, between the first sampling date and the study termination date (53 DAT) the maximum daily temperature was above this range all but four days. The period between the two studies was characterized by cooler temperatures, and 103.5 mm of precipitation which allowed the KBG to recover. As with the first study, during study 2, on only three days were the maximum daily temperature in the optimal growth range for KBG, all other days maximum daily temperatures were above this range.

Clipping production (fresh weight) of KBG increased linearly in study 1 as irrigation levels increased (Figure 3.7). KBG irrigated at 160% ET (76 g m^{-2}) produced 23% more clippings than turfgrass irrigated at 80% ET (62 g m^{-2}). Turfgrass irrigated at 40% ET (48 g m^{-2}) produced 30.4% fewer clippings than KBG irrigated at 80% ET. A quadratic increase in KBG clipping production in response to increased irrigation amounts occurred in study 2 (Figure 3.8). KBG irrigated at 40% ET (31 g m^{-2}) produced 47% less clippings than turfgrass irrigated at 80% ET (46 g m^{-2}), while turfgrass irrigated at 160% ET (71 g m^{-2}) produced 55% more clippings than KBG irrigated at 80% ET. Similar changes in clipping dry wight per m^2 were observed with dry weight measurements in both studies (Figure 3.9, Figure 3.10). As reported by others, turfgrass growth declines in response to reduce water availability (Bittman and Simpson, 1987; Ervin, 1995; Qain, 1999). Additional growth of KBG irrigated at 160% ET could present disposal problems for individuals and landscape maintenance companies that remove the clippings after mowing. Season long average clipping production was 35% greater for KBG irrigated at 160% ET (665 g m^{-2}) compared to turfgrass irrigated at 80% ET (492 g m^{-2}).

Leaf moisture percentage decreased linearly with decreasing irrigation levels for both studies (Table 3.2). In study 1, leaf moisture percentage remained relatively constant for all sampling dates for KBG irrigated at 80% and 160%, but was decreased significantly for turfgrass irrigated at 40% ET at all sampling dates except June 16, 16 DAT (Figure 3.11). In study 2, leaf moisture percentage decreased slightly for KBG in the 80% and

160% ET irrigation treatments, while a larger decrease was observed for KBG irrigated at 40% ET (Figure 3.12).

Turf maintained at 40% ET began to exhibit visible water stress symptoms approximately four weeks into the first study. The turfgrass began to wilt and turn off color at this time, symptoms progressed until the turf was brown about six weeks into the study. A similar trend was observed during study 2 with symptoms of water stress becoming evident two weeks after treatment initiation, and dormant turf four weeks after treatment initiation (Figure 3.13 and Figure 3.14). Both 80% ET and 160% ET treatments maintained aesthetically pleasing turf for the duration of both studies. In subsequent years, additional quality ratings similar to those described by Keeley (1996), should be conducted to determine if differences in turf quality and leaf-firing are evident between the sub-plots. Turfgrass maintained under 80% ET did not grow as rapidly and could have been mowed less frequently than the seven day cycle used. Turfgrass irrigated at 160% ET maintained relatively rapid growth throughout both study periods and would have benefitted from more frequent cuttings to reduce clipping buildup.

Soil moisture Due to a problem with the neutron probe, not enough sample dates were collected to permit analysis of the data for study 1, the problem was corrected prior to the start of study 2, so only results from that study are presented (Table 3.3). Analysis of variance indicated a Date x Irrigation interaction ($P = 0.0108$) for the 15 cm sampling depth (Figure 3.15). Volumetric soil moisture (VSM) remained relatively constant for both 80% ET and 160% ET irrigation regimes, while VSM in the 40% ET irrigation regime declined throughout the study. At all other sampling depths only the main effect of irrigation level was significant (Table 3.3). VSM decreased quadratically at 60, 90, 120, and 150 cm sampling depths (Figure 3.16).

Summary

These results indicate that Kentucky bluegrass growth is directly related to the amount of water applied during the growing season. Increased volumes of water increased the growth of bluegrass across the growing season, which increased the frequency of mowing. Trees in the landscape, even if relatively small, may decrease turfgrass growth compared to turfgrass only areas. The cause of this decrease could be due to root competition between the trees and the turfgrass or it may be an allelopathic response between the root systems of the plants. Additional research is needed in this area prior to making a conclusion. Landscape managers may be able to reduce the number of site visits by reducing irrigation volumes and still maintain aesthetically pleasing turf. For landscapes that require clipping removal this may be one way to manage the quantity of material that needs to be disposed off site.

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Table 3.1. Analysis of variance on fresh weight and dry weight of 'Livingston' Kentucky bluegrass clippings during study 1 and 2 in 1998 [Z].

Source	Study 1 (June 1 - July 23) Fresh weight (g)	Study 1 (June 1 - July 23) Dry weight (g)	Study 2 (Aug. 3 - Sep. 3) Fresh weight (g)	Study 2 (Aug. 3 - Sep. 3) Dry weight (g)
Species (S)	*** [Y]	***	NS	NS
Date (D)	***	***	***	***
Irrigation (I)	***	***	***	***
S x I	NS	NS	NS	NS
S x D	NS	NS	NS	NS
D x I	NS	NS	NS	NS
S x D x I	NS	NS	NS	NS
Irrigation rate	L*** [X]	L***	Q**	Q*

[Z] Clippings collected weekly from 1.5 m square plots, three samples per sub-plot for a total of nine samples per sub-plot per treatment per week.

[Y] NS, ***: non significant or significant at the 0.001 level, respectively.

[X] L, Q: linear or quadratic response, respectively, at the 0.05 (*), 0.01 (**), or 0.001 (***) level in regression analysis.

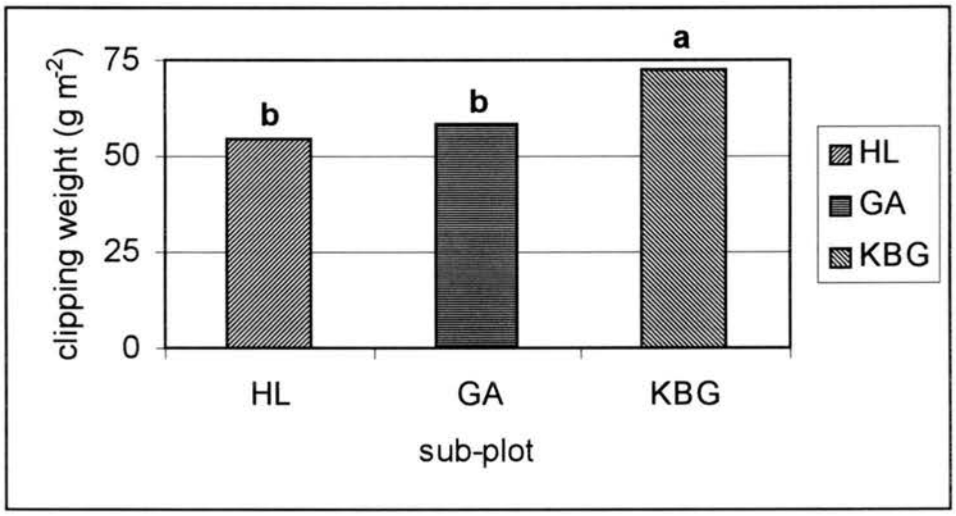

Figure 3.1. Fresh weight of 'Livingston' Kentucky bluegrass clippings as affected by species sub-plot in Study 1 (June 1 thru July 23, 1998). Clippings were collected from 1.5 m square plots, with three samples per sub-plot per whole plot. Sub-plot labels are (HL) 'Skyline' honeylocust, (GA) 'Patmore' green ash, and (KBG) 'Livingston' Kentucky bluegrass. Means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

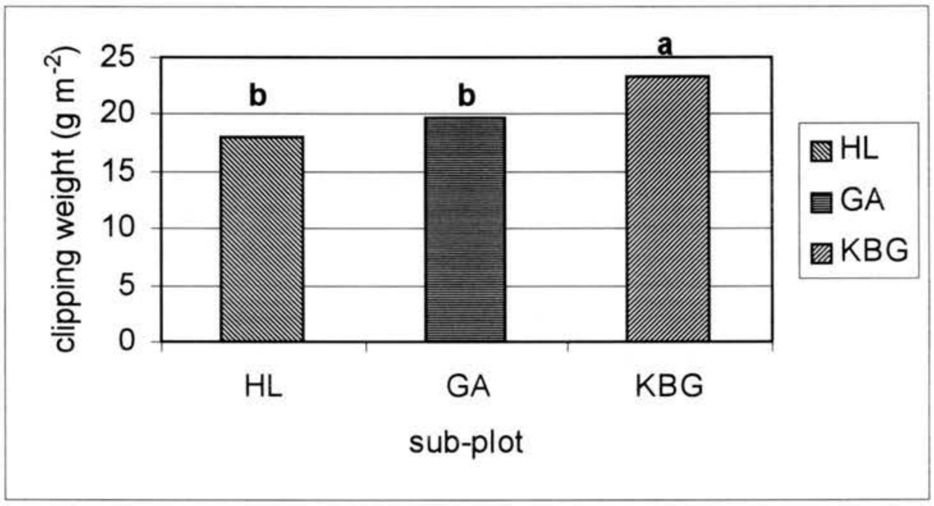

Figure 3.2. Dry weight of 'Livingston' Kentucky bluegrass clippings as affected by species sub-plot in Study 1 (June 1 thru July 23, 1998). Clippings were collected from 1.5 m square plots, with three samples per sub-plot per whole plot. Sub-plot labels are (HL) 'Skyline' honeylocust, (GA) 'Patmore' green ash, and (KBG) 'Livingston' Kentucky bluegrass. Means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

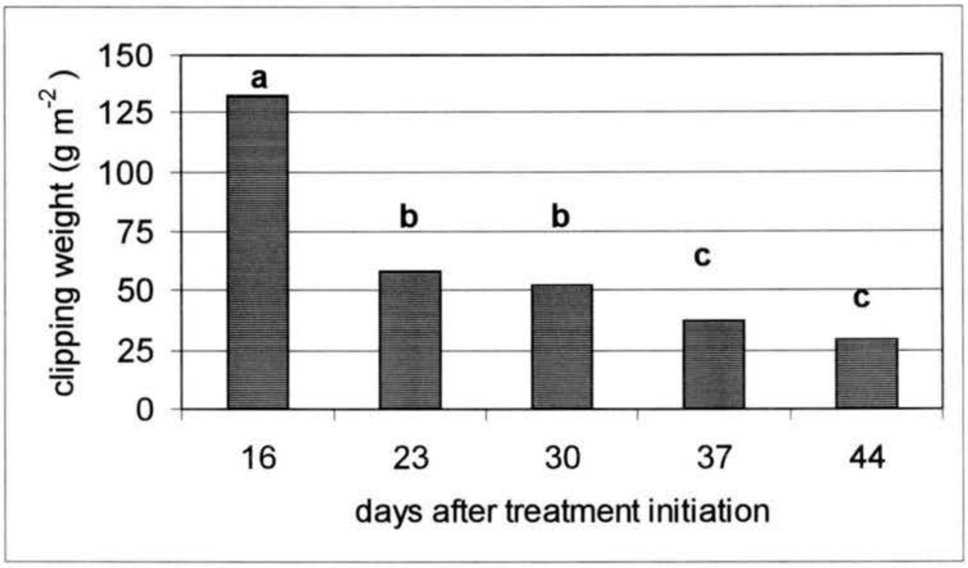

Figure 3.3. Changes in 'Livingston' Kentucky bluegrass fresh clipping weight during Study 1 (June 1 thru July 23, 1998). Samples were collected on June 16, (16 days after treatment initiation DAT), June 23, (23 DAT), June 30 (30 DAT), July 7 (37 DAT), and July 14 (44 DAT). Means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

