

1-1-2001

The effects of irrigation and nitrogen management on water use of tall fescue

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**THE EFFECTS OF IRRIGATION AND NITROGEN
MANAGEMENT ON WATER USE OF
TALL FESCUE**

by

Christopher Alan Brown

**Bachelor of Arts
Oberlin College, Oberlin, Ohio
1979**

**A thesis submitted in partial satisfaction
of the requirements for the**

**Master of Science Degree
Water Resources Program
College of Sciences**

**Graduate College
University of Nevada, Las Vegas
December 2001**

UMI Number: 1409024

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Thesis Approval
The Graduate College
University of Nevada, Las Vegas

July 27, 2001

The Thesis prepared by

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Entitled

The Effects of Irrigation and Nitrogen Management

On Water Use of Tall Fescue

is approved in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

The Effects of Irrigation and Nitrogen Management on Water Use of Tall Fescue

by

Christopher Alan Brown

**Dr. Dale Devitt, Examination Committee Chair
Adjunct Professor of Biology
University of Nevada, Las Vegas**

Tall fescue (*Festuca arundinacea* Schreb.) is a commonly cultivated turfgrass in Southern Nevada, one of North America's most arid climates. Recognized for its drought tolerance, tall fescue is nonetheless a significant water user in Southern Nevada. Since outdoor water use represents approximately 64% of all regional demand and peaks in the hot summer, efficient use of water on turfgrass such as tall fescue can make a significant contribution to water conservation as well as offset peak demand. Differing amounts of water were imposed, calculated as a leaching fraction (LF) of -0.40, -0.25, -0.15, 0.0 and +0.15 to reflect a continuum from severely- stressed to well-watered turfgrass. Nitrogen fertility treatments of 0, 1.2 and 2.4 Kg ha⁻¹ were imposed to reflect zero, low and high N fertility. The results of the study showed that counter to current cultural management techniques, which emphasize daily watering, tall fescue performed well with twice weekly watering. The findings of the study show that water savings of 6% to 12% can be achieved through switching from daily to twice weekly watering. Tall fescue also

performed well at a deficit irrigation of -0.15 LF. Water savings from combining deficit of -0.15 LF and twice weekly watering ranged from 26% to 29%. The most severely-stressed plots (-0.40 LF) showed threshold responses in Ψ_M , Ψ_{Lx} , Gs, tissue moisture content, turf canopy temperature, dry yield, color and cover when relative soil water moisture content dropped below 0.52. Despite steep declines in turf quality on the -0.40 and -0.25 LF irrigation treatments, all plots recovered to pre-experiment values after the stress period was ended and recovery irrigation amounts were imposed. The of interaction tissue N and tissue moisture content on turfgrass color was examined. Tradeoffs in N fertility and irrigation amounts were observed in producing acceptable turf quality while achieving water savings. Based on the threshold response to relative soil moisture contents and the complete recovery of all plots to the stress imposed, large water savings can be achieved if landscape managers are willing to accept a temporary loss in turfgrass color and cover.

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ACKNOWLEDGMENTS

I thank my wife, Ruth, and children, Zachary, Reilly and Lucas for their support. patience, and understanding over the last several years. I also owe thanks to my parents for the occasional well-timed babysitting to give me the time needed to finish.

Thanks to Thesis Committee members Jim Deacon, Dawn Neuman, and Dave Kreamer for their good humor and support during the lengthy duration of producing this document.

Many thanks to Dr. Robert 'Bob' Morris who helped make data gathering fun and always had a perspective on the research. The help of all who worked at the Center for Urban Water Conservation, Linda Verchick, Chris Schaan, Dorothy Dean, Ron Hammett, Jeff Andersen, Mary Bonine and the student workers for their help in the lab and the field.

Thanks to all who showed me hospitality on my trips back to Las Vegas over the past several years. The help and moral support of Peg and George Bean, Tara Pike, Blair Lund, Dr. Barb Brents, Mike Pawlak and Sydney has been indispensable. Finally, many thanks to Dr. Dale Devitt, who read countless drafts and revisions and who always had the time to look at another graph.

CHAPTER 1

INTRODUCTION

Tall fescue is a commonly used turfgrass in Southern Nevada, one of North America's most arid climates. Recognized for its relative drought tolerance and salt tolerance (Beard, 1973; Fry 1989), tall fescue is a popular turfgrass in Southern Nevada. It owes its popularity in part to desirable leaf texture, shoot density, mowing qualities and color (Bowman, 1991). As a cool season turfgrass, tall fescue retains its color during the winter months. Despite drought tolerance it can still be a significant water user (Biran *et al.*, 1981). In Southern Nevada turfgrass cultural management emphasizes daily watering during the hot summer months. Since 64% of water used in Southern Nevada is applied outdoors (Devitt *et al.*, 1992) and water use peaks during the hot summer months, more efficient use of water on turfgrass such as tall fescue could make a significant contribution to water conservation and also a reduction in peak demand.

Deficit irrigation has been found to reduce water use by tall fescue in semi-arid climates (Fry, 1989). Deficit irrigation is defined as applying water in amounts less than that lost through the process of evapotranspiration (ET). Watering restrictions applied during a drought may necessitate imposing deficit irrigation conditions to achieve water conservation goals. The results of this study help determine the impact of deficit irrigation of tall fescue as a strategy for urban water conservation in the arid southwest.

Studies in semi-arid areas have shown that tall fescue does well with less frequent watering (Fry, 1989; Tovey *et al.*, 1969). This research examined twice weekly versus daily watering in an arid climate for its impact on both tall fescue quality and water use under a range of irrigation to evapotranspiration rates and its viability under deficit irrigation conditions.

Beard (1973) recommended regular applications of nitrogen (N) in a range of 2 Kg ha⁻¹ to 4 Kg ha⁻¹ on tall fescue during the growing season. Other turfgrass studies have found significant differences in evapotranspiration of turfgrasses due to variance in application of N. Devitt *et al.* (1992) found differences in actual evapotranspiration (ETa) in common bermudagrass (*Cynodon dactylon* L.) due to fertilizer input in other Southern Nevada studies. Feldhake *et al.* (1983) found lower water use in N deficient treatments of Marion Kentucky bluegrass (*Poa pratensis* (L.) var. Marion), a cool-season grass, in a semi-arid climate. In this study, N treatments lower than the recommended range represented the low maintenance approach of many homeowners in Southern Nevada.

The experimental design tested the hypothesis that twice weekly watering of tall fescue is sufficient and that fescue can survive the arid summer in good shape with watering levels less than ET and nitrogen levels less than optimum. A number of parameters were important in determining plant water use and plant response to soil water deficits. The parameters measured included available soil moisture, turf canopy temperature, tissue moisture content, dry yield, tissue nitrogen levels, plant water status, and ET.

CHAPTER 2

LITERATURE REVIEW

Understanding water use and conservation opportunities requires knowledge of the movement of water through the soil-plant-atmospheric continuum. The measurement of water use by crops and plant cover is called (ET), which accounts for water evaporated from plant and soil surfaces and that which is transpired by the plant. Transpiration may be defined as the loss of water from the plant to the atmosphere along a gradient of decreasing water potential (Turner, 1978). Most of the water transpired by plants leaves through openings called stomata. Although transpiration occurs as a result of the stomata opening to fix CO₂ in the process of photosynthesis, transpiration does benefit the plant by regulating leaf temperatures via evaporative cooling (Duble, 1995). As the plant grows and increases in biomass, these growth demands are also supplied by the water moving from the soil to the above and below ground tissue, ultimately leaving as transpiration (Pater, 1995). Nutrients necessary for plant growth are carried with the water flow (Carrow, 1996). The rate of water movement in the soil-plant-atmospheric continuum is dependent on the soil moisture, internal plant resistance (root and stomata), and meteorological conditions (Turner, 1978).

Studies of plant water relations have examined the various factors that influence water movement from the soil through the plant to the atmosphere. Relationships between soil water content, soil water potential, leaf water potential, leaf moisture

content, dry yield, stomatal conductance and canopy temperature have all been examined to provide insight into the water use and conservation opportunities with crop and ornamental plants. Results of these studies have given greater insight into ET and plant responses to water and nutrient stress. This information can then be used to determine optimal irrigation strategies where supplemental irrigation is needed to meet water demands of plants or where water supply is limited.

Tall Fescue - Growth Characteristics and Water Use

Tall fescue is a C3 cool-season, deeply rooted, bunch type grass, with erect leaf orientation, low shoot density and medium wide leaves. Tall fescue is adapted to a wide range of soil and climatic conditions, with a tolerance for high temperatures and drought (Beard, 1973; Kim, and Beard, 1988; Turgeon, 1987). Cool-season turfgrasses typically have a greater period of growth in the spring and cooler months of the fall, as compared to warm-season turfgrasses which have their principal growth period during the hot summer months (Nutter *et al.*, 1969). Tall fescue cultivars have been developed for use as forage grasses as well as turfgrass. As a forage species, tall fescue is sought after due to its high water use efficiency (WUE), commonly calculated as the quantity of dry matter produced per the quantity of water used (Johns, 1973).

In a Colorado study under identical management and microenvironment conditions, cool season grasses, Rebel Tall Fescue and Marion Kentucky Bluegrass used 20% more water than warm season grasses, Tifway T-49 Bermuda, and Buffalograss (Feldhake, 1983). Fry and Butler (1989a) found that Reliant hard fescue exhibited better turf quality than Marion Kentucky bluegrass when subjected to deficit irrigation. In a

Texas study of comparative turfgrass ET eleven C4 warm season turfgrasses had lower ET than the tall fescue cultivar being studied (Kim and Beard, 1989).

An ET assessment of six tall fescue cultivars grown under field conditions in mini-lysimeters on a Sharpsburg silty clay loam at the University of Nebraska found a difference in ET by as much as 18% (Kopec, 1988). Turf types had lower ET than forage with rates of 6.6 and 7.2mm day⁻¹ respectively. Tall fescue turf types also appear to exhibit lower ET rates than tall fescue forage types (Carrow, 1996). In a study of tall fescue in the humid east, Carrow found ET rates in four tall fescue cultivars were 33 to 73% less when grown on clayey, kaolinitic, thermic typic hapludult soil in Griffin, Georgia, than ET rates reported for tall fescue grown in arid and semi-arid climates (Carrow, 1996). Kopec *et al.* found that tall fescue had better high temperature and drought performance than other cool season turfgrasses in part due to its deep roots system and physiological characteristics (1988).

There is no universally accepted definition of arid and semi-arid, so specific distinctions are difficult to define. However, Las Vegas, Nevada is generally accepted as being located in the arid southwest of the North American continent. Skujins (1991) defined the distinction between arid and semiarid based on to both rainfall and potential evapotranspiration (ET_o). In arid regions, the average growing season determined by rain and ET_o is less than 2½ months with no cultivation possible and little grazing unless irrigation or methods of concentrating water are available. In semi arid regions the average growing season is 2½ to 4 months. There is a short season in which drought resistant annual crops can be cultivated without irrigation. According to Duble, (1995) transpiration rates are higher in arid climates than in humid climates because of the

greater vapor deficit between the leaf and the atmosphere. Thus, transpiration losses may be 75% higher on a daily basis than in humid climates at the same temperature.

Physiological Responses to Drought

Tall Fescue and related fescue cultivars have been recognized for their drought tolerance among cool-season grasses (Aronson, 1987; Carrow, 1996). In general terms, plants respond to drought conditions, defined as prolonged water stress, by slowing growth and experiencing wilt, dormancy and even death, if the drought continues for a sufficient length of time (Beard, 1973). Shortage of water in leaves has the obvious effect of causing them to wilt. Wilt in tall fescue is indicated by blue green coloring and leaf rolling or folding (Carrow, 1996). In addition, following the slowing of growth rate there is often a loss of chlorophyll accompanied by yellowing of leaves (Naylor, 1972; Carrow 1996). Water stress can also lead to reduced tillering and a hastening of the death of tillers and leaves (Turner, 1978).

Drought resistance is a general term utilized to describe protective response of plants to prolonged water stress and as such is difficult to measure directly (Levitt, 1980).

Resistance includes drought avoidance; drought tolerance; and escape (Beard, 1988). Differences exist among the basic definitions of these terms (Carrow, 1996). For the purpose of this discussion, the concept of drought resistance is meant to include all physiological mechanisms which allow plants to withstand a period of dry weather. Leaf rolling is an important drought resistance mechanism characteristic of tall fescue (Beard, 1973; Johns and Lazenby, 1973; Richardson. *et al.*, 1993). Drought avoidance includes mechanisms which avoid tissue damage due to drought stress (Beard, 1989). Deep

rooting, with access to greater volume of soil water, and dormancy are characteristics of drought avoidance. Beard (1973) noted that dormant turfs also provide a mulch like resistance to evaporation from the soil surface. Escape refers to turfgrasses which escape soil water deficits by means of a short life cycle, in which germination, establishment, and seed production happen within a short growing period (Beard, 1973).

Heat and water stress often occur simultaneously, which makes the effects difficult to separate, but soil water deficits combined with higher temperatures have an additive effect on plant drought response (Beard, 1973). Stress hardening or stress adaptation has been pointed out as an advantage to plants that are less sensitive to subsequent stress (King, 1985). Pater (1995) noted that plants which have high water use efficiency have a competitive value over less efficient plants especially during times of moisture stress. However he also referred to studies which showed no significant correlation between WUE and drought tolerance such as the work of Miller & Hunt (1966).

Fry and Butler (1989a) found that drought resistance of tall fescue prevented large decreases in turf appearance as soils dried and observed little correlation between soil matric potential and turf quality scores (R^2 ranging from 0.30 to 0.39 in three out of four test dates). They attributed the lack of this correlation to tall fescue's deep root system and to extraction of water from deeper in the soil profile than the matric potential was being measured (10 cm). In contrast they observed a significant correlation between hard fescue turf quality and soil matric potentials on two dates ($R^2 = 0.66$ and 0.63 on July 2 and 30 respectively in summer 1986). White *et al.* (1992) found that tall fescue was able to maintain positive leaf turgor, a sign of physiological health, when exposed to drought

conditions in a laboratory experiment. Soil moisture was measured as a percentage of available soil water by weight (g g^{-1}). Grown in a fritted clay, the turfgrass maintained leaf water potential of -1.0 MPa, and acceptable leaf rolling scores at approximately level values, as soil moisture levels declined from 0.70 to approximately 0.47. After soil moisture levels declined below the threshold value, leaf water potential declined rapidly and leaf rolling increased dramatically. Carrow (1996) found that extraction of water from deeper in the soil profile was associated with maintaining higher visual quality by the Rebel II cultivar in a test of six tall fescue cultivars while depleting the largest amount of water from the 20 to 60 cm depth of the soil profile after a 14 day dry down period on five of seven test dates. He found that deep root length density explained 48% of the variability in wilt response to drought stress. In another study, two *Festuca* species, *Festuca rubra* var. *commutata* Gaud. 'Jamestown' and *Festuca ovina* var. *duriuscula* (L.) Koch 'Tournament,' maintained relatively constant leaf water potential down to soil water potentials of -400 KPa in a greenhouse experiment grown in a silt loam soil (Aronson *et al.*, 1987).

The tall fescue cultivars studied by Kopec *et al.* (1988) differed in their wilting performance which was not entirely dependent on soil water stress. Since irrigation is often scheduled based upon visible wilt these difference are important. 'Mustang' and 'Rebel' cultivars were reported as having lower mean daily ET rates, used less available water and reached moderate wilt values at higher soil moisture than other cultivars. Kopec *et al.* hypothesized that the lower ET rates and wilt response to soil water availability had to do with mechanisms such as depth and extension of rooting, soil

moisture extraction, osmotic adjustment, morphology, arrangement of bulliform cells and sensible heat loss.

Osmotic adjustment has been found in tall fescue tissue in response to drought (West, 1990). There is a large body of evidence indicating that abscisic acid (ABA) has an important regulatory role in the resistance of plants to environmental stress by causing stomatal closure (Levitt, 1980).

Stomatal conductance (g_s) is a measurement of gas exchange rate. It is evaluated through the use of a steady state porometer in which a living leaf is placed inside a chamber and the water loss from the leaf is measured. Stomatal conductance at any constant temperature is probably controlled by the rate of transpiration (Collatz, 1991). The stomata occupy the key position between the plant and atmosphere for the regulation of both transpiration and photosynthesis. The stomata respond to ψ_L or leaf relative water content, light intensity, vapor pressure, and CO_2 concentration (Levitt, 1980). When a critical threshold is reached, and then stomata close over a narrow range of ψ_L , relative water content. The lack of correlation between ψ_L and g_s is typically accounted for by differences in osmotic potential or osmotic adjustment in plants. However, since stomata regulate CO_2 exchange, water deficits which result in closed stomata must also depress photosynthesis and plant growth (Turner, 1978).

In conditions where soil and plant water status are not limiting, the climatic conditions which primarily control transpiration vary rapidly with time and in particular possess pronounced diurnal fluctuations (Cowan 1964). Cowan also observed that when soil water became limiting or where atmospheric conditions promoted a high rate of evaporation that the atmospheric conditions may no longer primarily. Determine the rate

of transpiration. In conditions where ψ_L fell to the point that leaves lost turgor, and stomata closed the resistance to vapor transport from mesophyll tissue increased and the rate of transpiration decreased. Further loss of water was controlled by plant and soil, rather than atmospheric conditions.

In a study of southern peas, Clark and Hiler (1973) observed that while measurements of leaf water potential (ψ_L), stomatal conductance and canopy minus ambient temperature (ΔT) are not independent and all give an indication of plant water status, leaf temperature and stomatal conductance were more dependent on climatic conditions at the time of measurement than was ψ_L , which was more responsive to change in plant water status. Hirawasa (1997) evaluated the relationship between ψ_{Lx} and transpiration in a study of rice plants growing in submerged soils, where soil water potential can generally be regarded to be at 0 MPa. Hirawasa (1997) calculated the resistance to water transport from soil through root to leaf (R), whole plant resistance, by $R = -\psi_{Lx} / T$, where ψ_{Lx} was leaf xylem water potential and T was transpiration. Whole plant resistance decreased rapidly as transpiration increased, when transpiration rates were low in the early morning. Hirawasa (1997) found close linear correlation between ψ_{Lx} and transpiration at high transpiration rates in rice plants.

There are numerous studies where leaves were reported to be cooler than the air above the canopy when a crop was well watered (reviewed by Clark and Hiler, 1973). Kramer (1983) observed that the difference between canopy temperature and ambient temperature when measured at about 1400 hours in wheat crops increased as leaf water potential decreased. Transpiration serves to minimize tissue injury due to high temperature by cooling the leaves as long as the process is operative. Once water deficit

occurs, the air – canopy temperature differential grows, with the stressed canopy having higher temperatures than the well-watered plants. Jackson *et al.* (1981) evaluated the use of hand held infrared thermometers to measure canopy temperature and to calculate a crop water stress index (CWSI) in wheat. The index was designed to evaluate the relationships between canopy temperature differential ($T_c - T_a$) and the vapor pressure deficit as related to crop yield and water requirements. Hatfield (1983) found a threshold relationship between ψ_L and $T_c - T_a$ in a field study with grain sorghum. When ψ_L decreases below -1.1 MPa, $T_c - T_a$ increased above zero. $T_c - T_a$ also increased rapidly when more than 65% of the available soil water was depleted.

Johns and Lazenby (1973) also pointed out that stomatal mechanisms in temperate plants exposed to high temperatures may be inefficient. Their research indicted that the inability of the plant to prevent temporary water stress may have led to reductions in yield and to the death of leaves in temperate pasture grasses. In a study of stomatal density among 12 cool-season grasses, including tall fescue, Green *et al.* (1990) found no significant correlation between ET rate and either abaxial or adaxial stomatal density. In contrast, Casnoff *et al.* (1989) found significant correlation between stomatal density and ET rates under non-limiting conditions. Green *et al.* (1990) concluded that in the cool-season turfgrasses, plant characteristics which increased canopy resistance and decreased leaf area were more important than stomatal density in reducing water use under non-limiting soil moisture conditions.

Jackson *et al.* (1981) found evidence for the close coupling of soil water and plant temperatures, thus providing strong support for the use of plant temperatures to evaluate plant water stress. Jackson *et al.* used this relationship to develop an empirically-based

equation for determining the CWSI based upon canopy temperature. They noted limits on developing a unique relationship between CWSI and water use. These limits included the amount of extractable water available to the plant, since roots grow and extract water from an increasing volume of soil, while the equation requires an estimate of extractable water based on a fixed volume of soil. CWSI is dependent on evaporative demand, if the evaporative demand exceeds the ability of the roots to take up water or the rate at which water moves to the roots, then CWSI will increase without a corresponding increase in water use. Wind can affect CWSI but does not explicitly appear in the equation. Rapidly changing cloud conditions can cause serious errors in the CWSI measurement, especially if the air temperature is measured a few minutes before or after the canopy measurements. Shaded and sunlit canopies can exhibit different temperatures under such conditions (Jackson *et al.*, 1981).

Boyer (1968) observed that water is essential for growth and enlargement of plant cells. Since water moves along decreasing gradients the water potential of the supply needs to be higher than that of the growing plant. Measurement of ψ_L has been made in numerous experiments to help better understand both plant growth processes and plant response to water deficits.

Reduced leaf growth during drought stress has been reported (Beard, 1973; Aronson, 1987). Aronson attributed maintenance of turf quality in fescues to continued leaf growth during soil drying. In a study of pasture plants, including a number of grasses, Turner and Begg (1978) showed that extension growth was more sensitive to water deficits than was stomatal closure. They concluded that growth was affected before water deficits reached a level which directly reduces stomatal apertures and

photosynthesis. Shoot growth was affected before root growth, as shown by changes in the shoot:root ratio in water stressed plants. Mid-day peak high temperatures can cause situations of temporary water stress in plants, even in plants which are well watered (Johns and Lazenby, 1973). Johns and Lazenby found that the stomatal mechanism may be inefficient in cool season species under hot conditions. The inability of the plant to replace transient water losses may be responsible for loss of leaves and resulting reduction in dry yield. Johns and Lazenby (1973) pointed out that fescue's leaf rolling ability may contribute to drought resistance by reducing transpiration and the area exposed to solar radiation.

In examining tall fescue genotypes for carbon isotope discrimination (Δ) and dry yield, Johnson *et al.* (1993) found well watered plants showed a mean g_s of $410 \text{ mmol m}^{-2} \text{ s}^{-1}$ for high Δ , and a mean g_s of $330 \text{ mmol m}^{-2} \text{ s}^{-1}$ for low Δ genotype. However distinctions between genotypes were not as pronounced under conditions of water stress. Plants stressed with polyethylene glycol (PEG) solution showed a mean g_s of $110 \text{ mmol m}^{-2} \text{ s}^{-1}$ for high Δ , and a mean g_s of $100 \text{ mmol m}^{-2} \text{ s}^{-1}$ for low Δ genotype. The same experiment showed that the mean ψ_L values for well watered plants and PEG-stressed plants were -0.51 and -1.94 MPa, respectively. In irrigated versus dryland field plots ψ_L correlated well with dry yield ($R^2=0.73$) but not as well with mean Δ values ($R^2=0.44$). An experiment on warm season grasses exposed to water stress found that when water stress was evaluated based on ψ_X , dry yields dropped by approximately 38% in coastal bermudagrass and Kleingrass '75' (*Panicum coloratum* L.) as ψ_L measured predawn declined (Bade, 1985).



Physiological response to Nitrogen

Turfgrasses require N in larger quantities than any of the other essential nutrients, with the exception of carbon, hydrogen and oxygen (Beard, 1973). Nitrogen is a vital constituent of the chlorophyll molecule, amino acids, proteins, nucleic acids, enzymes and vitamins. It is therefore involved in photosynthesis, protoplasm composition, hereditary transfer of plant characteristics, and plant metabolism (Novoa and Loomis, 1981). Turfgrass dry tissue levels of N range from 3 to 6% providing there is sufficient soil N. According to Beard (1973) cool season turfgrasses grown above 21°C or with higher concentration of N show higher tissue N levels.

Nitrogen can affect shoot growth and density, color, disease resistance, heat and drought hardiness, and recuperative potential. Nitrogen substantially affects the growth rate of turfgrass tissues (Calhoun, 1964). In addition to tissue growth, higher N levels can increase the respiration rate of turfgrasses (Blaser and Schmidt, 1964). The growth response to N is limited by the availability of carbohydrates for protein synthesis. This leads to a suppression of root growth while shoot growth continues to respond to higher N levels (Beard, 1973). Excessive shoot growth due to high N levels can lead to root death due to lack of carbohydrates for maintenance of existing roots. The level of N has also been found to be directly correlated with turf color and shoot density (Goss and Law, 1967; Mantell and Stanhill, 1966; Montieth and Bengston, 1939). Nitrogen deficient stands of turfgrass will have a lighter shade of green, and as N deficits increase yellowing of the turf occurs (Beard, 1973). Nitrogen levels influence the drought hardiness of turf as the degree of tissue hydration is directly correlated with N levels (Carroll, 1943).

Tall fescue is recognized for its drought resistance and ability to maintain itself

under low fertility conditions (Hall, 1995). Kopec (1990) suggests that excessive N application in the spring will favor shoot growth over root growth. He also suggests that over application of N on cool season grasses during the summer will produce more leaf area and increase water use. According to Beard (1973) excessive N fertilization reduces drought resistance of turfgrasses due to rapid shoot growth, enlarged cell size and increased tissue hydration.

On the other hand, N deficiency is characterized by stunting of shoot growth including reduced tillering and leaf length (Beard, 1973). Nitrogen deficiency is known to increase stomatal resistance in a number of plants (Nagarajah, 1981). Nitrogen deficiency has been correlated to decreased leaf water potential, reduced transpiration, and increased sensitivity of stomata to water stress (Nagarajah, 1981). Nagarajah (1981) reported that N-deficient leaves have some of the characteristics associated with adaptation to drought. However, in tea, leaf water potential was not affected by N-deficiency. Nitrogen deficiency increased the sensitivity of transpiration and g_s to water stress. Water stress was induced by allowing the plants to deplete water after the sand medium was brought to field capacity. Nitrogen supplied plants received half-strength Hewitt's nutrient solution (includes 105 mg/l N) in the morning and tap water in the afternoon, after all plants reached an approximately 30 cm height, the supply of N was halted to half of the plants. The effects of N-deficiency (0 N) included a 13.2% decrease in transpiration and a 47% increase in stomatal resistance in the tea plants. The initial reduction in transpiration in the N-deficient plants was not caused by an increase in stomatal resistance, thus Nagarajah postulated that an increase in mesophyll resistance was responsible for the initial reduction in transpiration in N-deficient plants.

Interaction of Nitrogen and Water

When there is sufficient water, nitrogen can act to stimulate or limit plant growth and dry yield depending on its availability (Naylor, 1972; Campbell, 1977a). Nitrogen in its inorganic form is only held lightly by soil particles. As soil moisture decreases nitrogen may accumulate. As the soil solution becomes more concentrated this may lead to an accumulation of mineral nutrients in plants limited in growth by moisture. Numerous studies have found that for a given level of fertility, N content of crop plants increased as soil moisture decreased (Naylor, 1972). Naylor hypothesized that nitrogen in plants exposed to drought conditions is mobile and moves along concentration gradients.

Parameswaran *et al.* (1981) found in a study of the growth and yield of wheat that nitrogen fertilizer increased vegetative growth early in the growing season resulting in increased water use by the plant. Later in the growing season, under conditions of limited water, this can accentuate water stress and result in the loss of yield.

Dryland tall fescue plots planted to a forage type cultivar, 'Demeter,' produced more dry yield in months with higher rainfall than irrigated plots in a two year experiment in Australia due to greater availability of N in the dryland plots (Johns, 1973). Johns (1973) indicated that the N fertilizer remained in the soil in greater concentrations in the dryland treatment, and was only taken up by the plants when soil moisture levels increased with rainfall.

The interaction of N and water supplies has been studied to determine its impact on plant resistance to pathogens. Crutchfield *et al.* (1995) found that high irrigation high N treatments made tall fescue turf more susceptible to foliar damage from grub

infestation. While percentage decreases in yield were higher in grub-infested plots with high N and irrigation, mean yield by weight was higher in uninfested and infested plots with high irrigation and N fertilization than in low irrigation, no N fertilization treatments.

Low and Armitage (1959) indicated that in a climate with low evaporative demand (Great Britain), ryegrass production was higher with higher N and low soil water potential. In contrast Johns and Lazenby (1973) found that in Australia, with high evaporative demand, that a positive interaction between soil water potential and N dominated, and that irrigated swards of grass produced greater yield than dryland plots. They concluded that in conditions with high evaporative demand, lower soil water potential reduced the availability of nutrients to plants and that dry yield dropped more rapidly than transpiration, thus reducing WUE.

Dry matter accumulation in the aboveground vegetative parts of the plant in spring wheat (*Triticum aestivum* L. cv. Manitou) grown in metal lysimeters on Wood Mountain loam in Canada was related to N concentration ($DM = (\%N)^k$ where $k < 1$). Nitrogen accumulated in plants faster than dry matter. The maximum rate of N accumulation was not affected by moisture, however irrigated plants recovered one-half or more of the fertilizer N, and dryland plants recovered one-quarter to one-third (Campbell, 1977b). The rate of change in N accumulation with dry matter accumulation was also a function of both fertility level and soil moisture. The exponential K factor was calculated to be 0.63, 0.52, 0.37 and 0.43 under unfertilized wet and dry, and fertilized wet and dry conditions respectively. There was a threshold effect of plant N

concentration increasing as application N increased to 61.5 kg ha⁻¹ but higher rates gave no increase (Campbell, 1977b).

Approximately twice as much dry matter accumulation in the aboveground vegetative parts of the plant in spring wheat (*Triticum aestivum* L. cv. Manitou) was produced in the wet treatment as in the dry for all levels of N (Campbell, 1977a). Total ET increased with N in the wet treatment and was much higher than in the dry treatment. It was not affected by applied N in the dry lysimeters (Campbell, 1977a). Campbell *et al.* (1977a) found that under conditions of adequate moisture, high rates of fertilizer were beneficial to plant and roots growth. However, such high rates may result in detrimental effects on dry matter production under semiarid conditions by inducing rapid growth of leaves and roots which will accelerate the rate of ET and the depletion of limited soil moisture. In contrast, Heitholt (1989) found that shoot:root ratio in winter wheat grown in pots was consistently reduced by N stress, but not by water stress.