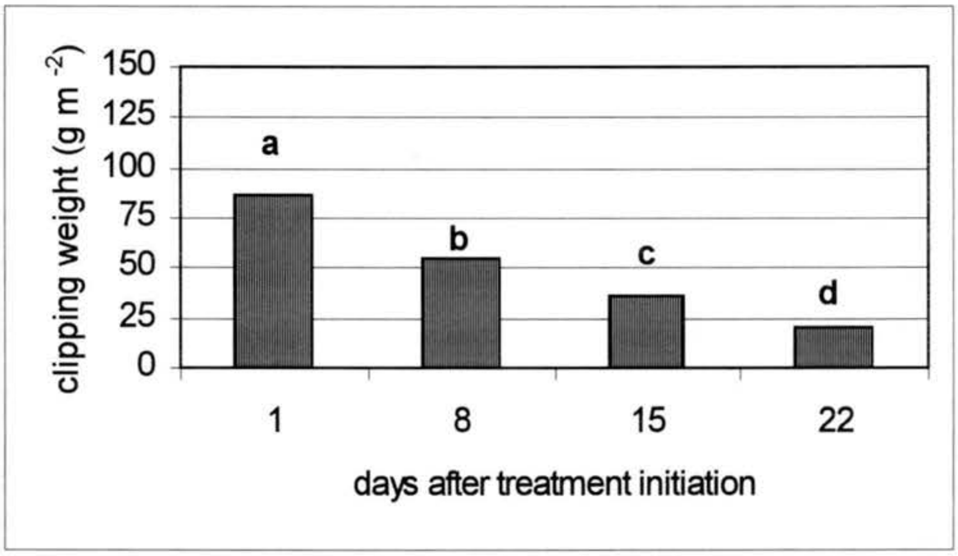

Figure 3.4. Changes in 'Livingston' Kentucky bluegrass fresh clipping weight during Study 2 (August 3 thru September 3, 1998). Samples were collected on August 3, (1 day after treatment initiation DAT), August 10, (8 DAT), August 17 (15 DAT), and August 24 (22 DAT). Means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

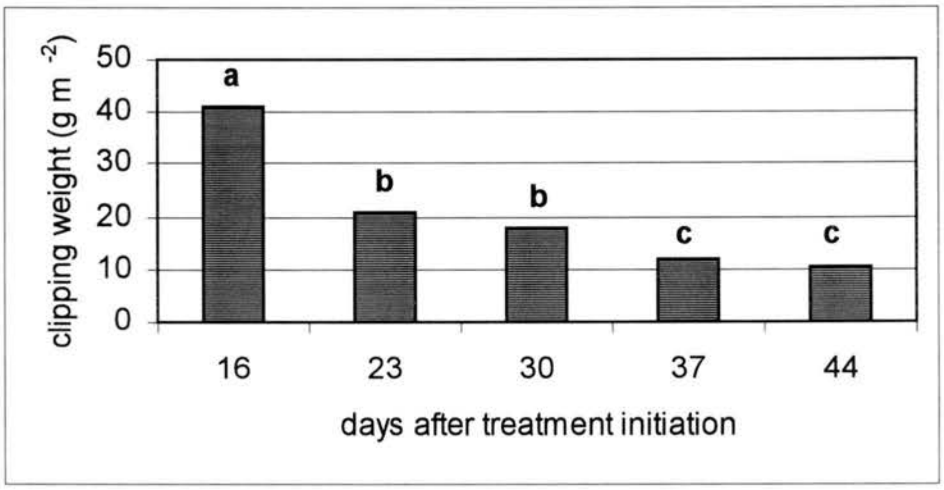

Figure 3.5. Changes in 'Livingston' Kentucky bluegrass dry clipping weight during Study 1 (June 1 thru July 23, 1998). Samples were collected on June 16, (16 days after treatment initiation DAT), June 23, (23 DAT), June 30 (30 DAT), July 7 (37 DAT), and July 14 (44 DAT). Means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

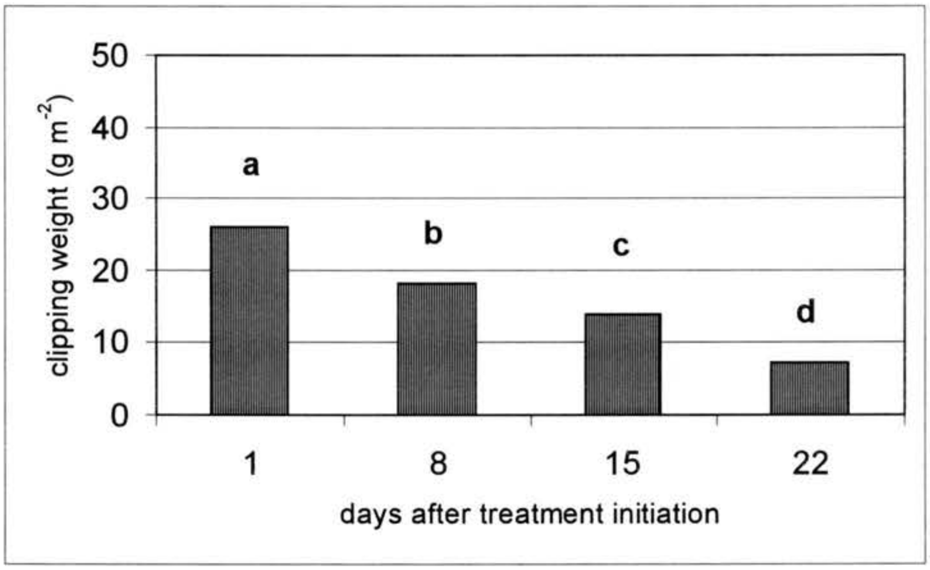

Figure 3.6. Changes in 'Livingston' Kentucky bluegrass dry clipping weight during Study 2 (August 3 thru September 3, 1998). Samples were collected on August 3, (1 day after treatment initiation DAT), August 10, (8 DAT), August 17 (15 DAT), and August 24 (22 DAT). Means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

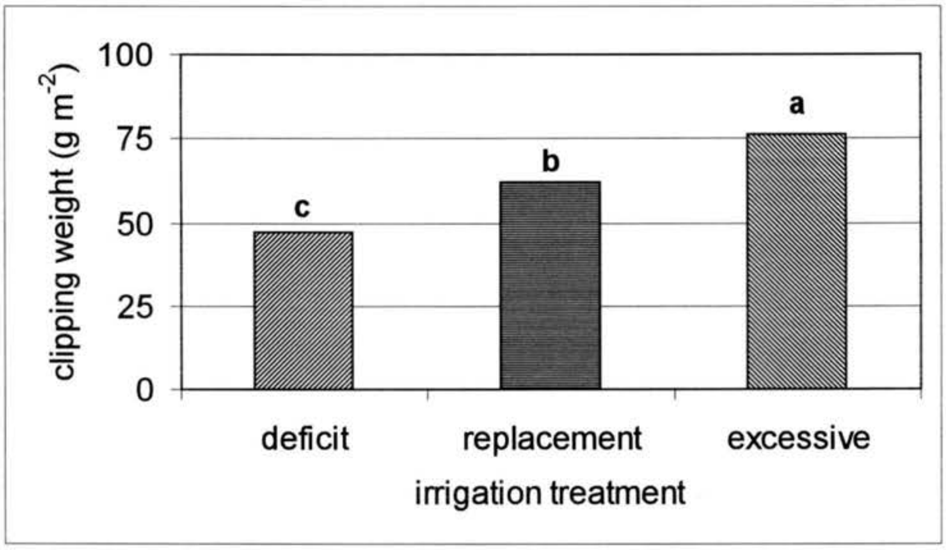

Figure 3.7. Changes in 'Livingston' Kentucky bluegrass fresh clipping weight during Study 1 (June 1 thru July 23, 1998) due to irrigation regime. Irrigation regimes were deficit (40% ET), replacement (80% ET), and excessive (160% ET). Average amount of irrigation applied weekly was 19.8 mm (40% ET), 39.7 mm (80% ET), and 79.2 mm (160% ET). Means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

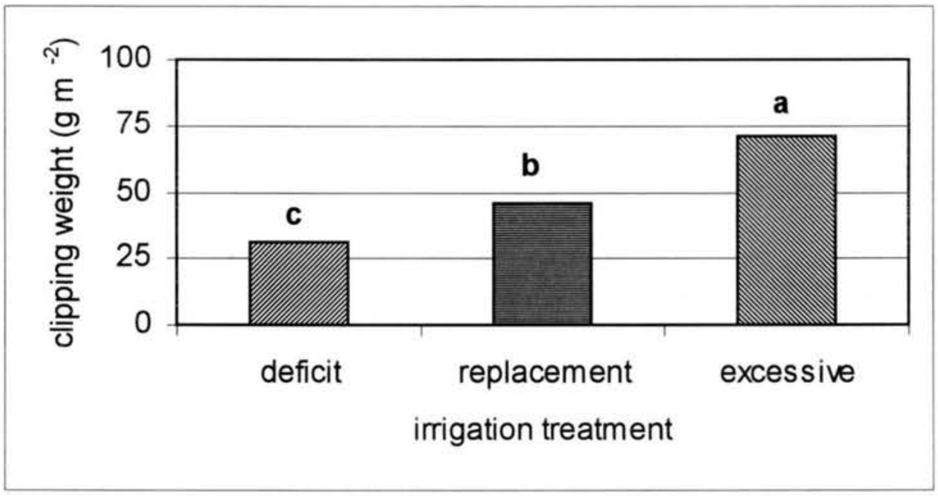

Figure 3.8. Changes in 'Livingston' Kentucky bluegrass fresh clipping weight during Study 2 (Aug. 3 thru Sep. 3, 1998) due to irrigation regime. Irrigation regimes were deficit (40% ET), replacement (80% ET), and excessive (160% ET). Average amount of irrigation applied weekly was 14.6 mm (40% ET), 30.3 mm (80% ET), and 77.5 mm (160% ET). Means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