Irrigation Management with Limited Water

Good irrigation management requires a properly designed irrigation system with adequate water pressure, proper spacing of sprinkler heads, and an application rate which does not exceed the soil infiltration rate (Beard, 1973). The timing and quantity of irrigation can be based on when the turfgrass shows visible signs of stress. The most common indicator of stress used to time irrigation is wilt (Beard, 1973). Mid-day irrigation is recommended to provide water during the time of greatest atmospheric stress, but this is also the greatest time of evaporative water loss. Drought and water

conservation plans by municipalities often limit or prohibit mid-day irrigation timing (Brown, 1998).

Kopec *et al.* (1988) pointed out that wilting may be a water conservation mechanism, but that it is not a desirable characteristic in most turfgrass situations. Six tall fescue cultivars evaluated by Kopec *et al.* (1988) in Nebraska differed in their wilting performance which was not entirely dependent on soil water stress. Since irrigations are sometimes scheduled based upon visible wilt these difference can be important.

Differences in response to irrigation frequency and amount have been studied for numerous turfgrasses, forage grasses and crop plants. Water deficit studies specific to tall fescue in arid and semi-arid climates have given greater insight into plant growth and water adjustments. Deficit irrigation is defined as supplying less water to replenish soil moisture than plants are removing through evapotranspiration (Kopec, 1990). Deficit irrigation studies have been performed on various cultivars of commonly grown turfgrasses in semi-arid climates. Substantially fewer studies have been performed in arid climates, where annual precipitation is less than 25 cm. Mean annual precipitation in Las Vegas, Nevada is 12.1 cm (Western Regional Climate Center, 2001).

A study of tall and hard fescues in Colorado found significant difference in appearance based on the interaction of irrigation intervals of 2, 4, 7 and 14 days and amounts when irrigated at 50 percent of ETo (Fry and Butler, 1989a). However when irrigated at 75 or 100% ETo, irrigation frequency was not significant in turfgrass appearance. For the 50% ETo treatment the 4 day interval resulted in acceptable turfgrass quality during all but the final two weeks of the stress period, while the 2 day interval resulted in acceptable turfgrass quality ratings throughout the experiment. In a

similar study by Madison (1961), irrigation frequencies of 2, 10 and 20 days on Marion Bluegrass, showed significant difference in the percent of water extracted from a deep Yolo clay loam soil.

Carroll (1943) noted that turfgrass grown under limited soil moisture develops greater drought resistance than those grown under adequate soil moisture conditions. Beard (1973) pointed out that turfs which are subjected to intensive irrigation during a drought and then miss several weeks will develop more dehydration damage than those subjected to limited irrigation.

Deficit Irrigation

Tall fescue's drought tolerance and physiological response to water stress make it an excellent candidate for deficit irrigation (Fry and Butler, 1989a). However, Fry and Butler (1989b) found that the use of deficit irrigation at 50% of ETo produced poor germination of 'Rebel' tall fescue during establishment in lysimeters containing a sandy clay loam soil.

An experiment in San Antonio, Texas with warm-season turfgrasses found that deficits as low as 50% of ETo were tolerated by St Augustine, Bermuda grass, and Buffalo grass varieties (Guz *et al.*, 1998). While stress was observed in all species at the deepest deficits during the peak of summertime environmental stress, all plots recovered.

Irrigation Frequency

Beard (1973) cited problems with too frequent irrigation, including reduced root growth, reduced chlorophyll content and increased water use rate. Soil types and climate

affect the optimal irrigation frequency as clay soils in cool humid climates may become saturated when irrigated three times a week, and sandy soils in hot arid climates may develop soil water deficits at the same frequency (Beard, 1973).

Kopec (1990) recommended to Arizona irrigators, that 15% water savings could be achieved by changing irrigation frequencies from once every two days to three times a week without changing the quantity of water applied each time.

Stress Recovery

All plants go through a diurnal stress cycle in response to changing temperature, solar radiation and vapor pressure deficit. Changes in wind speed can increase the stress on the plant. When stresses exceed the capacity of the plant to replace water lost to transpiration, plant stress response ensue, including stomatal closure, loss of turgor, and temporary wilting (Levitt, 1980; Turner, 1978). The water potential of the soil has been shown to set a limit on the recovery possible by the plant (Turner, 1978). In situations of prolonged water stress, the question of plants' ability to recover from the impacts of these stress responses has interested a number of researchers.

Kentucky bluegrass was shown to have a rapid recovery of 3 to 5 days from dormancy in response to rainfall (Beard, 1973). Beard indicated that a brown dormant turf may be in better physiological condition and better able to recover from a drought than a turf which has been excessively irrigated. Dormancy includes complete cessation of growth, and usually leaves turn brown and die. When more favorable growing conditions return, perennial grasses are capable of initiating new growth from the meristem or from buds on rhizomes or stolons (Beard, 1973). Summer dormancy is

controlled by availability of moisture in most cool-season turfgrasses including tall fescue.

Jackson (1981) found that after irrigation, the CWSI did not drop immediately to zero. A five to six day period after irrigation was still required to reach a minimum CWSI and for the plants to recover from a stressed condition.

Boyer (1968) in examining whole leaf response to deficits found that recovery from water deficit occurred in two phases in a study of the leaves of sunflower (*Helianthus annuus* L.), tomato (*Lyconthperiscon* Mill.), papaya (*Carica papaya* L.) and *Abutilon striatum* Dickson. In the first phase of recovery the water deficit in the leaf was eliminated; in the second, cell enlargement occurred. The second phase was distinguished by steady water uptake and a relatively constant ψ_L .

In an experiment on cotton leaves exposed to repetitive stress cycles, Brown *et al.* (1975) found that plants pre-conditioned to stress recovered faster than those which had not been pre-stressed, and that stomata opened at lower water potentials than non-conditioned plants.

CHAPTER 3

MATERIALS AND METHODS

A six month experiment to determine the potential for water savings available through altering irrigation frequency, irrigation volume and N application on 'Monarch' (Tall Fescue) was run from May 21 to November 27, 1996 at the Center for Urban Water Conservation in North Las Vegas, Nevada, USA. The experimental plots consisted of twenty 5.49 m x 5.49 m plots of three-year-old stands of 'Monarch' tall fescue sod separated by approximately 6.7 m buffer areas seeded with Monarch tall fescue. Soil at the site was classified as Las Vegas loam (loamy, carbonitic, thermic shallow typic petrocalcids).

Each of the experimental plots had a 120 cm deep 51 cm diameter draining lysimeter in the center which was used to calculate ET of the turfgrass. The lip of the lysimeter was slightly above ground surface level to prevent runoff to or from the surrounding plot. The lysimeters were each filled with blended native surface soil from the same field to reduce variation between lysimeters. The lysimeters were drained by means of two ceramic drainage extraction cups placed in 10 cm of diatomaceous earth at the bottom of each lysimeter. Water in storage was estimated by means of a neutron probe which was lowered into a stainless steel access tube in the center of each lysimeter.

Four Toro 300 rotary sprinkler heads provided irrigation to each plot with a 112° spread, centered on the lysimeter, ensuring even coverage of the plot, and eliminating

cross-watering of adjacent plots. Half of the plots were watered daily and the other half were irrigated twice weekly. For each irrigation frequency two replicates received five different irrigation amounts selected in a randomized block design (see Figure 1). The irrigation quantities were calculated to impose set leaching fractions (LF), where the LF is defined as the drainage volume divided by the irrigation volume. The irrigation amount was then calculated to obtain LFs of +0.15, 0.0, -0.15, -0.25, and -0.40, where ETa was from the previous week's water balance for each plot. After the peak demand period ended on Julian Day 260 and plant stress reached a peak, the turfgrass was allowed to recover by imposing the +0.15 LF treatment on all plots. The recovery period was monitored until Day 331 when full recovery was determined to have occurred based on evaluation of color and cover.

Actual evapotranspiration was calculated for turfgrass growing in each lysimeter on a weekly basis by means of the water balance equation:

$$ETa = I - \Delta S - D$$

where ETa: actual evapotranspiration

I: irrigation (I)

ΔS : change in storage

D: drainage

Irrigation quantities for the subsequent week were calculated by means of the equation:

$$I = ETa / (1 - LF)$$

where LF: leaching fraction.

Thus, a deficit soil water status was attained by placing a theoretical negative LF into the equation, resulting in each weeks total irrigation for the -0.15 , -0.25 , and -0.40 LF treatments to be less than the previous week's ET.

In addition to the irrigation treatment, each plot was subdivided into three 1.83 m wide subplots which were given monthly N treatments of ammonium nitrate fertilizer. The fertilizer was applied at rates of 0, 1.2, or 2.4 Kg ha⁻¹ of N. The control group was considered to be the 2.4 Kg ha⁻¹ of N treatment which was applied to the center subplot, which contained the lysimeter. The control N application rate falls at the low end of the range recommended by Beard (1973). The other two treatments were applied to the outside subplots; all 3 subplots were oriented in a N-S or E-W randomized design within each plot (see Figure 2).

The effects of irrigation quantity, frequency and N treatments on the soil-plant-water status of the tall fescue were monitored. Tensiometers were placed in each lysimeter at 30 cm depth no less than 12 cm from the side of the lysimeter to measure matric potential (Ψ_M). (Rawlins and Campbell, 1986).

Figure 1 North Las Vegas Experimental Design—Tall Fescue by Plot, Irrigation Frequency, and Leaching Fraction
(N1, N2, etc...indicates plot designation; twice weekly or daily indicates irrigation frequency; and numbers such as -0.25, +0.15 etc...indicate leaching fraction.)

N1 Twice Weekly -0.25	N2 Daily +0.15	N3 Daily -0.40	N4 Daily -0.25	N5 Twice Weekly +0.15
N6 Twice Weekly -0.15	N7 Daily -0.15	N8 Daily 0.00	N9 Twice Weekly -0.40	N10 Twice Weekly 0.00
S1 Twice Weekly +0.15	S2 Daily -0.15	S3 Daily +0.15	S4 Daily -0.40	S5 Twice Weekly -0.40
S6 Twice Weekly 0.00	S7 Twice Weekly -0.25	S8 Daily 0.00	S9 Twice Weekly -0.15	S10 Daily -0.25

Figure 2
(not to scale)

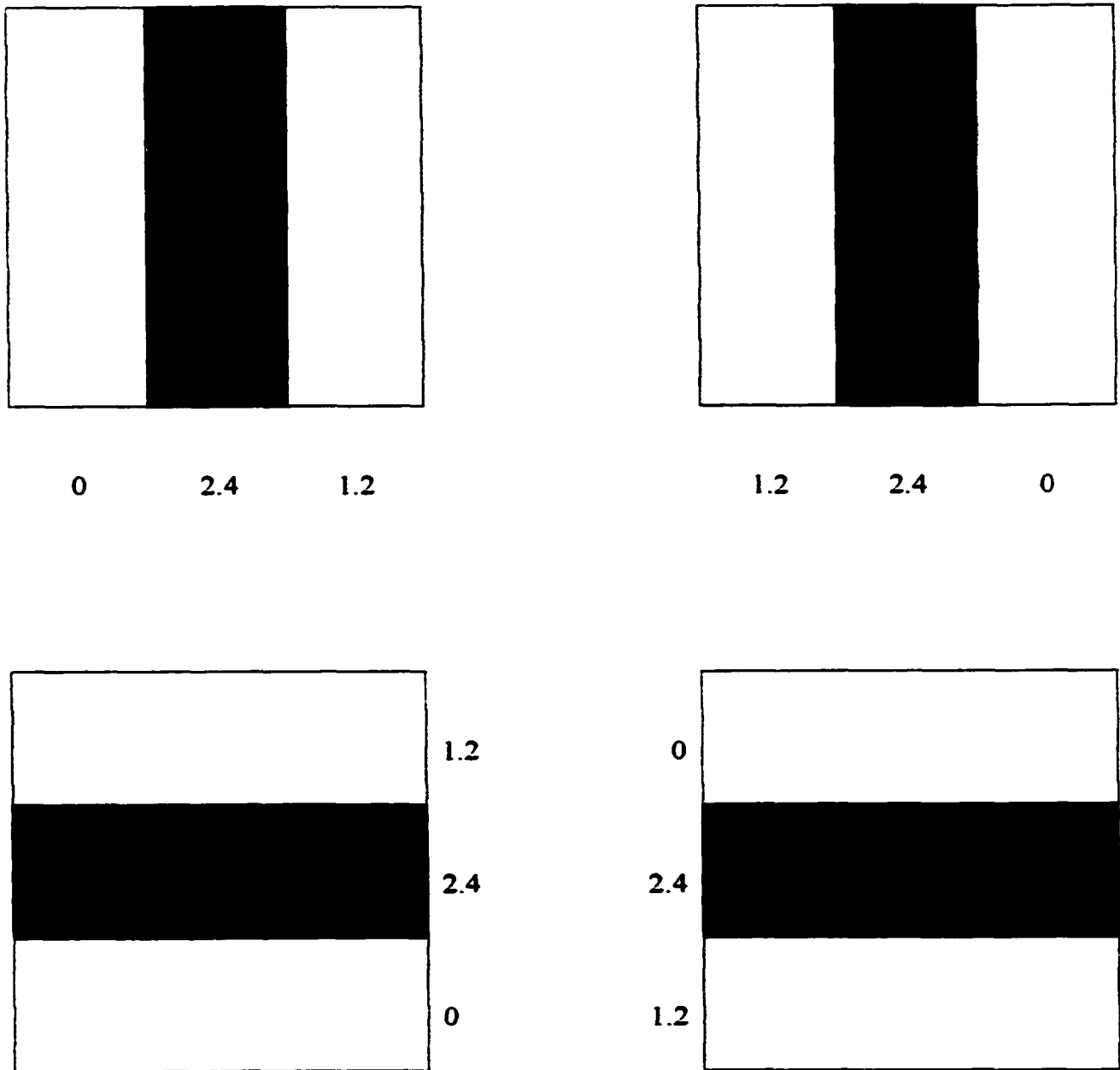


Figure 2. Subplots were oriented E-W or N-S with three different levels of N fertilizer applied in a randomized block design.

Leaf xylem water potential (Ψ_{Lx}) was measured by means of a plant water status console (pressure bomb; SoilMoisture Corp.) at mid day. Leaf stomatal conductance was measured with a steady-state porometer (Li-Cor). Tissue moisture was determined from weekly turfgrass samples taken from the lysimeter and from a single strip of grass mowed at a 5 cm height from each sub-plot. All of these measurements were taken on a bi-weekly basis until plant stress response was apparent; thereafter the measurements were increased to a weekly basis until the end of the stress period. At that point, the recovery irrigation treatment (+0.15 LF) was imposed on all plots.

Turf dry weight production was measured weekly on both subplots and lysimeters. Turfgrass was harvested from each subplot by mowing a single strip 2.9 m² through the center of each subplot at a 5.1 cm height. The turfgrass was collected in plastic bags, sealed, placed in a cooler and delivered to the laboratory where it was weighed to determine total fresh yield. The sample was then oven dried for 48 hours at 70°C to determine tissue moisture content (g H₂O)/(g fresh weight) and dry yield of each sample.

Measurements of turf canopy temperature, color and cover were taken at three locations evenly spaced along the median of each subplot. Turf canopy temperature was measured by means of two hand held infrared thermometers (Everest Interscience, Tustin, CA). The thermometers were calibrated in the laboratory and cross-correlated under field conditions. The subplot values for each plot were collected on 3 evenly spaced sites within each subplot. ΔT and g_s values on Day 253 (end of stress period) were used in the final statistical analysis due to the fact that Day 260 was overcast.

Turf color and cover were evaluated bi-weekly. Turf color was reported on a scale of 1-10 with 1 as brown dead grass, and 10 as dark green healthy turf. Turf cover was reported on a scale of 0 - 100, representing the percentage of area covered by green turfgrass.

Tissue N content was evaluated as Total Kjeldahl Nitrogen (TKN) of samples taken on Day 241. After oven drying, three 0.05g samples of turfgrass harvested from each subplot were digested in sulfuric acid with a mercuric oxide catalyst using a block digester, (Tecator Digestion System 40, 1016 Digester). The samples were then analyzed colorimetrically for TKN using an automated salicylate procedure utilizing the (Alpkem autoanalyzer, Alpkem Flow Solution Model 301).

Statistical analyses were run on data sets collected from the lysimeters and the subplots. A multivariate analysis of the data (MANOVA) was run based on irrigation frequency, leaching fraction and when applicable the N application rate. Variables analyzed included cumulative totals of ETa, irrigation amount ψ_M , ψ_{Lx} , g_a , tissue moisture content, turf canopy temperature, color, cover and soil water in storage. The data were analyzed at the end of stress and recovery periods and on Day 241 (Day of highest environmental demand).

Regression analyses were run on various parameters to describe the significance of varying cultural practices in the management of tall fescue in an arid climate. Only those regression equations that had p values <0.05 are reported, with a *, ** and *** indicating levels of significance of 0.05, 0.01 and 0.001 respectively.

CHAPTER 4

RESULTS

Treatments

The experiment was designed to establish clear differences in soil water status by varying both LF and irrigation frequencies. Estimates of ET from lysimeters was used as a feedback tool to adjust weekly irrigations so steady state LF conditions could be approached. Information on the water balances of each treatment at the end of the 119 day stress period are reported in Table 1. Analysis of variance indicated that irrigation amounts applied based on the ET feedback separated based upon the LF imposed ($p=0.05$, $n=20$) but not on the irrigation frequency imposed ($p=0.73$, $n=20$). A water savings of 60.4 cm was realized when the -0.40 LF was compared to the +0.15 LF over the 119 day stress period. Even comparing the 0.00 LF with the +0.15 LF still led to a savings of 19.8 cm over this same time period. Figure 3 illustrates that LF was highly correlated with Irrigation/Potential Evapotranspiration (I/ET_o) suggesting that irrigators could use knowledge of this relationship to predict LF ($I/ET_o = 1.04 + 1.03 \text{ LF}$, $R^2 = 0.96$).

All Plots irrigated at or below the 0.0 LF depleted soil water in storage relative to the maximum storage, as calculated as the mean storage value of the lysimeters watered at the +0.15 LF ($\text{Storage}^{\text{max}}$) on the first day of the experiment (Day 141). The ratio of water in storage at the end of the stress period relative to the maximum storage value is

plotted in Figure 4 as a function of the imposed LF. The data was fit to a third order polynomial ($\text{Storage}/\text{Storage}^{\max} = 0.85 + 1.39\text{LF} - 3.88\text{LF}^2 - 9.74\text{LF}^3$, $R^2=0.976^{***}$).

Table 1

Water Balance Parameters by Leaching Fraction and Irrigation Frequency on Final Day of Stress Period (Day 260)

LF	I		D(I)		$\Delta S(I)$		ETa (cm)		ETo
	D	TW	D	TW	D	TW	D	TW	
+0.15	127.60	127.20	63.90	59.35	2.75	8.35	93.80	94.30	105.40
0.00	112.90	102.20	11.35	23.25	7.45	8.05	105.00	92.50	
-0.15	95.30	90.10	1.35	3.85	25.15	23.05	102.10	93.40	
-0.25	85.90	76.70	6.25	2.70	36.80	36.75	96.10	88.20	
-0.40	66.50	67.50	0.05	0.30	42.70	43.05	82.20	83.50	
LSD	2.74		3.36		2.08		3.38		

D = daily irrigation, TW = twice weekly irrigation

Storage depletions were approximately 15, 40, 60 and 70% (0.00, -0.15, -0.25, -0.40 LF) of the maximum storage after 119 days of imposed treatments. Data from all treatments were included in this polynomial fit, regardless of the irrigation frequency imposed, which had a non-significant impact on the relationship ($p=0.904$, $n=20$).

As the soil water in storage declined, so did the drainage collected at the bottom of the lysimeters. Irrigation frequency had no significant effect on measured drainage. The date which drainage ceased during the stress period was tightly controlled by the LF

imposed indicating the impact deficit irrigation had on storage and internal drainage (End Day = $69.9 + 177 \text{ LF}$, $R^2=0.78^{***}$, where End Day equaled the number of days from inception of the experiment to cease of drainage.) Only the +0.15 LF lysimeters continued to drain throughout the stress period. By Day 190 all other lysimeters had ceased draining.

Matric potential was measured by means of a tensiometer in each lysimeter at a depth of 30 cm. Ψ_M estimates showed separation by LF ($p=0.001$, $n=16$) but not separation by irrigation frequency ($p=0.758$, $n=16$). The +0.15 LF treatment showed the least amount of stress at -6.33 ± 2.3 KPa on the final day of the stress period. The mean Ψ_M for the -0.25 LF treatments was -66.23 ± 10.5 KPa. The mean Ψ_M for the 0.0, and -0.15 LF treatments were -11.45 ± 2.2 and -64.88 ± 10.04 KPa. On the final day of the stress period Ψ_M positively correlated with LF ($\Psi_M = -26.31 + 3.52 \text{ LF}$, $R^2=0.83^{***}$). The -0.40 LF treatment were excluded from this analysis due to the apparent loss of suction on two of the four replicates.

Stress Period

The turfgrass showed signs of stress associated with falling soil water status and deficit LF irrigation treatments. By the end of the stress period on Day 260 the deficit LF treatments all showed some signs of stress as measured by color, cover, Ψ_X , matric potential, tissue moisture levels, and turf dry yield.

The effects of LF and soil water status were reflected on ETa. Analysis of variance of ET estimates showed separation by LF ($p=0.007$, $n=20$) but not separation by irrigation frequency ($p=0.108$, $n=20$). The 0.0 LF treatment showed the highest

estimated ET for the stress period at 98.75 ± 7.55 cm. The +0.15 LF treatment had an estimated ET of 94.05 ± 3.07 cm, while the deficit irrigation treatments showed estimated water use of 97.7, 92.15 and 82.85 cm (-0.15, -0.25, -0.40 LF). However, when mean values by treatment are examined the significance of frequency on ETa becomes apparent (Figure 5). The slope of the daily irrigation treatment is higher than that of the twice weekly, with a drop in value at +0.15 LF level. The twice weekly data was highly correlated with LF in a linear fit (TW ETa = $95.9 + 28.9\text{LF}$, $R^2 = 0.67^{**}$). The daily irrigation treatment showed less correlation with a linear fit (D ETa = $95.9 + 22\text{LF}$, $R^2 = 0.29$, $p = 0.112$) and greater correlation when fit to a second order polynomial (D ETa = $103.1 - 26.8\text{LF} - 2.02\text{LF}^2$, $R^2 = 0.93^{***}$). Figures 6 and 7 show ETa plotted by LF and irrigation frequency as compared to ETo. Arrow marks on the figures indicate the end of the stress period. The difference between ETa and ETo for lysimeters receiving the lowest irrigation amounts, -0.40 LF and the -0.25 LF treatments were more pronounced as the stress period progressed. The daily irrigation at +0.15 LF showed the greatest amount of variation in relation to ETo, while the other treatments appear to overlap the ETo line from week to week as the experiment proceeded.

Like Ψ_M , Ψ_{Lx} showed the effects of LF treatments and soil water status. Ψ_X estimates showed separation by LF ($p = 0.001$, $n = 20$) but not separation by irrigation frequency ($p = 0.315$, $n = 20$). The +0.15 LF treatment showed the least amount of stress at -1.105 ± 0.1455 MPa for the stress period. The mean Ψ_{Lx} for the -0.40 LF treatments was -3.445 ± 0.7432 MPa. The mean Ψ_X for the 0.0, -0.15, and -0.25 LF treatments were at -1.255 ± 0.1535 , -1.445 ± 0.2527 and -1.95 ± 0.4081 MPa. On the final day of the stress period Ψ_X was positively correlated with LF at ($\Psi_X = -1.33 + 3.94\text{LF}$,

$R^2=0.67^{***}$). Figures 8 and 9 show Ψ_X measured over time. A decreasing trend with time can be observed in the plots with water deficit conditions. The mean values of the -0.40 LF treatments declined to their lowest values on Day 253 for plots irrigated at both frequencies. Daily irrigated plots fell to -4.28 ± 0.028 MPa, while Ψ_X dropped to -3.42 ± 0.71 MPa for the plots irrigated twice weekly.

Stomatal conductance showed separation by LF ($p=0.01$; $n=20$), but not by irrigation frequency ($p=0.784$, $n=20$). The 0.0 LF treatment showed the highest mean g_s at $321.8 \pm 14.8 \text{ mol m}^{-2} \text{ s}^{-1}$. The +0.15 and -0.15 LF treatments had mean values of g_s of 267.3 ± 80.6 and $254.3 \pm 65.1 \text{ mol m}^{-2} \text{ s}^{-1}$ respectively. The -0.40 LF treatment showed the greatest response to stress at g_s of 93.5 ± 76.8 , while the -0.25 LF treatment had a value of $198.5 \pm 35.8 \text{ mol m}^{-2} \text{ s}^{-1}$. Stomatal conductance correlated with Ψ_X ($g_s = 365.6 + 75.3 \Psi_{Lx}$, $R^2=0.55^{***}$)

Turf canopy temperature differential estimates were separated by LF ($p=0.001$, $n=180$) but not by irrigation frequency or by N ($p=0.997$, and $p=0.803$ respectively, $n=180$). The +0.15 LF treatment showed the least amount of stress at $-0.15 \pm 2.0^\circ\text{C}$ on the final day of the stress period. The mean T_c-T_a for the -0.40 LF treatments was $7.2 \pm 3.9^\circ\text{C}$. The mean T_c-T_a for the 0.0, -0.15 and -0.25 LF treatments were 0.03 ± 1.5 ; 1.0 ± 2.2 and $2.9 \pm 2.9^\circ\text{C}$ respectively. On the final day of the stress period T_c-T_a inversely correlated with LF ($T_c-T_a = 0.530 - 12.8 \text{ LF}$, $R^2=0.43^*$).

Tissue moisture was evaluated from samples of turf taken from three evenly spaced locations within each subplot. Turf samples collected on the final day of the stress period showed significant variation based on LF ($P=0.001$, $n=180$), but not on irrigation frequency nor on N ($P=0.360$, and $P=0.408$ respectively, $n=180$). Mean tissue

moisture values ranged from $48 \pm 15\%$ for the -0.40 LF treatments to $68.8 \pm 6\%$ for the +0.15LF treatment. Tissue moisture correlated linearly with I/ETo (Tissue Moisture = $0.26 + 0.37 \text{ I/ETo}$, $R^2=0.52^*$) (Figure 10).

Turf Yield

Turfgrass dry yield separated by LF ($p=0.001$, $n=60$) and N ($p=0.001$, $n=60$) but not by irrigation frequency ($p=0.652$, $n=60$). Figure 11 shows stacked graphs of yield by I/ETo by N. Increasing the quantity of N led to greater correlation between irrigation and yield. ($R^2 = 0.68$, $p=0.001$; 0.566 , $p=0.001$; and 0.362 , $p=0.01$; for 2.4, 1.2 and 0.0 kg ha⁻¹ N respectively on Day 260). A multiple regression analysis showed that N and LF were positively correlated with dry yield (Dry Weight (g) = $143 + 259\text{LF} + 35.5\text{N}$, $R^2= 0.598$, $p=0.001$). The mean dry yield of the four subplots irrigated with +0.15 LF and fertilized with 2.4 kg ha⁻¹ N was 327.6 ± 108.6 grams. Yield dropped off quickly as irrigation and N decreased. The 0.0 LF with the 2.4 kg ha⁻¹ N showed a 30% decline in average yield while the +0.15 LF with 1.2 kg ha⁻¹ N treatment showed a 39.6% decline in yield. The amount of water applied had a greater influence over turfgrass dry yield than did fertility. The increase in yield as irrigation amounts increased was significantly higher than when compared to the increase in yield from the 0.0 to 2.4 kg ha⁻¹ N treatments. The average yield of the -0.40 LF subplots was 66.4% lower than the +0.15 LF subplots, while the average yield of the 0 N subplots was 41.4% below the level of the plots fertilized with 2.4 kg ha⁻¹ N.

Color

Color ratings for daily and twice weekly irrigation frequencies separated by LF and N treatments are shown plotted by time in Figures 12 and 13. The 2.4 kg ha⁻¹ N treatment showed the least amount of variability over both stress and recovery periods. Both the 0.0 and the 1.2 kg ha⁻¹ N treatments showed a decline in color over the course of the stress period in the plots watered with a deficit irrigation. As the irrigation deficit increased, both daily and twice weekly treatments showed a greater decline in color ratings at the peak of the stress period. Pre-experiment mean color rating for all plots was 8.47 ± 0.4 . The -0.40 LF treatment with 0.0 kg ha⁻¹ N declined to a mean value of 6.6 ± 0.6 at the end of the stress period on Day 260. The -0.15 LF treatment with 0 kg ha⁻¹ N declined to a value of 8.1 ± 0.5 on Day 260. In contrast, the +0.15 LF treatment with 0 kg ha⁻¹ N was 9.1 ± 0.3 on Day 260.

The lowest color rating during the stress period was a mean value of 4.3 ± 1.9 for the daily irrigation frequency, -0.40 LF with 1.2 kg ha⁻¹ N on Day 253. The twice weekly irrigation frequency declined to a mean value of 5.1 ± 1.7 for the -0.40 LF with 0 Kg ha⁻¹ N on Day 241. Water savings and Ψ_{Lx} were inversely correlated with color. Data from the end of the stress period was fit to a multiple regression ($\text{Color} = 9.40 + 0.658 \text{ I/ET}_o + 0.512 \Psi_{Lx}$, $R^2=0.68^{***}$). The three dimensional graph in Figure 14 illustrates the interaction. Water savings of 40% were obtained while a color rating of 8.0 was achieved when Ψ_{Lx} was measured at levels above -2 MPa. When I/ET_o dropped below 0.73 and Ψ_{Lx} below -2.48 MPa, color was shown to drop off rapidly.