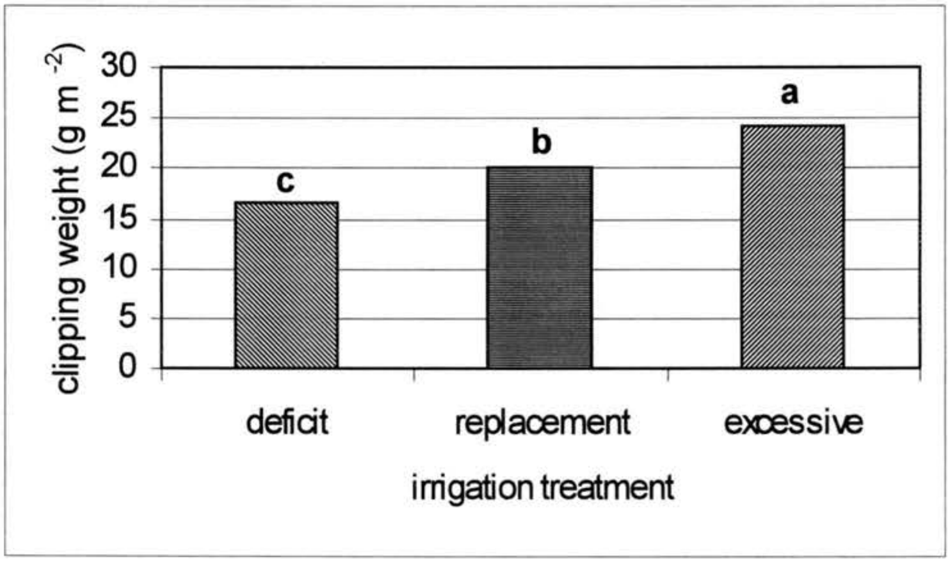

Figure 3.9. Changes in 'Livingston' Kentucky bluegrass dry clipping weight during Study 1 (June 1 thru July 23, 1998) due to irrigation regime. Irrigation regimes were deficit (40% ET), replacement (80% ET), and excessive (160% ET). Average amount of irrigation applied weekly was 19.8 mm (40% ET), 39.7 mm (80% ET), and 79.2 mm (160% ET). Means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

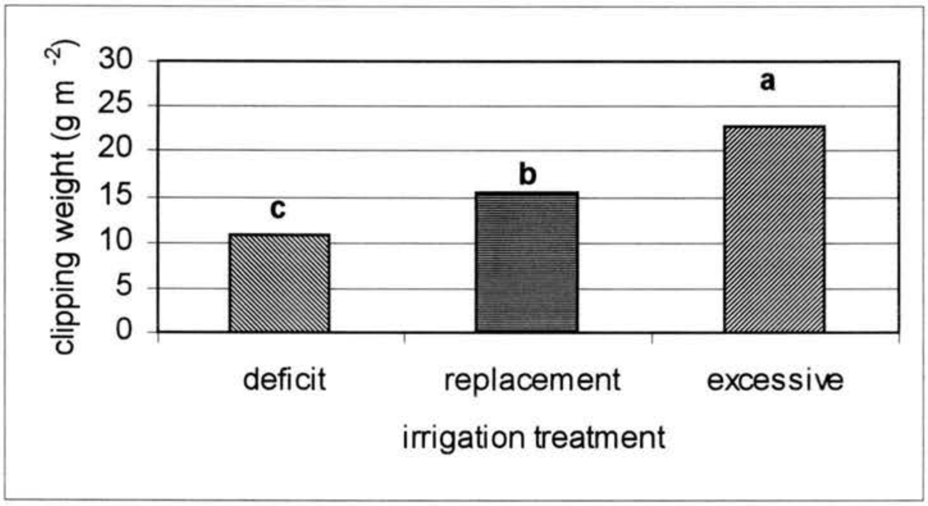

Figure 3.10. Changes in 'Livingston' Kentucky bluegrass dry clipping weight during Study 2 (Aug. 3 thru Sep. 3, 1998) due to irrigation regime. Irrigation regimes were deficit (40% ET), replacement (80% ET), and excessive (160% ET). Average amount of irrigation applied weekly was 14.6 mm (40% ET), 30.3 mm (80% ET), and 77.5 mm (160% ET). Means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

Table 3.2. Analysis of variance on moisture percentage 'Livingston' Kentucky bluegrass clippings during study 1 and 2 in 1998 [Z].

	Study 1	Study 2
	(June 1 - July 23)	(Aug. 3 - Sep. 3)
Source	Moisture percentage [Y]	Moisture percentage
Species (S)	NS [X]	NS
Date (D)	***	***
Irrigation (I)	***	***
S x I	NS	NS
S x D	NS	NS
D x I	***	*
S x D x I	NS	NS
Irrigation rate	L*** [W]	L***

[Z] Clippings collected weekly from 1.5 m square plots, three samples per sub-plot for a total of nine samples per sub-plot per treatment per week.

[Y] Moisture percentage calculated by the formula (fresh wt. - dry wt.)/(fresh wt.).

[X] NS, *, **, ***: non significant or significant at the 0.05, 0.01, or 0.001 level, respectively.

[W] L: linear response 0.001 (***) level in regression analysis.

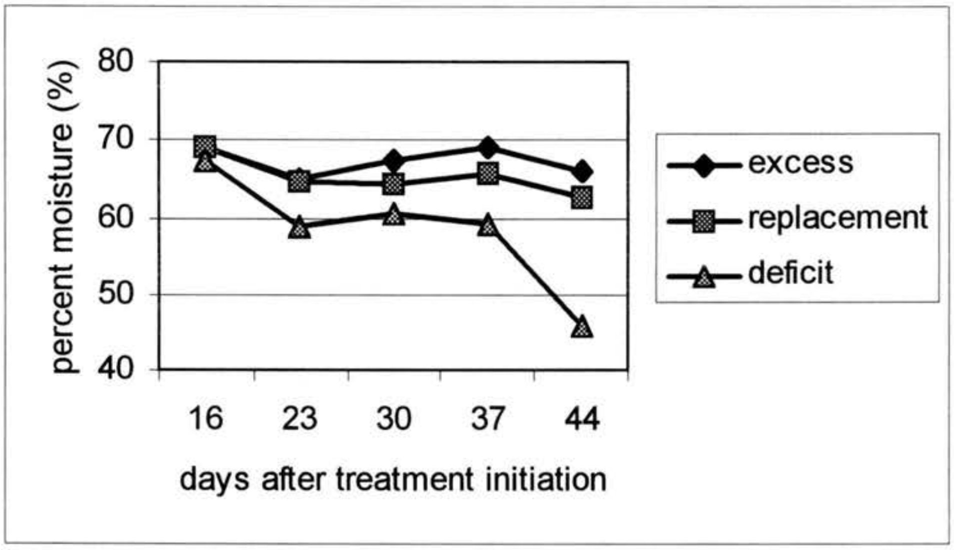

Figure 3.11. Interaction between Irrigation treatment and Sampling date significant (P=0.001) for 'Livingston' Kentucky bluegrass clippings in Study 1 (June 1 thru July 23, 1998). Irrigation regimes were deficit (40% ET), replacement (80% ET), and excessive (160% ET). Samples were collected on June 16, (16 days after treatment initiation DAT), June 23, (23 DAT), June 30 (30 DAT), July 7 (37 DAT), and July 14 (44 DAT).

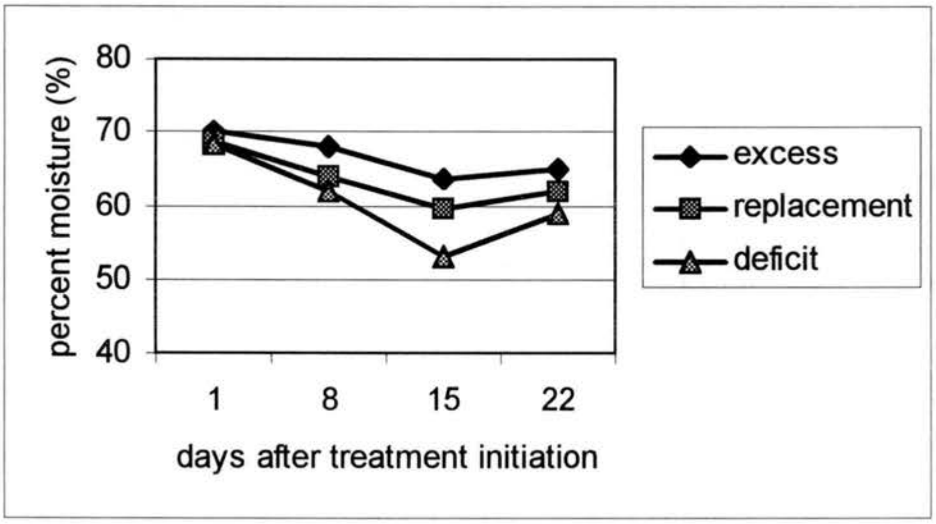

Figure 3.12. Interaction between Irrigation treatment and Sampling date significant (P=0.001) for 'Livingston' Kentucky bluegrass clippings in Study 2 (Aug. 3 thru Sep. 3, 1998). Irrigation regimes were deficit (40% ET), replacement (80% ET), and excessive (160% ET). Samples were collected on August 3, (1 day after treatment initiation DAT), August 10, (8 DAT), August 17 (15 DAT), and August 24 (22 DAT).

Figure 3.13. Aerial view of research site at the Agricultural Research Development and Education Center (ARDEC) from south (left) to north (right). Picture taken August 27, 1998, 24 days after irrigation treatments initiated.

Figure 3.14. Visual symptoms on August 26, 1998 of water stress on 'Livingston' Kentucky bluegrass 23 days after irrigation treatments were initiated in Study 2. Turfgrass in the foreground was irrigated at 80% ET, the center was irrigated at 40% ET, and the background was irrigated at 160% ET.

Table 3.3. Analysis of variance on volumetric soil moisture measured with a Troxler model 4302 neutron probe during study 2 in 1998 [Z].

	Study 2 (Aug. 3 - Sep. 3)				
Source	D1 [Y]	D2	D3	D4	D5
Species (S)	NS [X]	NS	NS	NS	NS
Date (D)	*	NS	NS	NS	NS
Irrigation (I)	***	***	***	***	***
S x I	NS	NS	NS	NS	NS
S x D	NS	NS	NS	NS	NS
D x I	*	NS	NS	NS	NS
S x D x I	NS	NS	NS	NS	NS
Irrigation rate	L*** [W]	Q**	Q***	Q*	Q*

[Z] Volumetric soil moisture (VSM) readings collected weekly from three access tubes per sub-plot, for a total of nine tubes per sub-plot per treatment per week.

[Y] VMS sample depths D1 (30 cm), D2 (60 cm), D3 (90 cm), D4 (120 cm), D5 (150 cm) below soil surface.

[X] NS, *, **, ***: non significant or significant at the 0.05, 0.01, or 0.001 level, respectively.

[W] L, Q: linear or quadratic response at 0.5 (*), 0.01 (**), or 0.001 (***) level in regression analysis.