Cover

Cover ratings were evaluated as a percent of green turf on three subplots within each treatment that received differing amounts of N. The average value of three regularly spaced evaluations within each subplot demonstrated that cover ratings separated by LF treatments ($p=0.001$, $n=180$) but not by frequency or N ($p=0.587$; and $p=0.295$ respectively; $n=180$). The +0.15 LF treatment showed the least amount of variability over both stress and recovery periods. At the end of the 119 day stress period the +0.15 LF treatment had a mean cover rating of $99.6 \pm 1.4\%$. As the irrigation deficit increased the turf showed a greater decline in cover ratings at the peak of the stress period. The -0.40 LF treatment declined to a mean value of $56.1 \pm 19.6\%$. The -0.25 LF declined to $82.9 \pm 15.1\%$, while the -0.15 and 0.0 LF treatments remained above 90% cover (93.1 ± 7 , and $98.8 \pm 2.5\%$ respectively). The -0.40 LF treatment average cover was rated below 90% cover on day 28 of the stress period at $85.5 \pm 25.1\%$, while the -0.25 LF treatment declined to $83.8 \pm 22.8\%$ on day 56. The -0.15 LF average cover was rated below 90% on day 100 at $86.2 \pm 17.6\%$. The two non-deficit treatments never declined below 90% cover. Leaching fraction was positively correlated with turf cover at the end of the stress period (Cover = $95.9 + 75\text{LF}$, $R^2=0.53^{***}$). Cover and color were also significantly correlated (Cover = $-26.1 + 13.4 \text{ Color}$, $R^2=0.75^{***}$).

The lowest cover ratings during the stress period were 52.7 ± 21.9 percent occurring on Day 241 on the -0.40 LF treatment. The -0.25 LF treatment declined to its lowest level of $78.3 \pm 22.7\%$ on Day 246, while the -0.15 LF treatment declined to its lowest cover rating of $86.2 \pm 17.6\%$ on Day 241.

Color and cover both showed a threshold relationship to I/ET_o, as illustrated in Figures 15 and 16. Color and cover were maintained at optimum levels down to I/ET_o ratios of 0.8. I/ET_o ratios in the range of 0.7 to 0.8 revealed only slight evidence of stress (cover greater than 90% and color greater than 8.0). Regressions run on data collected for I/ET_o ratios of 0.8 and below showed strong correlation, $\text{Color} = 0.57 + 9.8 \text{ I/ET}_o$. $R^2=0.66^{***}$ and $\text{Cover} = -10.0 + 140.2 \text{ I/ET}_o$. $R^2=0.82^{***}$

Tissue Nitrogen

On Day 241, during the height of the stress period, tissue moisture was measured along with TKN. Total Kjeldahl Nitrogen values separated by all of the experimental factors, irrigation frequency, LF and N. Leaching fraction and N had the greatest impact on TKN ($p=0.001$, $n=180$) while tissue N separated out by frequency at the 0.05 level ($n=180$). Mean values of TKN were $1.4 \pm 0.3\%$ for the driest plots with the 0 Kg ha⁻¹ of N fertilizer. The wettest treatment with 2.4 Kg ha⁻¹ of N fertilizer had a mean value of $2.6 \pm 0.3\%$ tissue N. A multiple linear regression analysis of the relationship between TKN and the experimental factors illustrated a positive correlation between LF, frequency and N fertility with N uptake. ($\%N = 1.76 + 0.241 \text{ N} + 1.15 \text{ LF} + 0.0174 \text{ Frequency}$, $R^2=0.57^{***}$).

Mean tissue moisture values on Day 241 ranged from $34 \pm 7\%$ for the -0.40 LF treatments to $67 \pm 5\%$ for the +0.15 LF treatment. Tissue moisture and color correlated inversely with Tc-Ta (Tissue Moisture = $0.59 - 0.024 \text{ Tc-Ta}$, $R^2=0.68^{***}$; Color = $8.48 - 0.025 \text{ Tc-Ta}$, $R^2=0.643^{***}$). Figure 17 shows the relationship between tissue moisture and Tc-Ta.

Both tissue moisture and TKN showed a linear relationship with color. Color was well correlated with tissue moisture, $\text{Color (Day 241)} = 2.90 + 9.25 \text{ Tissue Moisture}$, $R^2 = 0.749^{***}$ (Figure 18). However, less color correlation occurred with TKN at Day 241 ($\text{Color} = 3.19 + 0.230 \text{ TKN}$, $R^2 = 0.36^{***}$). The interaction of tissue N and moisture in producing color was examined using a variable created through multiplying mean TKN values by mean tissue moisture for each subplot. Data was fit to a second order polynomial and accounted for a significantly higher amount of the variation in the turf color ratings ($\text{Color} = 2.75 + 0.68x - 0.02x^2$, $R^2 = 0.96$, where $x = \text{TKN} * \text{tissue moisture}$). This relationship is illustrated in Figure 19. The 0.15 LF treatments, which received 1.2 or 2.4 Kg ha⁻¹ N, maintained color ratings above 9 at the end of the stress period. Both irrigation frequencies at 0.0 LF and 2.4 Kg ha⁻¹ N were rated above 9.0. As irrigation LF was reduced, color ratings were maintained above a rating of 8.0 by the N treatment. Mean color ratings for LF of the -0.25 LF and -0.15 LF treatments at 2.4 Kg ha⁻¹ N were 8.0 and 8.7 respectively. The 0.0 LF with 1.2 or 0.0 kg ha⁻¹ N also maintained color ratings ($\text{Color} = 2.75 + 0.68x - 0.02x^2$, $R^2 = 0.96$, where $x = \text{TKN} * \text{tissue moisture}$). This relationship is illustrated in Figure 19. The 0.15 LF treatments, that received 1.2 or 2.4 Kg ha⁻¹ N, maintained color ratings above 9.0 at the end of the stress period. Both irrigation frequencies at 0.0 LF and 2.4 Kg ha⁻¹ N were rated above 9.0. As irrigation LF was reduced, color ratings were maintained above a rating of 8.0 by the higher nitrogen application. Mean color ratings for LF of the -0.25 LF and -0.15 LF treatments at 2.4 Kg ha⁻¹ N were 8.0 and 8.7 respectively. The 0.0 LF with 1.2 or 0.0 Kg ha⁻¹ N also maintained color ratings at 8.4 and 8.1 respectively. The remaining deficit irrigation treatments with 1.2 or 0 Kg ha⁻¹ N had mean color ratings below 8.0 on Day 241.

Impacts of Deficit Irrigation

When the -0.40 LF deficit irrigation treatments are separated out and examined over time the interaction of declining soil moisture on the turfgrass physiology becomes apparent. Figures 20 through 26 show the impact of increasing stress as the -0.40 LF treatment is imposed, available soil moisture storage declines and the plants respond to stress. As soil moisture declines steadily over time (Figure 20) plant response tends to show a threshold response in ETa, and cover (Figures 21 & 22). Turfgrass cover and ETa appear to remain steady as $\text{Storage}/\text{Storage}^{\text{max}}$ remains above 0.52. However below this value they decline rapidly. Color, Tissue moisture content, Ψ_M , and Ψ_X declined slowly from $\text{Storage}/\text{Storage}^{\text{max}} \gg 1.0$ to 0.52. However below this apparent threshold value they declined more rapidly.

Recovery

After the treatment period had ended (Day 260), a recovery period was imposed in which all plots were irrigated with 0.15 LF. By Day 288 all treatments recovered to equal or better pre-experiment visual quality status. The recovery period was continued until Day 331, with continued increase in soil water in storage. The effects of LF and N treatments continued to be evident during recovery, although not for all parameters. Analysis of variance indicated that while plant parameters of color, cover, g_s , and Ψ_X did not separate significantly by LF treatment, that Tc-Ta, dry yield and tissue moisture content continued to separate during the recovery period ($p=0.05$, $p=0.01$ and $p=0.001$ respectively, $n=20$). Soil moisture parameters of $\text{Storage}/\text{Storage}^{\text{max}}$, drainage and Ψ_M

also continued to show separation ($p=0.001$ and $p=0.05$ respectively, $n=20$) by treatments throughout the recovery period.

The impacts of the imposed LF on soil water storage lasted well into the recovery period, with an excellent correlation between LF and soil water storage on Day 288 ($\text{Storage}/\text{Storage}^{\text{max}} = 0.779 + 0.843 \text{ LF}$, $R^2 = 0.83^{***}$). Although the correlation was not as strong by the end of the recovery period, a significant relationship still existed ($\text{Storage}/\text{Storage}^{\text{max}} = 0.912 + 0.393 \text{ LF}$, $R^2 = 0.61^{***}$). The relative soil water depletion was demonstrated through the inverse relationship between the LF and the change in soil water storage from the end of the stress period (Day 260) through the end of the recovery period [$\Delta \text{Storage}/\text{Storage}^{\text{max}} = -0.00317 - 0.426 \text{ LF}$, $R^2 = 0.86^{***}$; and $\Delta \text{Storage}/\text{Storage}^{\text{max}} = 0.130 - 0.876 \text{ LF}$, $R^2 = 0.90^{***}$; where $\Delta \text{Storage}/\text{Storage}^{\text{max}} (\text{Day X}) = \text{Storage}/\text{Storage}^{\text{max}} (\text{Day X}) - \text{Storage}/\text{Storage}^{\text{max}} (\text{Day 260})$].

A one way ANOVA of Ψ_M based on the experimental LF treatments continued to show separation on Day 288 of the recovery period, ($p=0.001$, $n=20$). Both the -0.40 LF and -0.25 LF treatments showed little recovery of matric potential at the 30 cm depth by Day 288. The -0.15 LF lysimeters showed a rise in Ψ_M of approximately 23%, while the 0.0 and 0.15 LF treatments had approximately the same matric potentials during the experimental and recovery periods. Irrigation frequency continued to show no significant impact on the matric potential on Day 288 and Day 331, ($p=0.852$, and $p=0.773$ respectively, $n=20$). By Day 331, Ψ_M continued to separate by LF but at a lower level of significance ($p=0.05$, $n=20$). The -0.40 LF treatment had a mean value of -15.5 ± 3 KPa, whereas the mean value for all other treatments was -7.9 ± 3 KPa.

The impact of deficit irrigation and resultant decline in soil water in storage was evident on drainage from the lysimeters during the recovery period. All four of the 0.15 LF lysimeters continued to drain throughout the stress and recovery periods. By Day 288, 2 of the 0.0 LF lysimeters had resumed draining. By Day 331, 11 of the 20 lysimeters had resumed draining, including all of the 0.0 LF lysimeters, and 3 of the 4 -0.15 LF lysimeters. When considered separately from drainage collected during the stress period, drainage during recovery separated by LF but not by the irrigation frequency imposed during the stress period ($p=0.05$, and $p=0.615$ respectively, $n=20$). Since the irrigation treatment was identical during the recovery period, the depletion of storage during the experimental period must have been the driving force in separating drainage during recovery.

Dry yield from the end of the stress period to Day 288 had a significant correlation with both the LF and N treatments imposed during the stress period (Dry yield Day 288 = $25.8 + 19.6 N + 70.2 LF$, $R^2=0.73^{***}$). A similar analysis run at the end of the experiment showed that both N and LF influenced dry yield, but that the significance of LF was less important (Dry yield Day 331 = $20.0 + 9.07 N + 16.0 LF$, $R^2 = 0.65^{***}$).

Color and cover ratings showed significant recovery for even the most deficit irrigation treatments. By Day 288 turf cover had recovered to 100% on all treatment plots. All treatments maintained 100% cover throughout the recovery period. Color ratings failed to separate by LF or irrigation frequency, but did separate by N treatment on Day 288 ($p=0.54$, $p=0.369$, and $p=0.001$ respectively, $n=180$). The -.40 LF treatment with 0 Kg ha⁻¹ N declined to a mean value of 6.6 at the end of the stress period on Day 260 and recovered to 8.3 on Day 288. The -.15 LF treatment with 0 Kg ha⁻¹ N declined

to a value of 8.1 on Day 260 and recovered to a value of 8.46 on Day 288. In contrast, the color rating on the +0.15 LF treatment with 0 Kg ha⁻¹ N was 9.09 on day 260 but only 8.75 on Day 288. A linear regression fit to the increase in color rating from Day 260 to Day 288 showed an inverse correlation between the rise in color rating and the experimental LF, ($\Delta\text{Color} = 0.131 - 3.99 \text{ LF}$) indicating a greater level of recovery on the subplots which had been most stressed. Color values declined slightly from Day 288 to Day 331, but for the subplots receiving N, color values were still at or above pre-experiment levels. Only the 0.0 kg ha⁻¹ N subplots had color values by Day 331 significantly below pre-experiment values ($p=0.05$, $n=180$).

CHAPTER 5

DISCUSSION

This study demonstrated the viability of twice weekly irrigation and deficit irrigation strategies on tall fescue turfgrass in arid Southern Nevada. Irrigating twice a week, as compared to daily, saved water. The interaction of deficit and twice weekly irrigation strategies produced water saving in a range of 6 to 29% without significant loss in cover or color. Turfgrass color did not separate significantly based on frequency, while it did separate based on irrigation amount. This suggests that the water savings obtained through reducing irrigation frequency can be achieved in an arid climate on tall fescue without significant impact on turf quality. By restricting sprinkler irrigation to two days a week, municipalities can use this information to reduce water demands. Using an odd-even address assignment system, 51 irrigation days can be saved in a 17-week summer season in Southern Nevada. Reducing the peak even further can be accomplished by assigning businesses to one of two non-residential days a week, although this will decrease the savings in terms of number of irrigation days. Drought and water shortage management programs from across the United States often use landscape watering restrictions to reduce peak demands (AWWA, 1992). The results of this study support the use of such measures in Southern Nevada, as a measure to reduce peak demands, although public education on the impact decreased irrigation frequency would have on turfgrass would be a necessary component for a successful program. Twice a week

watering restrictions have been successfully used to reduce water use system-wide in summertime drought situations in some semi-arid communities (Brown, 1998). This study suggests that Las Vegas water managers can offset peak summertime demands by imposing twice a week watering restrictions while assuring customers that their lawns will not die.

The maintenance of color and cover ratings while saving water through reducing irrigation frequency were similar to field experiments performed in Colorado that found that irrigation frequencies of up to 14 days between irrigations failed to show significant separation in turf quality at 75 or 100% of ETo (Fry and Butler, 1989a), but did find differences when fescue was irrigated at 50% ETo. However, Brian *et al.* (1981) found significant reduction in dry matter production and water use in 'Alta' tall fescue when irrigation frequency was decreased from 6 to 8 times over a two week period to 2 to 3 times over two weeks in an experiment where temperature was held at a constant 34.5°C.

The irrigation frequency findings in this study contrast with local watering recommendation that currently emphasize daily irrigation during summertime months (SNWA, 2001). Other studies have found that less frequent irrigation helps strengthen turf root systems (Qian and Fry, 1996) and condition plants to better resist the effects of drought (King and Bush, 1985; Marcum, 1994). These results suggest that landscape managers in the arid southwest can successfully use twice a week irrigation schedules as a landscape management tool while minimizing plant stress, as long as the I/ETo is above the 0.8 threshold for tall fescue determined by this experiment.

Total irrigation amounts and ETa of daily versus twice weekly irrigation treatments were significantly different for the middle three LF treatments, but not on

either the wettest (+0.15) or driest (-0.40) treatments. Excessive quantities of water may result in waterlogged soils and lack of aeration in the root zone (Beard, 1973). This phenomenon may explain the observed reduction in ETa in the +0.15 LF treatment in this study. The similarity between ETa values for the -0.40 LF treatments is likely explained by the lack of sufficient water to sustain plant growth and transpiration processes even on the daily watered plants.

Twice a week irrigation scheduling showed savings of 10, 5.8 and 11.9% for the 0.0, -0.15 and -0.25 LFs respectively (10.7, 5.2 and 9.2 cm respectively). This compares with Kopec's recommendations to irrigators in Arizona (1990), achieving a 15% reduction in irrigation quantity by shifting irrigation frequency. He recommended changing from an every other day watering schedule to a three times weekly schedule over a two week period. By reducing from irrigations to 6 irrigations over two weeks, and irrigating for the same amount of time each run, the water savings were achieved. The results of this study suggested a greater water savings can be obtained by combining the twice weekly irrigation with the deficit irrigation strategies. The maintenance of acceptable color and cover ratings by the -0.15 LF treatment suggests that deficit irrigation strategies can work in the arid southwest. Water savings achieved by using the -0.15 LF strategy were 33.3 and 37.1 cm (approximately 26 and 29%) for the daily and twice weekly frequencies respectively. However, this strategy may need to be limited to occasional use in Southern Nevada, where landscape irrigators use Colorado River water, which is high in dissolved salts (Devitt *et al.*, 1992).

Plant Physiology

This study found no significant separation in g_s , ψ_{Lx} , ψ_M , or T_c-T_a based upon irrigation frequency. In contrast, Qian and Fry (1996) found ψ_L was 32 to 36% lower in infrequently watered than daily watered Meyer zoysiagrass. However, the zoysiagrass was watered and the first signs of wilt rather than on a regular schedule.

Elberson and West (1996) found reduced stomatal conductance in water stressed treatments of tall fescue genotypes grown in a greenhouse experiment. Richardson *et al.* (1993) reported strong correlations between g_s and ψ_{Lx} when fitted to second order regressions for tall fescue. This study found a linear relationship between g_s and ψ_{Lx} at the end of the stress period with no apparent threshold. However, thresholds did exist if the parameters were plotted as a function of I/ET_o . Ghashghaie and Saugier (1989) reported that both stomata and plant growth in tall fescue were highly sensitive to N deficiency. Although this study did not examine the effects of N on g_s , the lower yields for 1.2 and 0.0 kg ha⁻¹ N subplots are in agreement with the Ghashghaie and Saugier study.

Dry yield from the subplots separated significantly based on LF and N treatments both during the stress and recovery periods. The slopes of the dry yield versus I/ET_o regression curves for the low and no N treatments were almost identical (Figure 11) at 178.9 and 183.5 respectively. They were well below the slope of the 2.4 kg ha⁻¹ treatment at 363.6 indicating slower plant growth and potential water savings could be achieved by managing N as a conservation tool. Bowman and Macaulay (1991) found ET to be strongly correlated with dry yield in a study of 20 tall fescue cultivars.

Biran *et al.* (1981) noted that at temperatures ranging from 30 to 35°C the transpiration rate of tall fescue increased dramatically. The mid-day high temperatures in Southern Nevada averaged 34.6°C throughout the stress period, and was above 30°C for 14 of the 17 weeks of the experiment. The high temperatures in this study appeared to be the driving force in water use and stress observed in tall fescue. The higher mid-day temperatures on Day 241 versus those on Day 260 (38.1 versus 22.6°C) were mostly likely what caused the interaction found between treatments on tissue moisture, Tc-Ta, and turf quality (color and cover)(Table3).

Turfgrass studies have shifted over the years to evaluating not only biomass but also visual quality. When turfgrass is used in an urban setting, the aesthetics of the landscape, whether it be a lawn, a playing field or a golf course are desirable and an indication of plant health (Biran *et al.*, 1981; Feldhake *et al.*, 1984; Guz *et al.*, 1998).

The I/ETo threshold effect on color and cover found in this study reinforces similar effects found in a line source gradient study on tall fescue performed in Las Vegas, Nevada (Dean *et al.*, 1997). By following ETo, and multiplying by a factor of 0.8, the irrigator who wishes to save water through the use of deficit irrigation could maintain turf color and cover (Figures 15 and 16). Above the 0.8 threshold, turf quality ratings of 100% cover and color ratings as high as 9 were achieved on Day 260.

At the end of the stress period, color ratings of 8 or higher were associated with turf canopy temperatures lower than ambient temperatures and relative tissue moisture contents greater than 60% (Figures 17 and 18). Turf canopy temperatures below ambient temperature are an indication of healthy, adequately transpiring turf (Clark and Hiler, 1973; Kramer, 1983). Figure 14 indicates that water savings of up to 20% were achieved

while maintaining color ratings well above a rating of 8.0 and ψ_{Lx} values above -1.5 MPa. As the color ratings dropped toward 8.0, water savings of between 30 and 40% were attained, and ψ_{Lx} values were between -1.5 and -2.5 MPa. Figure 14 elucidates and underlying relationship between water savings, plant stress and color. A step like function existed indicating that greater water savings could occur if color and ψ_{Lx} tradeoffs were acceptable. Although plant stress increased with these water savings, it did not exceed levels which would be associated with stomatal closure and the cessation of plant growth. However, below the color rating of 8.0, water savings in excess of 40% were achieved, but ψ_{Lx} values in the range of -2.7 to -4.4 MPa occurred which is an indication that tall fescue is being subjected to severe stress (Johnson *et al.*, 1993).

The I/ETo color threshold curve gives landscape managers an additional tool to evaluate stress relations, and to plan for water savings in tall fescue without waiting for leaf rolling, loss of leaf turgor or other indications of more severe plant stress which have been utilized in previous studies (Fry and Butler, 1984; Levitt, 1980). This study demonstrated the value of color as an indicator of plant health. However, Kopec (1990) cautioned that deficit irrigation is best practiced on turf areas which are not subject to high foot traffic.

As the stress period progressed, ETa levels dropped well below ETo for the -0.25 and -0.40 LF treatments (Figure 6 and 7). On the final day of the stress period, g_s , ψ_{Lx} and turf dry yield of the -0.40 LF treatment were well below the values of the -0.15 , 0.00 , and $+0.15$ LF plots, indicating that the growth processes had been affected by the imposed treatments. Soil water in storage was not capable of sustaining plant needs, and over the final several weeks of the stress period turf color and cover values also declined.

Guz *et al.* (1998) found similar declines in turf quality ratings with large irrigation deficits on St. Augustine and Bermuda grasses in a San Antonio, Texas study.

The driest irrigation treatment showed the greatest stress response. The deficit of -0.40 LF caused a cessation of plant growth, the discoloration and desiccation of significant amounts of plant leaf tissue resulting in the deepest losses of plant color and cover of any of the treatments. At -0.40 LF, the water provided was equivalent to 0.63 ± 0.01 ETo by Day 260. The water in soil storage was sufficient to supplement the deficit in irrigation water until Day 197 when $\text{Storage/Storage}^{\text{MAX}}$ reached approximately 0.52 and mean total soil water potential (ψ_T)(soil psychrometer) reached -2.1 MPa. After this threshold had been reached plant physiological processes declined rapidly. In Biran *et al.* (1981), tall fescue ETa declined rapidly after all irrigation was ceased for 13 days and ψ_T reached -1.5 MPa. However the complete recovery of all -0.40 plots to pre-experiment levels of color and cover by Day 288 indicates that plant death did not occur.

Nitrogen and Water

Both tissue moisture and TKN showed strong positive correlation with turf color. The correlation of color with tissue moisture ($R^2=0.75^{***}$) was expected by tissue N did not correlate well in a linear fashion ($R^2=0.36^{***}$). However, the interaction of tissue N and tissue moisture provided the strongest correlation with color ($R^2=0.96^{***}$). As indicators of tissue health, nitrogen's role as a building block of proteins, enzymes and hormones (Novoa and Loomis, 1981), and water's essential contribution (Levitt, 1980) to plant health and viability are reflected in turf color (Feldhake *et al.*, 1984; Fry and Butler,

1989a). The interaction (Figure 19) indicates that tradeoffs exist between N and irrigation in maintenance of color values.

Beard (1973) recommended N fertility for tall fescue to be in the range of 2.0 to 10.0 kg ha⁻¹ per growing month. In contrast, the application of 1.2 kg ha⁻¹ produced acceptable quality turf on all plots irrigated at -0.1 LF or greater. The tissue N and moisture interaction on color indicates that landscape managers need to balance N with water needs to provide optimum results while conserving both.

Tissue N varied significantly with all three of the imposed treatments, although more with fertilizer N and LF ($p < 0.001$) than with irrigation frequency ($p = 0.05$). Tissue N was reduced in low-N fertilized plants compared to high-N fertilized plants. Measured as a percent of dry weight, N was 2.2% for low-N and 3.1% for high-N plants, with no color differences. In an experiment in which water was not a limiting factor, Belanger *et al.* (1992) found N to be limiting in tall fescue growth.

Figures 12 and 13 show that the deepest drop in color ratings was on the -0.40 LF plots, low-N subplots, irrigated daily which reached 51% of pre-experiment values on Day 253. The 0.0 kg ha⁻¹ N subplots, irrigated twice weekly at -0.40 LF reached their lowest rating on Day 241 at 61% of pre-experiment values. The apparent increase in color ratings prior to the end of imposed stress was likely caused by a reduction in environmental demand. Daily high temperatures fell from a peak for the growing season of 38.1°C on Day 241, to 22.5°C on Day 260 at the end of the stress period, which was a partly cloudy day. Cover showed similar responses to stress and an initial recover that preceded the end of the stress period. The lowest cover rating reached was 48% by the -0.40, low-N subplots on Day 241.

Recovery

In a study of cotton plants grown under different N regimes and exposed to drought stress, Radin and Parker (1979) found that high N plants wilted beyond recovery while low N plants did not wilt after six days without water. Gashgaie and Saugier (1989) examined the effects of N deficiency and water deficits on tall fescue and found that ψ_{Lx} recovered to a greater degree on the N deficient than on the high N plants. The results of this experiment showed a greater level of recovery for high N treatments as measured by color and dry yield, but no significant difference in Tc-Ta whereas ψ_{Lx} was not measured on the subplots which were treated with lower levels of N.

Qian and Fry (1996) found that 'Meyer' zoysiagrass showed higher quality ratings during drydown and recovery periods when watered infrequently rather than daily. In contrast this study found no significant separation in turf quality ratings of tall fescue based on frequency during drydown, and a slight increase (1.0%, $p=0.05$) in quality for daily watered plots compared to twice weekly after recovery.

In other studies of tall fescue, the relative improvement of stressed versus non-stressed plants has been noted (King and Bush, 1985). The increase in color in this experiment followed a similar pattern with regard to irrigation amount, with the lowest treatments showing the greatest recover. However, the higher N subplots had higher color ratings at the end of recovery relative to the low or no N plots.

Slowing growth and plant response to lower daily temperatures, in addition to the impact of the treatments, may have contributed to declines in recover color ratings from Day 288 to Day 331.

The continued separation of dry yield by plots during the course of the recover

period, and the reduced yield for deficit plots may be explained by the mowing height at which the turf was harvested. However, all of the plots, even the most stressed treatments, returned to 100% cover ratings within four weeks. This study did not evaluate leaf elongation rates, but clearly, the 5.1 cm height that leaves would need to reach would take some time in the case of plots where plants had been desiccated and growth had ceased or slowed dramatically during the stress period.

In conclusion, the results of this study provide water managers several tools for water conservation. The water savings from twice a week frequency, without loss of turf quality, can be used to estimate and achieve reductions in peak summer demand by local water managers. The results can also be used to educate local landscape irrigators and homeowners to the benefits of reduced water bills through twice a week watering. The maintenance of color and cover by tall fescue exposed to mild deficits supports the use of deficit irrigation strategies by irrigators interested in reducing summer irrigation bills. The recover of all plots, even the most deficient, to pre-experiment levels of turf quality and plant physiological health suggests that further savings can be achieved in times of water shortage, through imposition of larger deficit irrigation strategies. The apparent I/ET_o and soil moisture threshold values in the deficit treatments provides another tool landscape managers can use who have access to weather stations and soil moisture monitoring equipment. The interaction of N and water on turf color and yield suggests that further study is needed to quantify even greater water savings through a better understanding of the relationship of water, N and ET_a .

APPENDIX A

TABLES AND FIGURES

Table 2. Analysis of variance and significant effects of LF, frequency, and N on various soil and plant parameters (Day 260)

Factor	df	g	Ψ_x	Ψ_M	Storage/ Storage^{Max}	ETa	I	Drainage	Color	Cover	Tissue Moisture	Tc-Ta	Dry Yield
LF	4	***	***	***	***	**	***	***	***	***	***	***	***
Freq	1	NS	NS	NS	NS	*	**	NS	NS	NS	*	NS	NS
N	2								***	NS	NS	NS	***
LF x Freq	4	NS	NS	NS	NS	NS	*	NS	NS	NS	**	NS	NS
LF x N	8								NS	NS	NS	NS	NS
Freq x N	2								NS	NS	NS	NS	NS
LF x Freq x N	8								NS	NS	NS	NS	NS

NS Not Significant

Table 3. Analysis of variance and significant effects of LF, frequency, and N on various soil and plant parameters (Day 331)

Factor	df	g _a	Ψ_x	Ψ_H	Storage/ Storage ^{Max}	ETa	I	Drainage	Color	Cover	Tissue Moisture	Tc-Ta	Dry Yield
LF	4	*	NS	NS									
Freq	1	NS	NS	NS	NS	*	**	NS	NS	NS	*	NS	
N	2								***	NS	NS	NS	
LF x Freq	4	NS	NS	NS	NS	NS	*	NS	NS	NS	**	NS	
LF x N	8								NS	NS	NS	NS	
Freq x N	2								NS	NS	NS	NS	
LF x Freq x N	8								NS	NS	NS	NS	

NS Not Significant

Table 4. Analysis of variance and significant effects of LF, frequency, and N on various soil and plant parameters (Day 331)

Factor	df	g	Ψ_x	Ψ_H	Storage/ Storage ^{Max}	ETa	I	Drainage	Color	Cover	Tissue Moisture	Tc-Ta	Dry Yield
LF	4	*	NS	NS	***	NS	NS	*	***	NS	NS	***	***
Freq	1	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS
N	2								***	NS	***	*	***
LF x Freq	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
LF x N	8								***	NS	NS	NS	NS
Freq x N	2								NS	NS	NS	NS	NS
LF x Freq x N	8								**	NS	NS	*	NS

NS Not Significant

Figure 3. I/ETo by Leaching Fraction (Day 260)