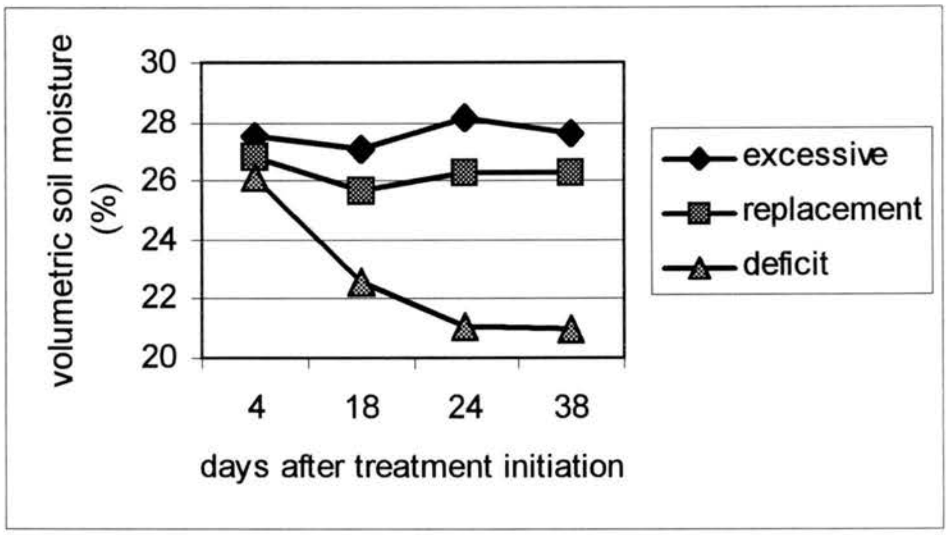

Figure 3.15. Interaction between Sample date and Irrigation treatment was significant for volumetric soil moisture at the 30 cm sampling depth (P=0.0108) in Study 2 (Aug. 3 thru Sep. 3). Volumetric soil moisture as measured using a Troxler model 4302 neutron probe at four sampling dates, August 7 (4 days after treatment initiation DAT), August 21 (18 DAT), August 28 (24 DAT), and September 9 (38 DAT). Irrigation regimes were deficit (40% ET), replacement (80% ET), and excessive (160% ET).

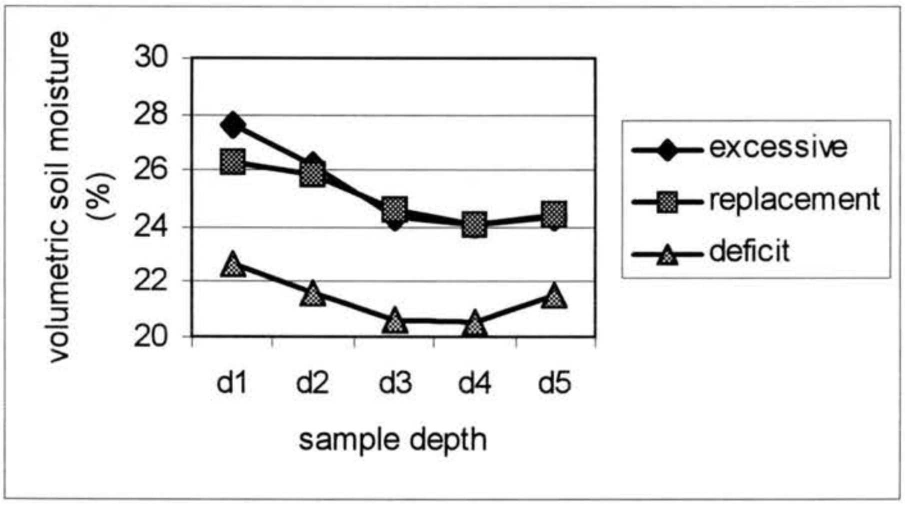

Figure 3.16. Volumetric soil moisture as measured using a Troxler model 4302 neutron probe at five sampling depths, 30 cm (D1), 60 cm (D2), 90 cm (D3), 120 cm (D4), and 150 cm (D5). Irrigation regimes were deficit (40% ET), replacement (80% ET), and excessive (160% ET).

CHAPTER 4.

IMPACT OF IRRIGATION REGIME ON SHADE TREES IN A LANDSCAPE SETTING

Introduction

Throughout the United States the demand for clean water is increasing as population growth continues. In arid regions of the country water management is becoming more important since only a limited amount of water is available for agricultural, industrial, and urban consumption. Large quantities of water are required for most traditional landscapes to remain green during periods when rainfall is not enough to meet plant demands. During times of drought, many municipalities place restrictions on landscape irrigation (Flack, 1982; Rodiek, 1984), resulting in plant injury and unattractive landscapes (Lohr and Bummer, 1992).

Water stress can impact plants in a variety of ways including visual quality, growth rate, and evapotranspiration (ET) rate (Kramer, 1983). Short term water deficits can reduce cell growth (Fitter and Hay, 1987), decrease leaf surface area (Borghetti et al., 1989; Hennessey et al., 1985), alter dry matter production and partitioning (Graves and Wilkins, 1991; Joly et al., 1989), alter osmotic and leaf water potential (Close et al., 1996; Ranney et al., 1991; Zwack et al., 1998), and reduce growth rates (Kramer, 1983).

Long term drought conditions, i.e. moisture stress lasting more than one growing season, can cause tree growth reductions, dieback, and general decline (Kramer, 1987). Drought stress may also predispose trees to insect or disease outbreaks, or interact with some pathogens thereby increasing these effects on trees (Butler, 1994; Ree, 1994; Smitley and Peterson, 1996; Vannini and Valentini, 1994).

Trees in urban landscapes face environmental challenges other than drought. Typically, homeowners or landscape managers do not accurately measure the amount of water being applied by a sprinkler system, and this can lead to excessive irrigation. Excessive irrigation is wasteful since extra water either runs off the soil surface or percolates beyond the tree root zone, thus becoming unavailable. Furthermore, extended periods of excessive soil moisture can cause reduced water uptake due to root death, causing increased leaf water deficits (Whitehead and Jarvis, 1981). Chlorosis, wilting, epinasty, leaf senescence, stem hypertrophy, and stunted leaf development have been reported as other plant responses to excessive soil moisture (Kawase, 1981; Kozlowski, 1985). The objective of this experiment was to determine both the short- and long-term effects of irrigation regime in a simulated urban landscape on tree growth and development.

Materials and Methods

In June 1998 a field study was initiated to examine the impact irrigation regime has on tree growth. Two studies were conducted during 1998; the first was conducted from 9 June 1998 to 20 July 1998, and the second from 3 Aug. 1998 to 17 Sept 1998. Each of these consisted of three irrigation regimes based on evapotranspiration (ET). During the time between the two study periods, 103.5 mm of precipitation was recorded at the research site, causing a reversal in soil moisture levels in the upper 90 cm of the soil profile. The irrigation treatments were excessive (160% ET), replacement (80% ET), and deficit (40% ET) based on the requirements of cool-season turfgrass compared to the reference crop alfalfa. ET was calculated with data obtained from a Colorado Agricultural Meteorological (COAGMET) weather station located 0.8 km south of the research site. The modified Penman equation, described by Buchleiter et al.(1988), was used to calculate daily ET requirements. Irrigation treatments were applied twice per week between 2000h and 0600h (8:00 pm and 6:00 am) to minimize the effects of wind on water distribution, and were corrected for any rainfall occurring since the last irrigation.

Experiments were based on a split-plot statistical design using a randomized complete block (RCB) with three replications. Each whole plot measured 32.9 m x 43.9 m divided into three sub-plots containing either trees and turfgrass, or turfgrass only. Tree and turfgrass sub-plots contained 27 honeylocust, *Gleditsia tricanthos inermis* L. 'Skyline' (HL) or green ash, *Fraxinus pennsylvanica* Marshall 'Patmore' (GA) trees spaced 4.9 m within rows and 3.7 m between rows. A mulch ring of aged bark 1 m in diameter was placed around each tree to reduce grass encroachment to tree bases. *Poa pratensis* L. (KBG) was established as the turfgrass between tree rows and as a turfgrass only sub-plot. In May and June 1998, diammonium phosphate (18N-20.1P-0K) fertilizer was applied at 45 kg ha^{-1} of N across all plots. The KBG was mowed weekly to a height of 7.6 cm and clippings were not collected during maintenance mowing.

Data collection included height, caliper, leaf sampling to determine area, fresh weight, and dry weight, predawn leaf water potential, fall color development, and cold hardiness development of the stems. Tree height was measured to the nearest cm, tree caliper was measured to the nearest mm at 15 cm above soil line per American Association of Nurserymen standards (Anonymous, 1997). All 27 trees of each species within a plot were used for height, and caliper.

Leaf sampling consisted of collecting ten leaves per tree from five trees of each species within a plot, thus provided a total of 30 leaves per treatment per species per week. Sampling occurred weekly beginning 18 May until maximum leaf expansion had occurred, bi-weekly leaf sampling was conducted after this. After collection, leaf area was determined using a leaf area meter (Model LI-2000, LI-Cor Inc., Lincoln, Nebraska), and samples were weighed to nearest 0.01 g using an Ohaus model GT 4100 electronic balance (Ohaus Corp., Florham Park, NJ) and placed in a 70C drying oven for 72 h. After drying, samples were reweighed and moisture percentage was calculated by the formula (fresh wt. - dry weight)/(fresh wt.). Predawn leaf water potential measurements were determined bi-weekly on seven trees per species per block using the pressure chamber technique with a PMS Model 600 pressure bomb (PMS Instrument Co., Corvallis, OR) (Waring and Cleary, 1967). Foliar fall color was evaluated weekly beginning 7 September using a scale of 1 to 10, with 1 indicating less to 10% of the leaves exhibited fall color, and 10 indicating 100% of the leaves exhibited fall color.

Cold hardiness evaluations were conducted over two seasons, one, 1997-1998 without irrigation treatments to establish a cold hardiness baseline, and a second, 1998-

1999 to investigate what effect irrigation treatments have on tree cold hardiness. Differential thermal analysis (DTA) was performed using 2 cm long internodal stem sections in which the bark and xylem were intact. Samples were collected between October 1997 and March 1998 during the first study, and October 1998 and February 1999 for the second season. Twigs of current seasons growth were collected and placed in sealed polyethylene bags with moist tissue. Samples were then stored at 5C until freezing tests with no storage duration of more than one week. The method used was adopted from Quamme et al. (1972). The differential temperature between the sample and a dried reference sample cooled in an aluminum block at a rate of 5C/h was recorded by 36-gauge type T, copper-constantan thermocouples placed in contact with the sample and wrapped with a narrow band of Parafilm. Millivolt signals were logged every second during freezing with an Omega high-resolution interface card. DTAs were determined on seven samples for each species per plot for a total of 21 samples per species per irrigation treatment.