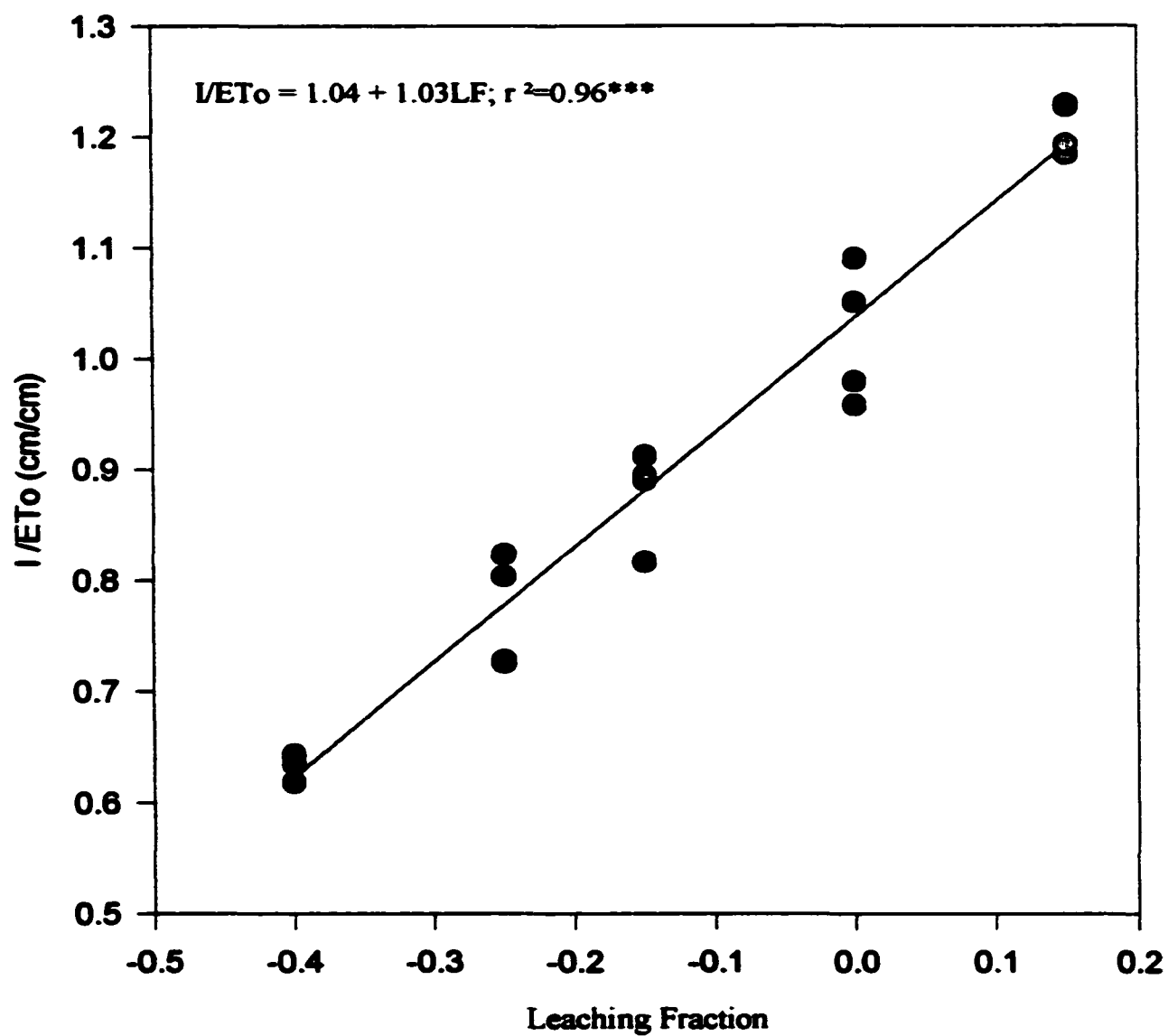


Figure 4. Storage/Storage^{Max} by Leaching Fraction (LF)