Data analysis. Plots were arranged in a completely randomized block with a split-plot factor. There were three treatments with three replications each. Data for fresh and dry clipping weight and moisture percentage were analyzed over all dates in a study using Statistical Analysis System's repeated measures analysis PROC GLM (SAS Institute, 1989). Percentage data were first arcsin transformed to satisfy normality assumptions. When a significant F statistic occurred, means were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

Results and Discussion

Irrigation treatments Weekly irrigation applications in study 1 averaged 19.8 mm for 40% ET treatment, 39.6 mm for 80% ET treatment, and 79.2 mm for 160% ET treatments. In study 2, weekly irrigation treatments averaged 14.6 mm, 34.1 mm, and 77.5 mm for the 40% ET, 80% ET, and 160% ET treatments, respectively.

Leaf weight and area Leaf weight and leaf area were not affected by irrigation regime during these studies (Table 4.1). This was probably caused by irrigation treatments not initiated until 1 June while budbreak for both species occurred 29 April. Maximum leaf area was attained 2 June, while maximum leaf fresh weight was observed 16 June for both species. No differences in leaf moisture percentage were determined due to irrigation treatment. Changes in leaf area due to water stress may require stress initiation to occur during leaf expansion (Boyer, 1968, 1970) instead of after, or may require multiple seasons of water stress to develop (Bussotti et al., 1995; Callaway and Mahall, 1996).

Tree height and caliper Irrigation treatments had no significant effect on height or caliper for GA (Table 4.2) or HL (Table 4.3) trees after one season. Trees irrigated at 160% ET had greater increases in both height and caliper than trees irrigated at the other two rates however those changes were not significant. After additional seasons of irrigation treatment application significant differences in both height and caliper may occur.

Water potential In both studies, reduced irrigation caused a decrease in predawn leaf water potential (ψ_l). The Date x Irrigation interaction was significant for both green ash (GA) and honeylocust (HL) for both studies (Table 4.4). At all three sampling dates during study 1, ψ_l of GA trees irrigated at 80% ET and 160% ET were similar (Figure 4.1). Water stress increased with increasing treatment duration for trees irrigated at 40% ET. Initially, on 11 June all trees had similar ψ_l measurements. Two weeks later GA trees in 40% ET treatment had ψ_l measurements 21% lower than trees in the other two treatments. By the 9 July sampling date, ψ_l of GA trees in the 40% ET treatment were 41% to 77% lower than GA trees irrigated at either 80% ET, or 160% ET.

A similar pattern in predawn ψ_l developed during study 2 with water stress increasing as treatment duration increased for trees irrigated at 40% ET (Figure 4.2). Initially, on 6 August, GA trees in 40% ET treatment had ψ_l measurements 14% lower than trees in the other two treatments. By the 3 September sampling date, ψ_l of GA trees in the 40% ET treatment were 37% to 43% lower than GA trees irrigated at either 80% ET, or 160% ET. A final ψ_l measurement was conducted on 17 September, however due to the initiation of leaf senescence, no differences in ψ_l due to irrigation treatment were detected.

Honeylocust trees (HL) demonstrated similar changes in ψ_l measurements as GA trees in both studies. Throughout study 1 ψ_l remained similar for trees irrigated at either 80% ET or 160% ET (Figure 4.3). A decrease in ψ_l occurred as treatment duration increased for HL trees irrigated at 40% ET. Initially ψ_l for all treatments was similar, by the 2 July and 16 July sampling dates trees irrigated at 40% ET had 25% and 52%, respectively, lower ψ_l than trees irrigated at 160% ET. In study 2, HL ψ_l measurements were 17% greater on 13 August and 43% greater on 27 August for the 40% ET trees compared to the 160% ET trees (Figure 4.4). By 10 September sampling, leaf senescence had begun and no differences in ψ_l measurements were observed among the irrigation treatments.

With both tree species, those trees irrigated at 40% ET had lower ψ_l measurements than trees under 80% or 160% ET irrigation regimes. The similarity in water potential measurements between 80% ET and 160% ET indicate no significant soil flooding was occurring; however, as irrigation treatments continue over the next several years this may change.

Fall color No difference in fall color development was evident for HL, however significant differences in fall color initiation were evident for GA (Table 4.5). On 15 September, fall color was developing on GA trees under 40% ET irrigation. By 22 September, fall color was extensive for trees irrigated at 40% ET and was becoming evident for trees irrigated at 80% ET. At both of these sampling dates, very little evidence of fall color development was observed on trees irrigated at the highest rate. By the final fall color evaluation date, 29 September, GA trees in 40% ET treatment were more than 40% defoliated, while trees in both 80% and 160% ET still retained 90% or more leaves in normal yellow fall color for this *Fraxinus* cultivar.

It appeared that the timing of leaf senescence was normal for trees irrigated at either 40% or 80% ET, but those under the highest irrigation level were still active two weeks later. It was difficult to determine what the impact this extended growing season would have on initial cold hardiness measurements since night temperatures were not conducive to full acclimation until mid-October, after all trees had dropped their leaves.

Cold hardiness Initial cold hardiness measurements using DTA indicated both species achieved similar degrees of cold hardiness at each sampling date (Table 4.6). Maximum levels of cold hardiness occurred in January with low temperature exotherms detected at -42.2C for GA and -39.9C for HL, both species LTEs similar to the LTEs reported by George et al. (1974). LTEs for the stem sections were recorded as the killing temperatures (Figure 4.5).

No significant effects of irrigation regime on cold hardiness were detected using differential thermal analysis (DTA) for either species (Table 4.7). This may have been due to insufficient low temperatures to induce the second stage of acclimation prior to ending irrigation treatments. Changes in cold hardiness induced by reduced irrigation levels have been reported for a number of plants (Anisko and Lindstrom, 1995, 1996; Chen and Li, 1977; Yelenosky, 1979). Increases in cold hardiness due to irrigation are generally only a temporary change and plants will lose some of the cold hardening acquired from a drought stress after normal irrigation practices are resumed (Amundson et al., 1993; Parsons and Li, 1979).

Summary

This study demonstrates that season long water stress can decrease predawn leaf water potential of trees growing in urban landscape settings, although not to the point of premature leaf senescence. Excessive irrigation may allow a tree to grow later into the fall, setting up the chance for winter injury or damage caused by an early cold snap or snowfall. Presently no significant differences in height or caliper were detected due to irrigation regime, as these same treatments are applied in subsequent growing seasons differences may develop for both of these growth measurements. No significant changes occurred in cold hardiness acquisition due to irrigation regime, but both *Fraxinus* and *Gleditsia* are both fairly cold hardy and more than one growing season of reduced or excessive irrigation levels may be required to alter cold hardiness.

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Table 4.1. Irrigation treatment effects on fresh weight, dry weight, percent moisture, and leaf area of green ash and honeylocust [Z].

Sample Date	Green Ash				Honeylocust			
	Fresh weight (g)	Dry weight (g)	Percent moisture	Leaf area (cm^2)	Fresh weight (g)	Dry weight (g)	Percent moisture	Leaf area (cm^2)
May 18	5.89 a[Y]	1.51 e	73.6% a	227 c	2.13 d	0.56 f	73.3% a	110 c
May 25	14.64 a	3.93 d	73.1 a	685 b	4.65 c	1.42 e	69.4 b	236 b
June 1	18.83 a	5.95 c	68.3 b	841 a	5.37 b	1.67 d	68.8 b	297 a
June 15	20.25 a	6.71 b	66.7 c	855 a	5.50 ab	1.87 c	65.9 c	303 a
June 30	19.48 a	7.04 b	63.7 d	831 a	5.41 b	2.12 b	60.7 d	252 b
August 3	20.18 a	8.68 a	56.9 e	838 a	5.94 a	2.82 a	52.3 e	315 a
Significant Terms								
Date (D)	*** [X]	***	***	***	***	***	***	***
Irrigation (I)	ns	ns	ns	ns	ns	ns	ns	ns
D x I	ns	ns	ns	ns	ns	ns	ns	ns

[Z] Leaf samples collected from five trees per species per plot for a total of 15 trees samples per irrigation treatment.

[Y] Means within columns were separated by Student-Newman-Keuls' (SNK) test at $P < 0.05$.

[X] NS, ***: non significant or significant at the 0.001 level, respectively.

Table 4.2. Impact of season long irrigation treatments on the height and caliper of 'Patmore' green ash in 1998 [Z].

Irrigation Level	Height 1998 (m)	Height 1999 (m)	Change in height (cm)	Caliper 1998 (cm)	Caliper 1999 (cm)	Change in caliper (cm)
Deficit [Y]	2.90 a [X]	3.57 a	67 a	3.63 a	4.61 a	0.98 a
Replacement	2.95 a	3.70 a	75 a	3.69 a	4.78 a	1.09 a
Excessive	3.03 a	3.92 a	89 a	3.85 a	5.11 a	1.26 a

[Z] Irrigation treatments were applied from 1 June 1998 thru 30 September 1998. Means are of 81 trees per irrigation treatment.

[Y] Irrigation levels correspond to 40% ET (deficit), 80% ET (replacement), and 160% ET (excessive).

[X] Means within columns were separated by Student-Newman-Keuls' (SNK) test at $P<0.05$.

Table 4.3. Impact of season long irrigation treatments on the height and caliper of 'Skyline' honeylocust in 1998 [Z].

Irrigation Level	Height 1998 (m)	Height 1999 (m)	Change in height (cm)	Caliper 1998 (cm)	Caliper 1999 (cm)	Change in caliper (cm)
Deficit [Y]	3.87 a [X]	4.42 a	55 a	4.24 a	5.20 a	0.96 a
Replacement	3.87 a	4.43 a	56 a	4.18 a	5.14 a	0.96 a
Excessive	3.84 a	4.58 a	74 a	4.22 a	5.30 a	1.08 a

[Z] Irrigation treatments were applied from 1 June 1998 thru 30 September 1998. Means are of 81 trees per irrigation treatment.

[Y] Irrigation levels correspond to 40% ET (deficit), 80% ET (replacement), and 160% ET (excessive).

[X] Means within columns were separated by Student-Newman-Keuls' (SNK) test at $P<0.05$.

Table 4.4. Analysis of variance on predawn leaf water potential measurements of 'Patmore' green ash (GA) and 'Skyline' honeylocust (HL) during study 1 and study 2 in 1998 .

	Study 1 (June 1 - July 23)		Study 2 (Aug. 3 - Sep. 3)	
Source	GA	HL	GA	HL
Date (D)	** [Y]	**	***	***
Irrigation (I)	**	***	***	***
D x I	*	***	**	**
Irrigation rate	Q** [X]	Q***	Q***	Q***

[Z] Species sampled bi-weekly with one leaf from seven trees collected for a total of 21 measurements per irrigation treatment.

[Y] *, **, ***: significant at the 0.05, 0.01, or 0.001 level, respectively.

[X] Q: quadratic response at the 0.01 (**), or 0.001 (***) level in regression analysis.

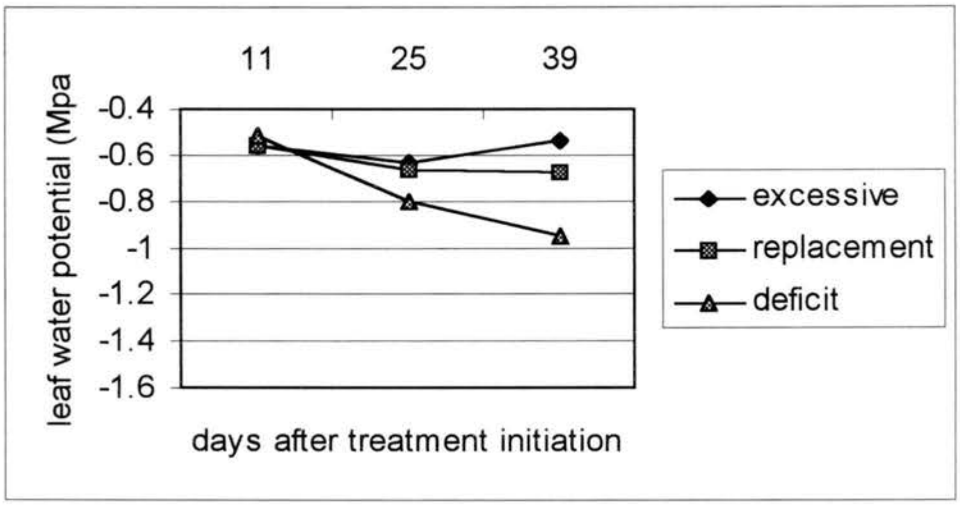

Figure 4.1. Predawn leaf water potential measurements of 'Patmore' green ash trees after the initiation of three irrigation treatments, 160% ET (excessive), 80% ET (replacement), and 40% ET (deficit), during Study 1, June 1 thru July 23, 1998. Each mean represents the average of twenty one samples per treatment. Sample dates were June 11, (11 days after treatment initiation DAT), June 25, (25 DAT), and July 9, (39 DAT).

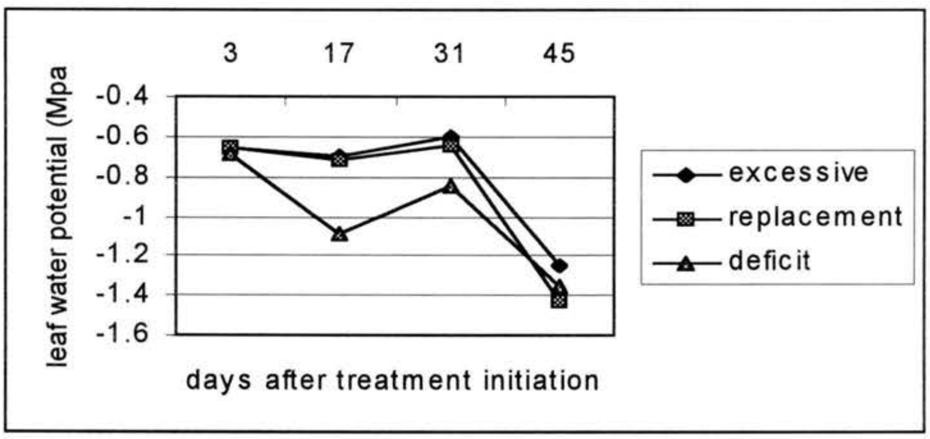

Figure 4.2. Predawn leaf water potential measurements of 'Patmore' green ash trees after the initiation of three irrigation treatments, 160% ET (excessive), 80% ET (replacement), and 40% ET (deficit), during Study 2, August 3 thru September 17, 1998. Each mean represents the average of twenty one samples per treatment. Sample dates were August 6, (3 days after treatment initiation DAT), August 20, (17 DAT), September 3, (31 DAT), and September 17 (45 DAT).

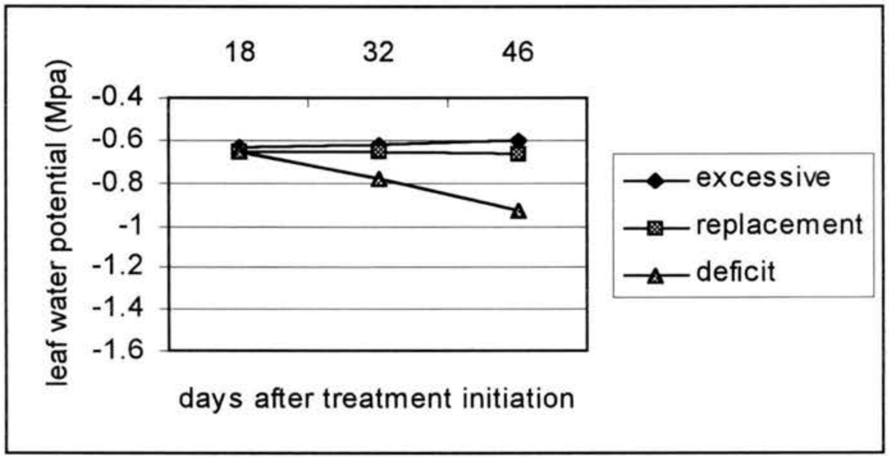

Figure 4.3. Predawn leaf water potential measurements of 'Skyline' honeylcust trees after the initiation of three irrigation treatments, 160% ET (excessive), 80% ET (replacement), and 40% ET (deficit), during Study 1, June 1 thru July 23, 1998. Each mean represents the average of twenty one samples per treatment. Sample dates were June 18, (18 days after treatment initiation DAT), July 2, (32 DAT), and July 16, (46 DAT).

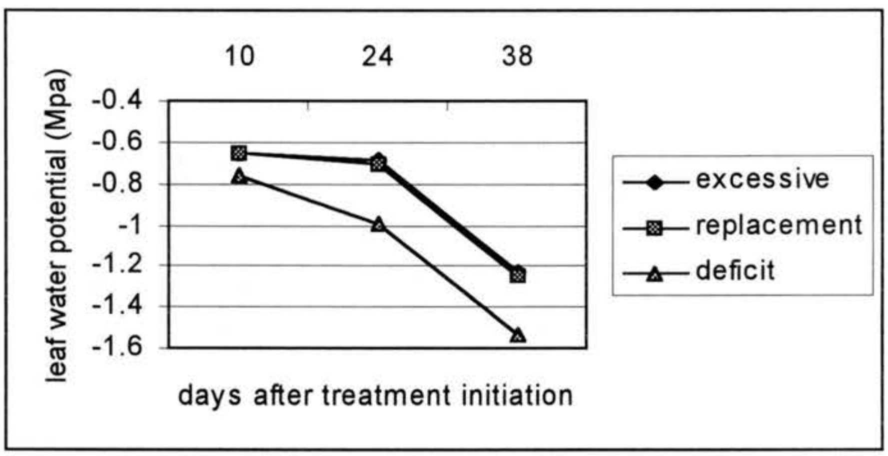

Figure 4.4. Predawn leaf water potential measurements of 'Skyline' honeylocust trees after the initiation of three irrigation treatments, 160% ET (excessive), 80% ET (replacement), and 40% ET (deficit), during Study 2, August 3 thru September 17, 1998. Each mean represents the average of twenty one samples per treatment. Sample dates were August 13, (10 days after treatment initiation DAT), August 27, (24 DAT), September 10, (38 DAT).

Table 4.5. Fall color development of green ash trees as influenced by irrigation regime throughout one growing season [Z].

Irrigation Treatment [Y]	Sample Date 9/15	9/22	9/29
Deficit	4.25a[X]	6.06a	10.0a
Replacement	2.43b	3.43b	9.57a
Excessive	1.41c	1.86c	9.32a

[Z] Treatment x Date interaction significant ($P \leq 0.01$).

[Y] Irrigation treatment corresponds with Deficit (40% ET), Replacement (80% ET), and Excessive (160% ET).

[X] Means within a column were separated by Student-Newman-Keuls' (SNK) test at, $P = 0.05$.

Table 4.6. Low temperature exotherms of 'Patmore' green ash and 'Skyline' honeylocust from October 1997 thru March 1998 as determined by differential thermal analysis (DTA). This evaluation was conducted to determine the dormancy profile of these tree species prior to irrigation treatment implementation [Z].

Sample Date	Green Ash (C)	Honeylocust (C)
October 15	-25.17 ± 0.3	-25.03 ± 0.2
November 15	-38.61 ± 0.8	-39.90 ± 0.4
January 15	-42.23 ± 0.7	-39.70 ± 0.9
February 19	-40.47 ± 0.2	-38.01 ± 0.5
February 26	-38.91 ± 0.4	-37.30 ± 0.3
March 5	-37.00 ± 0.6	-36.70 ± 0.5
March 12	-37.03 ± 0.9	-36.10 ± 0.7
March 19	-24.87 ± 0.7	-25.97 ± 1.3
March 26	-10.82 ± 1.2	-11.24 ± 0.9
Significant Terms		
Date	*** [Y]	***
Treatment	NS	NS
Date*Treatment	NS	NS

[Z] Data are the means of seven samples per species plus SE.

[Y] NS, ***: non significant or significant at the 0.001 level, respectively.

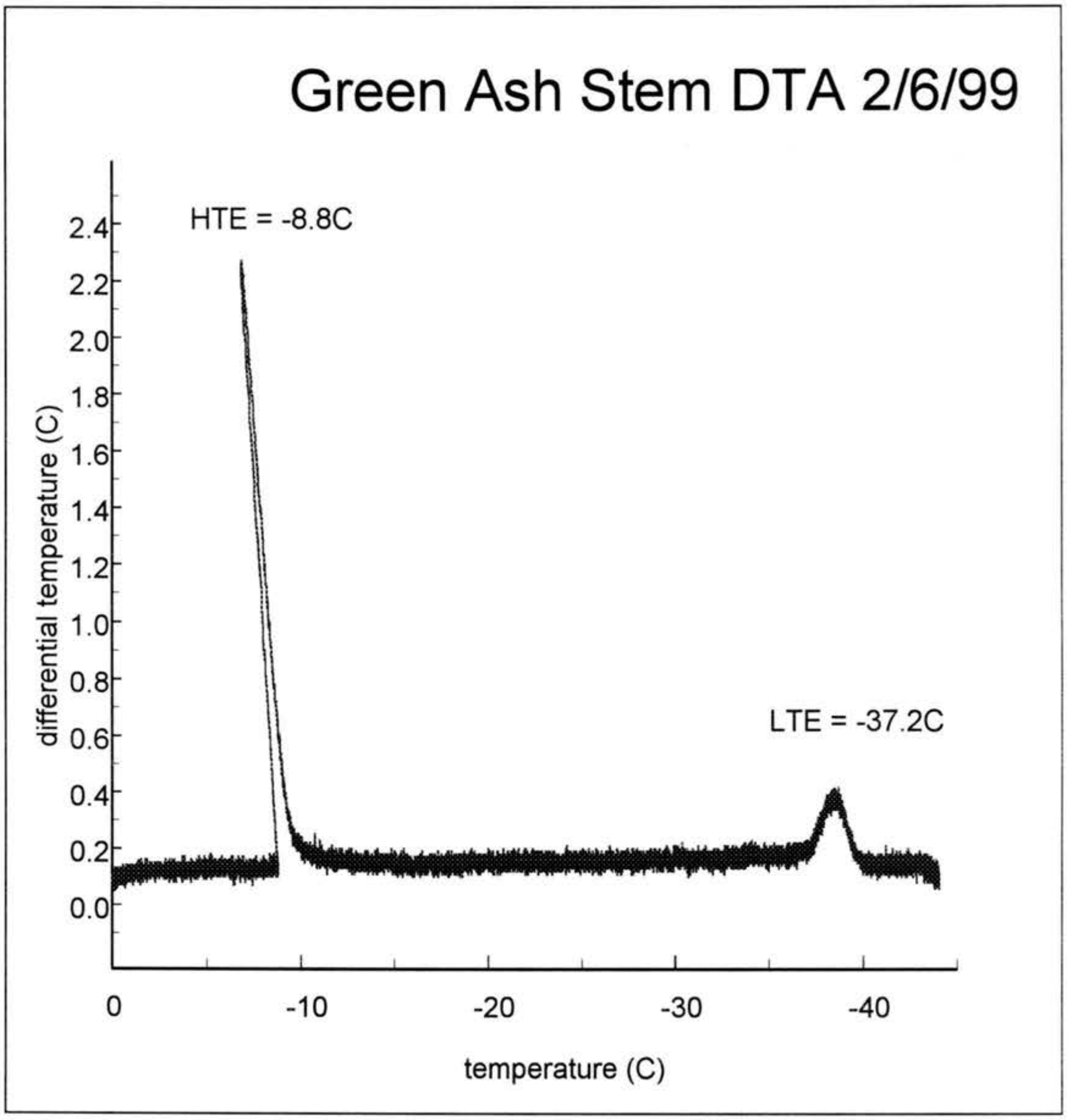

Figure 4.5. Differential thermal analysis profile of 2 cm green ash stem section collected on February 6, 1999. The peak occurring at the warmer temperature is the high temperature exotherm, or HTE which represents a freezing event at the extracellular level (no injury to cold tolerant plants). The peak occurring at the lower temperature is the low temperature exotherm, or LTE which represents freezing at the intracellular level (lethal temperature).

Table 4.7. Low temperature exotherms of 'Patmore' green ash and 'Skyline' honeylocust after one growing season of irrigation treatments [Z] from October 1998 thru February 1999 as determined by differential thermal analysis (DTA) [Y].

Sample Date	Green Ash (C)	Honeylocust (C)
October 19	-22.39 ± 1.4	-9.91 ± 0.8
October 30	-25.32 ± 1.1	-16.58 ± 0.6
November 6	-24.53 ± 0.7	-16.75 ± 0.9
February 6	-36.56 ± 0.4	-38.17 ± 0.4
Significant Terms		
Date	*** [X]	***
Treatment	NS	NS
Date*Treatment	NS	NS

[Z] Irrigation treatments consisted of deficit (40% ET), replacement (80% ET), and excessive (160% ET). Treatments were applied from 1 June 1998 thru 30 September 1998.

[Y] Data are the means of seven samples per species plus SE.

[X] NS, ***: non significant or significant at the 0.001 level, respectively.

APPENDIX A

Sources of plant materials utilized in the Tree and Turfgrass research site.

Shade Trees

Fraxinus pennsylvanica 'Patmore'

Bailey Nurseries, Inc.
1325 Bailey Road
St. Paul, Minnesota 55119-6199
1.8 m lightly branched bareroot

Gleditsia tricanthos inermis 'Skyline'
Femrite Nursery Company
13193 Arndt Road N.E.
Aurora, Oregon 97002
2.54 cm caliper, 2.4 m bareroot

Poa pratensis 'Livingston'
Sharp Brothers Seed Company
Greeley, Colorado 80631

APPENDIX B

Evapotranspiration (ET), rainfall, and irrigation occurring at the research site from June and July 1998. All measurements are in millimeters (mm).

		June						July			
Day	ET	Rain	40%	80%	160%	Day	ET	Rain	40%	80%	160%
1	13.7	0.0				1	6.7	0.0			
2	9.9	0.0				2	8.8	0.0			
3	2.7	2.0				3	6.6	0.0	9.0	17.9	35.8
4	2.2	8.9				4	5.8	0.0			
5	2.6	3.0	7.0	14.0	27.9	5	9.2	0.0			
6	5.1	0.0				6	4.6	0.0			
7	4.6	1.0				7	7.9	0.0	10.5	21.0	41.9
8	3.0	11.9				8	5.1	0.0			
9	4.1	0.0	0.0	0.0	0.0	9	5.6	0.0			
10	4.3	2.0				10	6.4	0.0	7.4	14.9	29.7
11	6.9	0.0				11	7.8	0.0			
12	6.9	0.0	5.0	10.0	20.0	12	9.3	0.0			
13	5.7	1.0				13	10.9	0.0			
14	7.0	1.0				14	9.3	0.0	13.7	27.5	55.0
15	6.6	0.0				15	9.4	0.0			
16	6.6	0.0	9.7	19.3	38.6	16	8.4	0.0			
17	5.0	2.0				17	9.1	0.0	10.8	21.7	43.3
18	10.1	0.0				18	9.6	0.0			
19	11.6	0.0	7.8	15.7	31.4	19	10.9	0.0			
20	8.0	0.0				20	11.3	0.0			
21	6.5	0.0				21	9.3	41.4	16.4	32.8	65.5
22	8.9	0.0				22	3.5	6.3			
23	8.2	0.0	14.0	28.0	56.0	23	4.3	0.0			
24	11.0	0.0				24	3.6	3.0	0.0	0.0	0.0*
25	10.5	0.0				25	4.9	3.0			
26	10.5	0.0	11.9	23.9	47.7	26	8.0	0.0			
27	9.2	0.0				27	9.1	0.0			
28	8.9	0.0				28	9.6	0.0	0.0	0.0	0.0
29	10.1	0.0				29	7.0	10.9			
30	6.9	0.0	15.5	30.9	61.9	30	2.9	29.0			
						31	4.6	0.0	0.0	0.0	0.0

* Study 1 was terminated July 23 due to both large rainfall events, and extended period of rainy weather, 103.5 mm between July 21 and August 1.

APPENDIX C

Evapotranspiration (ET), rainfall, and irrigation occurring at the research site from August thru September 1998. All measurements are in millimeters (mm).

		August						September			
Day	ET	Rain	40%	80%	160%	Day	ET	Rain	40%	80%	160%
1	3.8	9.9				1	5.1	26.9	11.9	23.8	47.5
2	7.8	0.0				2	7.1	0.0			
3	8.2	1.0				3	7.4	0.0			**
4	2.8	5.0	0.0	0.0	21.4	4	7.0	0.0	0.0	0.0	0.0
5	5.6	0.0				5	7.0	0.0			
6	6.7	0.0				6	7.9	0.0			
7	7.0	0.0	0.0	0.0	16.1	7	4.9	0.0			
8	8.1	0.0				8	5.1	0.0	0.0	10.2	47.4
9	4.6	0.0				9	7.2	0.0			
10	4.7	0.0				10	7.1	0.0			
11	6.2	1.0	0.0	19.5	39.0	11	8.3	0.0	7.8	15.5	31.0
12	9.1	0.0				12	4.7	0.0			
13	7.0	0.0				13	4.4	1.0			
14	7.5	0.0	8.5	17.1	34.2	14	5.9	0.0			
15	5.4	0.0				15	6.2	1.0	10.4	20.7	41.4
16	6.2	1.0				16	6.1	0.0			
17	7.3	0.0				17	6.2	0.0			
18	7.4	0.0	10.1	20.3	40.6	18	6.1	0.0	7.0	14.0	28.0
19	7.7	0.0				19	10.4	0.0			
20	6.2	0.0				20	5.6	0.0			
21	7.1	0.0	8.5	17.0	34.1	21	2.0	0.0			
22	7.8	0.0				22	2.6	0.0	9.6	19.3	38.6
23	7.3	2.0				23	1.2	0.0			
24	7.3	0.0				24	4.5	0.0			
25	6.3	0.0	11.0	22.0	44.0	25	6.5	0.0	3.3	6.6	13.3
26	6.7	0.0				26	5.7	0.0			
27	7.7	0.0				27	5.4	0.0			
28	7.6	0.0	8.3	16.6	33.2	28	5.5	0.0			
29	7.8	0.0				29	5.7	0.0	9.2	18.5	37.0
30	7.4	0.0				30	5.7	0.0			
31	6.9	0.0									

** Study 2 data collection was terminated September 3 due to large rainfall event, irrigation treatments continued until September 30.

APPENDIX D

June 1998

Mon	Day	Max Temp degF	Min Temp degF	Vapor Press mb	Solar Rad Lngly	Prec in.	Wind Run mi.	Soil Temp degF	Min RH Pct	Grow DegDay F.	Ref ET in.
6	1	85.7	43.7	6.65	705	0.00	369	59.0	9.7	605	0.538
6	2	80.7	45.8	8.29	658	0.00	256	61.1	20.0	621	0.389
6	3	47.7	38.6	7.83	133	0.08	239	55.5	69.8	621	0.105
6	4	47.3	38.7	8.41	174	0.35	218	49.5	84.2	621	0.087
6	5	49.8	33.1	7.45	297	0.12	115	46.7	62.8	621	0.103
6	6	67.9	32.0	8.78	563	0.00	169	44.6	29.8	629	0.202
6	7	71.8	41.5	11.35	469	0.04	171	52.3	34.2	640	0.182
6	8	63.1	43.1	11.17	266	0.47	213	53.7	58.2	647	0.118
6	9	66.2	44.6	11.51	435	0.00	134	52.7	46.2	655	0.160
6	10	68.5	43.7	11.83	438	0.08	133	53.6	44.2	664	0.169
6	11	74.6	42.6	9.22	521	0.00	192	52.8	20.5	677	0.270
6	12	80.6	44.3	10.15	626	0.00	113	55.2	19.3	692	0.270
6	13	71.2	49.8	9.95	296	0.04	233	59.0	29.2	702	0.225
6	14	69.2	47.4	10.06	336	0.04	373	56.7	39.3	712	0.275
6	15	69.7	38.3	8.68	525	0.00	184	51.6	25.5	722	0.261
6	16	73.4	45.2	10.05	358	0.00	267	56.6	33.4	734	0.258
6	17	62.6	46.0	9.38	279	0.08	290	54.6	36.8	740	0.197
6	18	73.1	43.0	7.40	572	0.00	368	52.7	24.9	752	0.397
6	19	88.5	42.0	7.91	650	0.00	261	55.0	11.8	770	0.457
6	20	78.6	54.8	9.31	516	0.00	202	61.3	23.2	786	0.315
6	21	77.6	48.5	11.48	419	0.00	181	61.3	32.0	800	0.255
6	22	84.0	43.8	12.18	609	0.00	229	58.6	25.4	817	0.352
6	23	85.7	51.4	11.21	619	0.00	145	66.1	11.6	836	0.324
6	24	86.1	45.4	7.52	671	0.00	218	62.0	8.4	854	0.435
6	25	87.6	43.9	10.46	670	0.00	222	61.9	10.5	872	0.415
6	26	91.2	46.8	8.59	643	0.00	175	59.9	12.0	890	0.414
6	27	85.4	48.9	9.48	652	0.00	158	60.1	19.5	907	0.362
6	28	88.9	45.3	11.07	655	0.00	132	59.4	20.9	925	0.350
6	29	90.6	54.4	11.15	640	0.00	192	63.4	16.9	946	0.397
6	30	82.6	57.1	15.01	489	0.00	163	65.4	39.8	965	0.271

Data is from a Colorado Agricultural Meteorological Network weather station located approximately 0.8 km south of the research site.

July 1998

Mon	Day	Max Temp degF	Min Temp degF	Vapor Press mb	Solar Rad Lngly	Prec in.	Wind Run mi.	Soil Temp degF	Min RH Pct	Grow DegDay F.	Ref ET in.
7	1	83.7	58.0	16.36	525	0.00	150	67.3	43.8	986	0.265
7	2	89.9	55.3	16.54	632	0.00	187	66.7	33.5	1007	0.345
7	3	79.8	59.2	15.96	492	0.00	169	65.6	44.6	1026	0.260
7	4	80.3	53.0	16.48	474	0.00	129	63.7	43.8	1043	0.229
7	5	92.5	52.2	14.38	600	0.00	175	62.5	18.6	1062	0.362
7	6	77.7	55.6	16.24	259	0.00	184	65.1	45.0	1079	0.181
7	7	85.6	51.3	15.30	547	0.00	203	61.5	33.2	1097	0.310
7	8	79.9	58.3	17.84	412	0.00	138	66.8	48.2	1116	0.202
7	9	78.7	57.1	17.51	466	0.00	168	65.4	51.3	1134	0.220
7	10	84.8	53.2	16.81	554	0.00	117	63.6	39.7	1153	0.251
7	11	88.7	55.9	15.21	549	0.00	158	65.5	27.4	1174	0.306
7	12	94.9	53.5	13.15	677	0.00	131	65.0	15.4	1194	0.368
7	13	96.8	53.2	11.12	672	0.00	165	65.8	11.0	1214	0.428
7	14	95.1	54.5	11.76	427	0.00	169	67.5	13.6	1234	0.366
7	15	86.4	53.0	13.48	554	0.00	229	65.4	20.9	1253	0.371
7	16	88.3	51.6	15.12	651	0.00	140	65.3	28.7	1272	0.329
7	17	93.0	54.1	14.89	655	0.00	148	67.3	19.6	1292	0.358
7	18	97.2	54.2	14.64	654	0.00	147	67.8	13.5	1312	0.379
7	19	98.3	57.0	14.19	631	0.00	197	69.3	16.2	1334	0.431
7	20	99.0	57.8	12.44	646	0.00	183	70.1	9.3	1356	0.444
7	21	92.6	57.5	16.03	423	1.62	236	65.8	23.1	1377	0.367
7	22	74.7	58.0	18.43	267	0.24	76	64.4	66.4	1394	0.138
7	23	76.6	59.2	19.05	390	0.00	93	65.9	58.7	1412	0.170
7	24	75.8	62.5	19.74	322	0.12	108	68.1	62.9	1431	0.142
7	25	77.1	60.9	10.99	286	0.12	96	66.8	0.5	1450	0.192
7	26	84.2	57.8	8.98	592	0.00	124	64.4	0.5	1471	0.316
7	27	84.0	57.4	6.84	628	0.00	143	65.0	0.5	1491	0.357
7	28	85.2	55.0	5.06	585	0.00	154	64.2	0.5	1512	0.377
7	29	81.1	58.9	7.72	348	0.43	131	67.4	4.8	1532	0.274
7	30	68.0	57.9	17.42	213	1.14	203	64.4	75.9	1544	0.114
7	31	75.5	58.2	17.78	403	0.00	154	63.7	33.5	1561	0.180

Data is from a Colorado Agricultural Meteorological Network weather station located approximately 0.8 km south of the research site.

August 1998

Mon	Day	Max Temp degF	Min Temp degF	Vapor Press mb	Solar Rad Lngly	Prec in.	Wind Run mi.	Soil Temp degF	Min RH Pct	Grow DegDay F.	Ref ET in.
8	1	80.7	56.3	16.30	246	0.39	114	63.8	11.3	1580	0.151
8	2	80.6	50.0	8.38	450	0.00	168	60.0	8.6	1595	0.308
8	3	74.6	57.9	3.64	330	0.04	182	63.6	3.3	1611	0.324
8	4	73.4	***	***	274	0.20	150	***	***	1623	0.000
8	5	75.8	52.7	15.22	575	0.00	107	***	42.2	1637	0.219
8	6	80.7	51.1	14.69	596	0.00	157	***	39.9	1653	0.264
8	7	83.1	50.4	14.21	597	0.00	145	***	32.3	1670	0.274
8	8	92.6	54.2	13.48	470	0.00	171	***	14.0	1690	0.317
8	9	79.3	56.8	14.88	318	0.00	118	***	35.0	1708	0.181
8	10	79.4	52.9	15.21	347	0.00	122	***	46.4	1724	0.187
8	11	82.5	54.7	14.68	467	0.04	139	***	27.8	1743	0.244
8	12	84.6	50.8	11.48	581	0.00	224	***	18.9	1761	0.360
8	13	87.1	49.7	12.20	538	0.00	122	***	17.7	1779	0.277
8	14	84.9	52.0	13.02	422	0.00	203	***	27.6	1797	0.295
8	15	80.1	50.2	14.73	421	0.00	138	63.3	25.9	1812	0.214
8	16	86.3	54.8	13.43	403	0.04	137	64.3	22.7	1833	0.243
8	17	89.2	51.7	13.74	531	0.00	143	62.4	22.2	1852	0.287
8	18	89.3	55.0	13.82	460	0.00	171	65.5	23.6	1872	0.291
8	19	84.7	53.5	14.07	480	0.00	210	65.5	30.1	1891	0.303
8	20	82.0	57.0	14.88	444	0.00	157	67.7	32.0	1911	0.245
8	21	85.2	53.6	14.53	450	0.00	197	66.3	31.3	1930	0.281
8	22	88.9	49.8	13.38	539	0.00	163	64.7	22.5	1948	0.306
8	23	91.2	52.0	14.02	436	0.08	163	65.3	18.0	1967	0.289
8	24	89.6	56.8	13.03	417	0.00	169	66.8	17.9	1988	0.289
8	25	80.5	51.0	14.07	424	0.00	180	64.9	38.4	2004	0.248
8	26	86.5	53.6	14.41	509	0.00	142	64.5	27.7	2024	0.264
8	27	83.2	50.4	11.17	433	0.00	209	63.4	17.8	2041	0.304
8	28	85.7	44.8	9.26	554	0.00	138	59.7	14.8	2059	0.298
8	29	87.7	46.8	9.67	533	0.00	148	59.8	14.0	2077	0.306
8	30	92.0	48.4	9.60	464	0.00	137	61.1	11.3	2095	0.292
8	31	80.7	58.2	12.17	356	0.00	225	65.1	22.6	2114	0.273

Data is from a Colorado Agricultural Meteorological Network weather station located approximately 0.8 km south of the research site.

September 1998

Mon	Day	Max Temp degF	Min Temp degF	Vapor Press mb	Solar Rad Lngly	Prec in.	Wind Run mi.	Soil Temp degF	Min RH Pct	Grow DegDay F.	Ref ET in.
9	1	77.1	51.7	12.87	404	1.06	127	61.3	26.5	2129	0.202
9	2	86.5	47.4	11.40	539	0.00	141	60.3	16.2	2147	0.280
9	3	90.8	51.3	11.07	534	0.00	139	61.1	10.0	2165	0.291
9	4	90.9	47.7	10.93	462	0.00	136	60.7	14.1	2183	0.275
9	5	91.3	50.0	12.48	514	0.00	129	60.8	17.1	2201	0.275
9	6	92.5	52.9	11.56	510	0.00	159	62.4	14.4	2221	0.312
9	7	79.7	53.5	15.46	409	0.00	130	63.2	42.6	2237	0.194
9	8	85.1	53.4	15.52	412	0.00	118	63.9	27.3	2256	0.202
9	9	89.0	52.0	12.13	464	0.00	162	63.4	16.3	2275	0.282
9	10	88.1	53.4	11.06	432	0.00	167	63.3	16.3	2295	0.278
9	11	88.6	52.6	10.91	465	0.00	207	63.8	18.5	2314	0.328
9	12	81.3	52.9	13.49	276	0.00	142	65.6	35.3	2332	0.186
9	13	74.3	47.8	11.50	277	0.04	137	60.9	32.5	2344	0.172
9	14	77.2	47.2	10.22	396	0.00	180	59.0	26.3	2357	0.234
9	15	76.2	44.0	10.61	468	0.04	195	58.8	30.4	2370	0.243
9	16	80.6	44.1	10.58	438	0.00	178	58.8	23.5	2386	0.239
9	17	84.9	45.5	9.62	462	0.00	145	58.0	17.5	2403	0.244
9	18	87.3	47.0	9.05	457	0.00	129	57.5	12.9	2421	0.241
9	19	80.3	49.0	6.92	441	0.00	326	59.0	15.4	2436	0.409
9	20	70.5	45.5	10.62	242	0.00	302	56.7	40.3	2447	0.221
9	21	49.7	43.6	9.94	124	0.00	268	53.7	78.7	2447	0.079
9	22	60.7	43.7	10.55	223	0.00	172	52.9	60.3	2452	0.103
9	23	65.9	47.5	12.39	119	0.00	88	55.6	54.7	2460	0.049
9	24	77.4	43.1	11.11	414	0.00	157	53.2	26.5	2474	0.176
9	25	88.1	43.8	8.78	436	0.00	164	54.4	10.2	2492	0.254
9	26	75.4	44.7	7.46	430	0.00	159	54.2	18.6	2504	0.223
9	27	74.8	40.5	8.84	425	0.00	164	53.7	25.4	2517	0.212
9	28	80.7	39.2	7.65	371	0.00	144	52.6	14.3	2532	0.217
9	29	81.3	44.4	8.69	294	0.00	187	55.5	17.7	2548	0.224
9	30	63.9	43.6	8.55	350	0.00	320	54.9	39.5	2555	0.224

Data is from a Colorado Agricultural Meteorological Network weather station located approximately 0.8 km south of the research site.