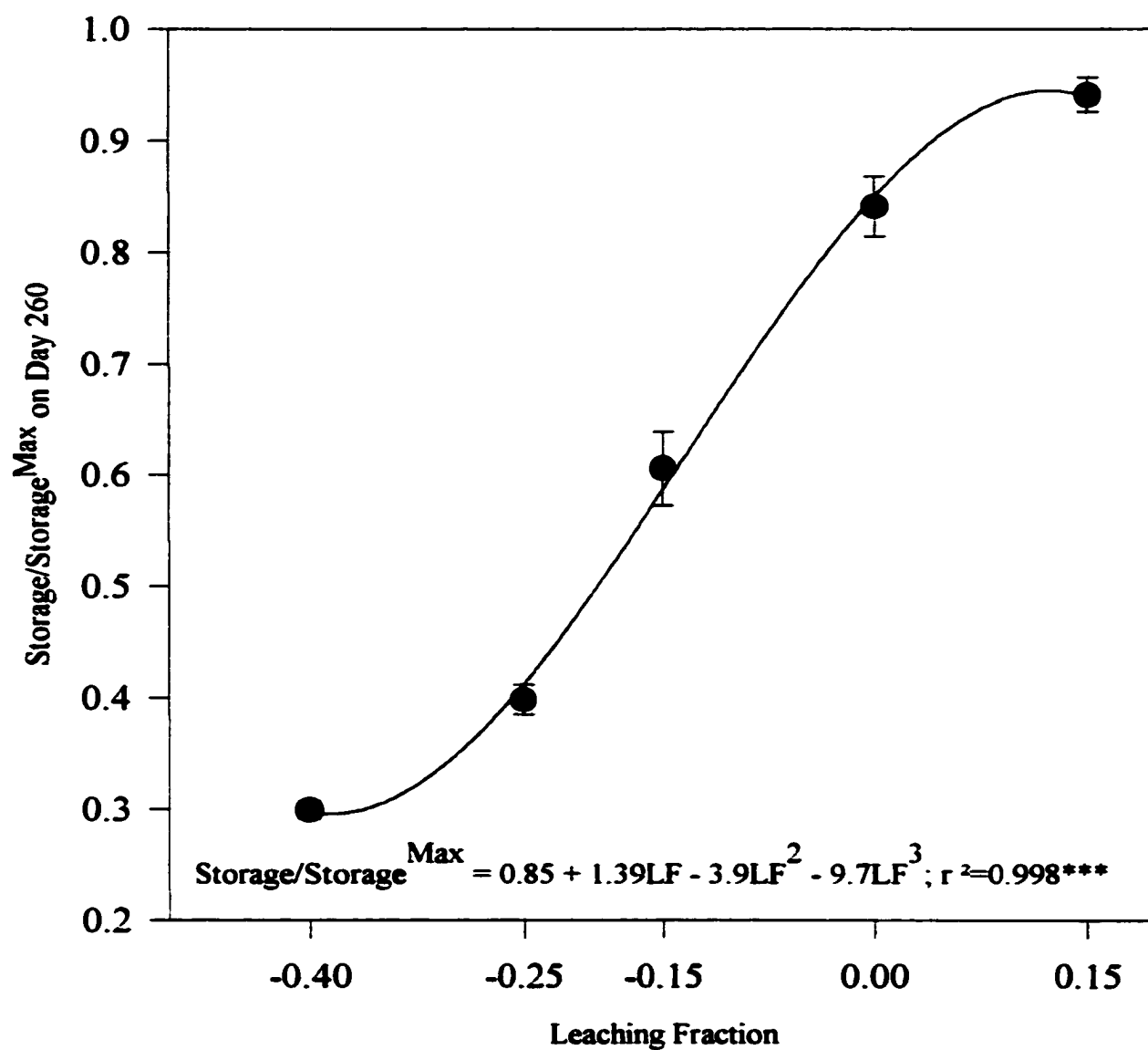


Figure 5. ETa by Leaching Fraction and Frequency

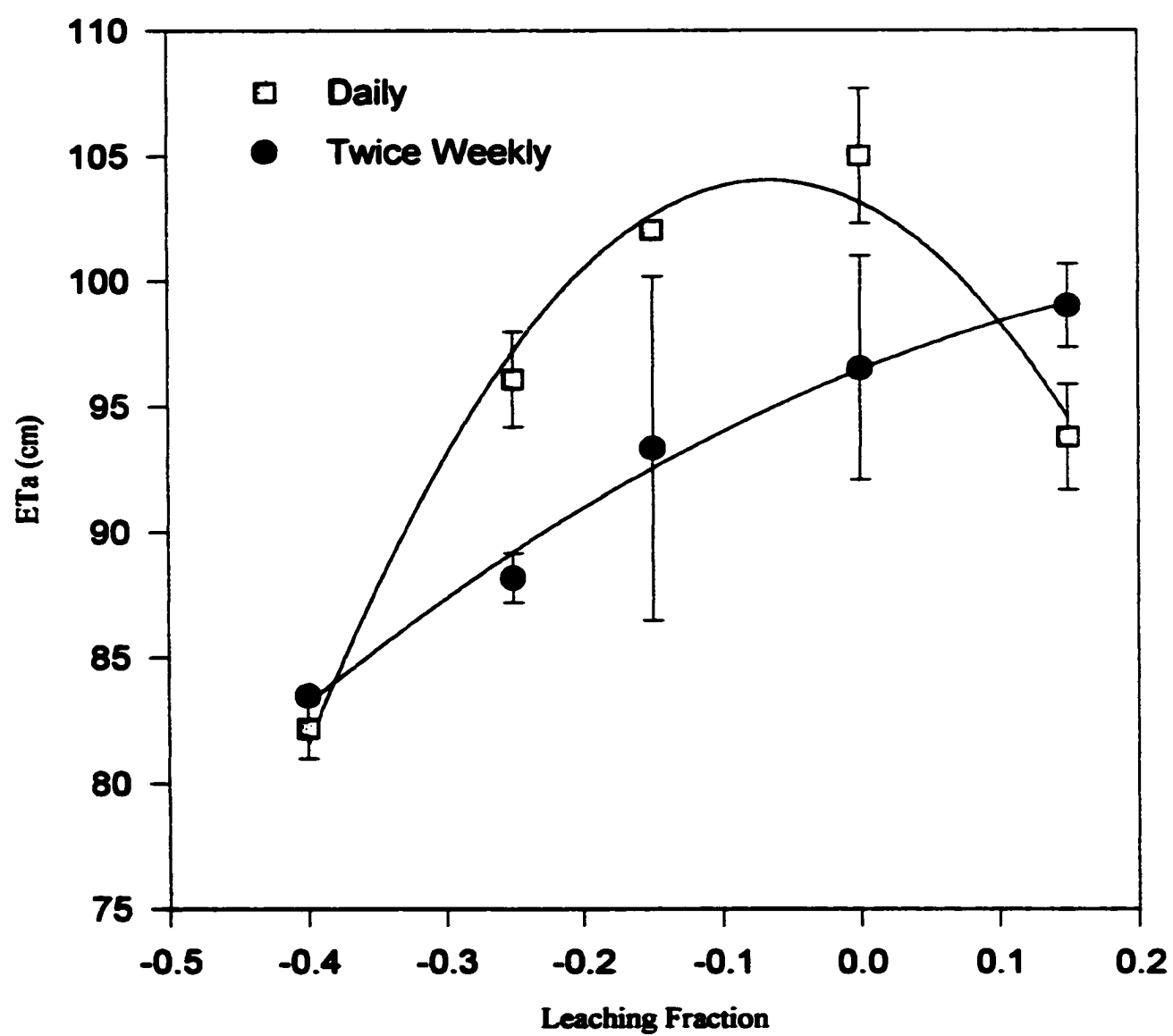


Figure 6. Daily Irrigation ETa vs ETo by LF Over Time

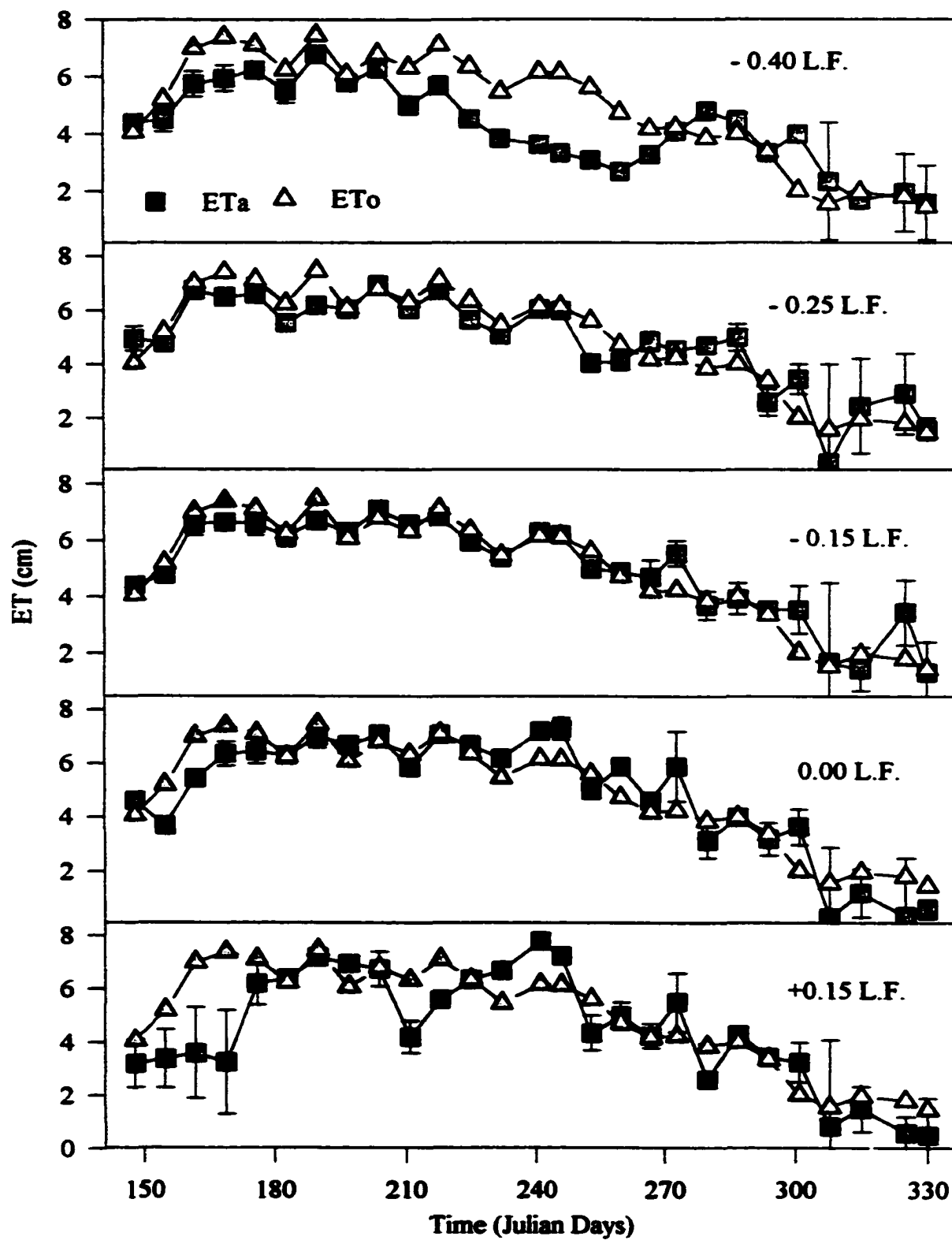


Figure 7. Twice Weekly Irrigation ETa vs ETo by LF Over Time

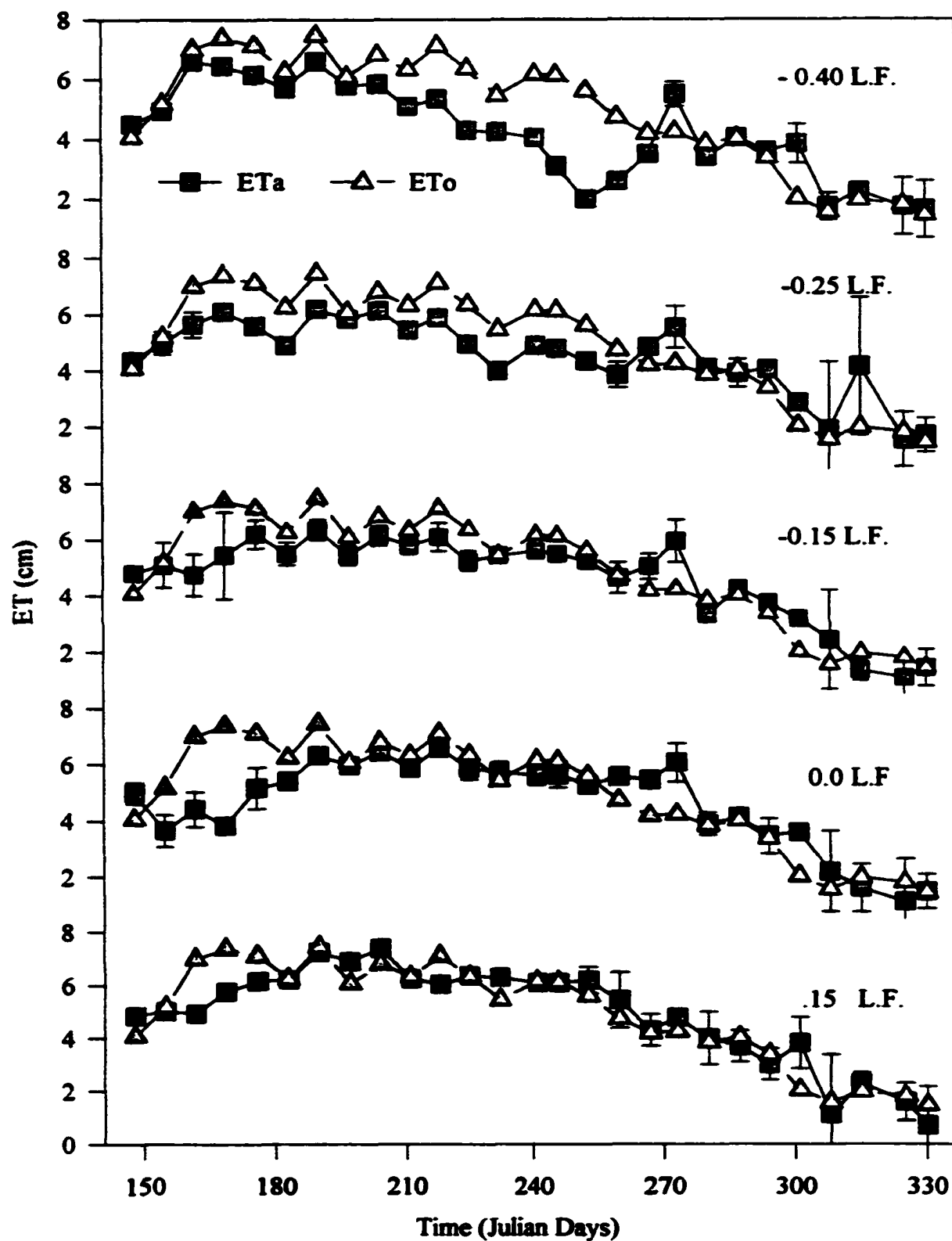


Figure 8. Daily Irrigation Leaf Xylem Water Potential by LF Over Time

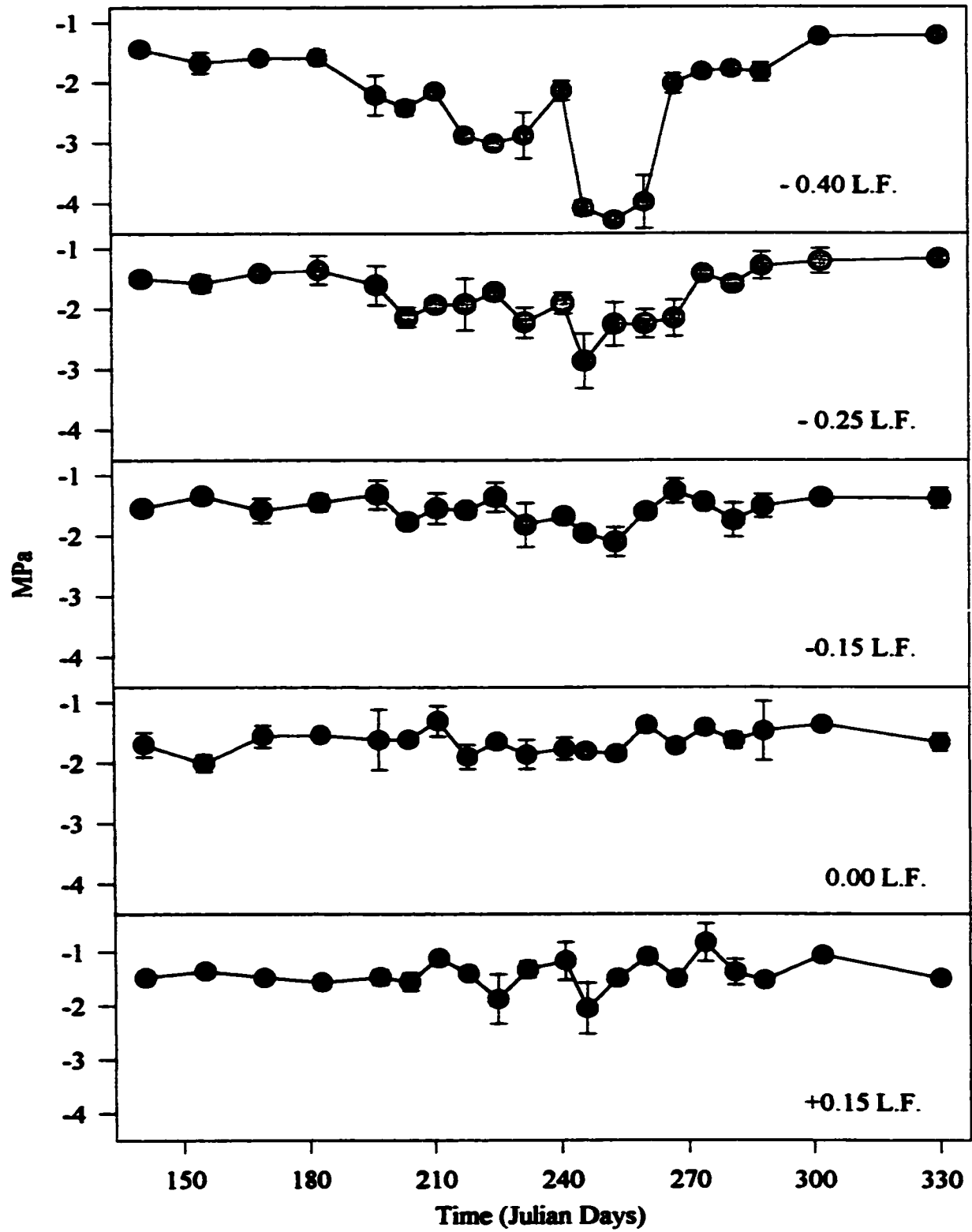


Figure 9. Twice Weekly Irrigation Leaf Xylem Water Potential by LF by Time

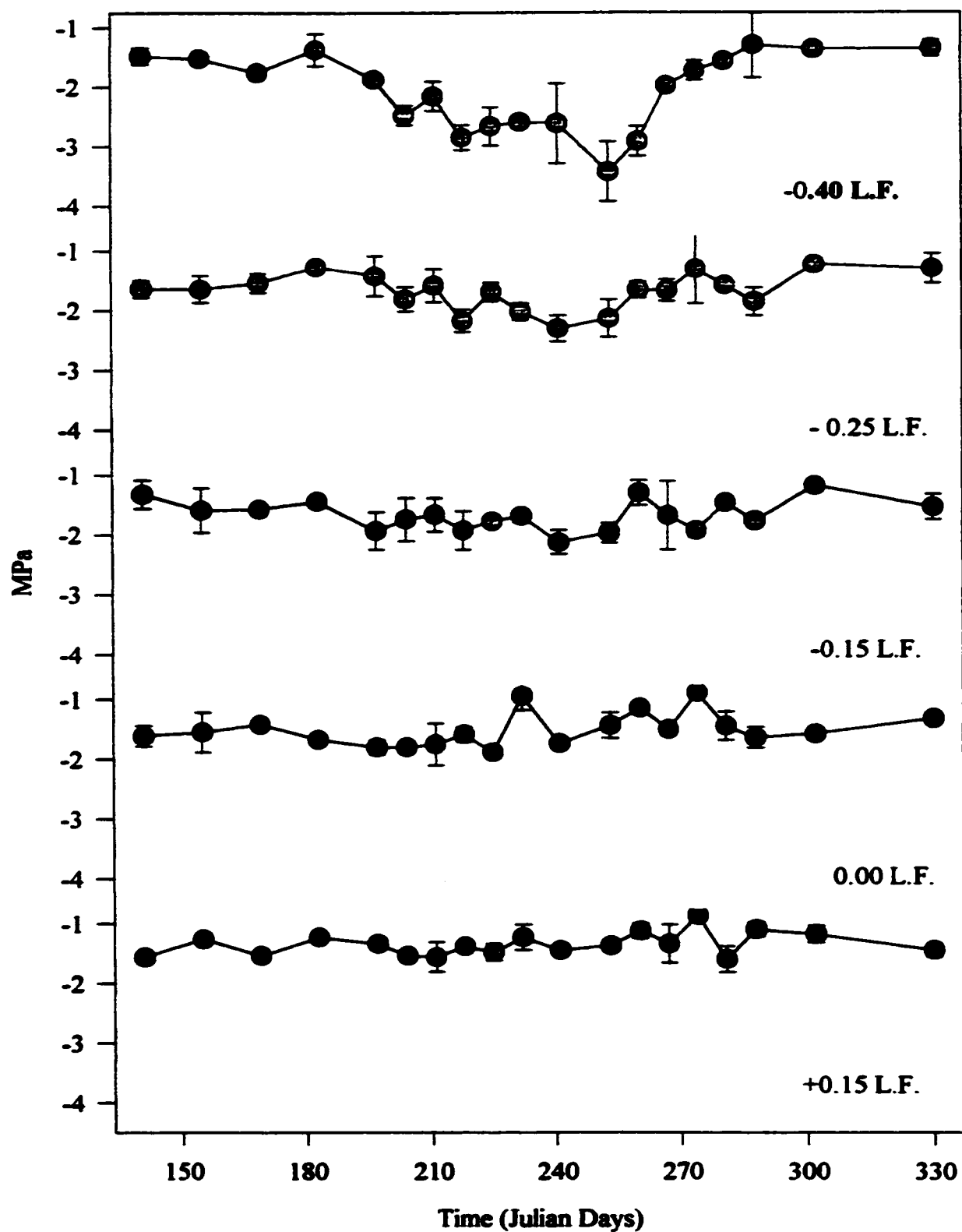


Figure 10. I/ETo vs Tissue Moisture (Day 260)

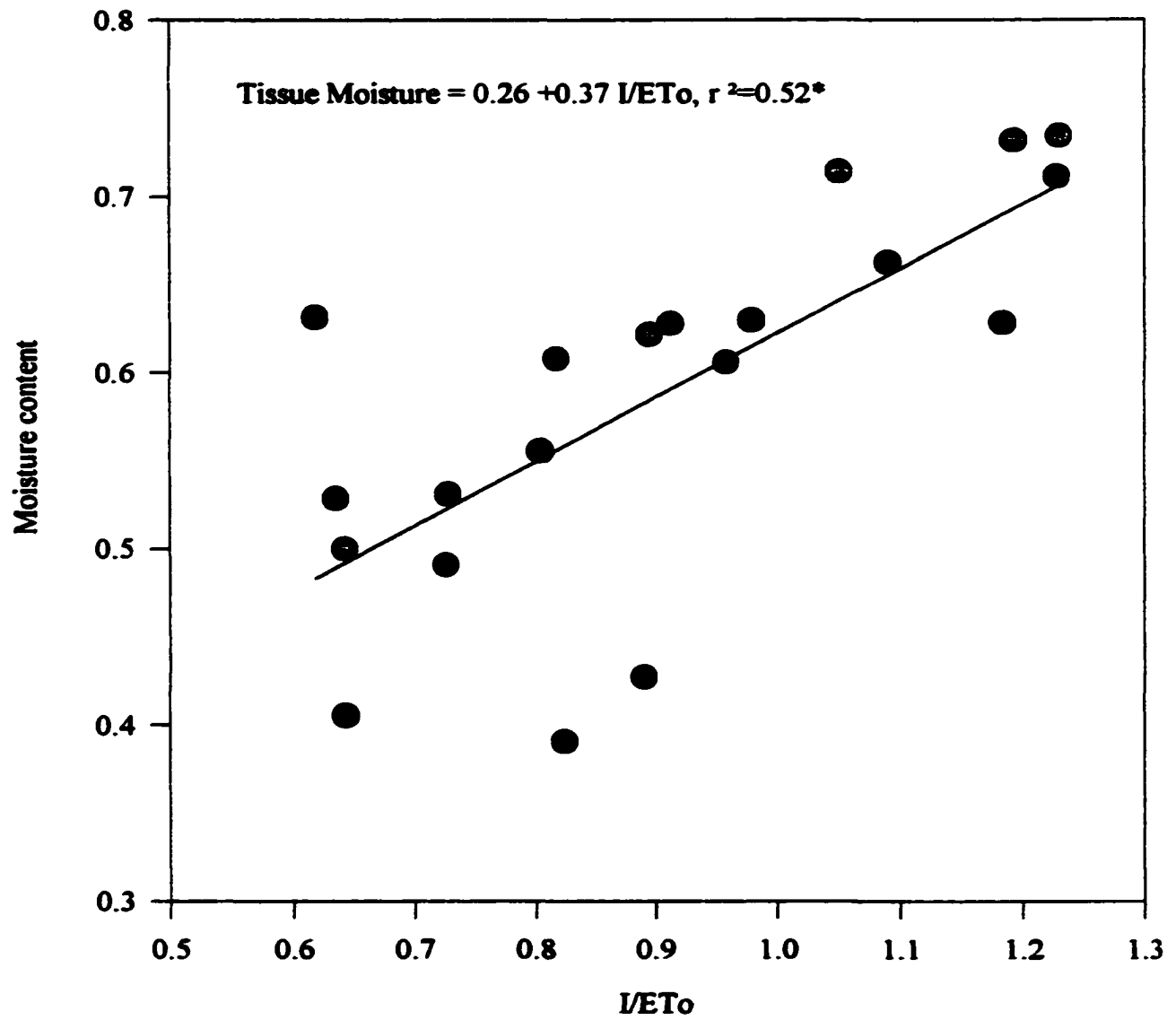


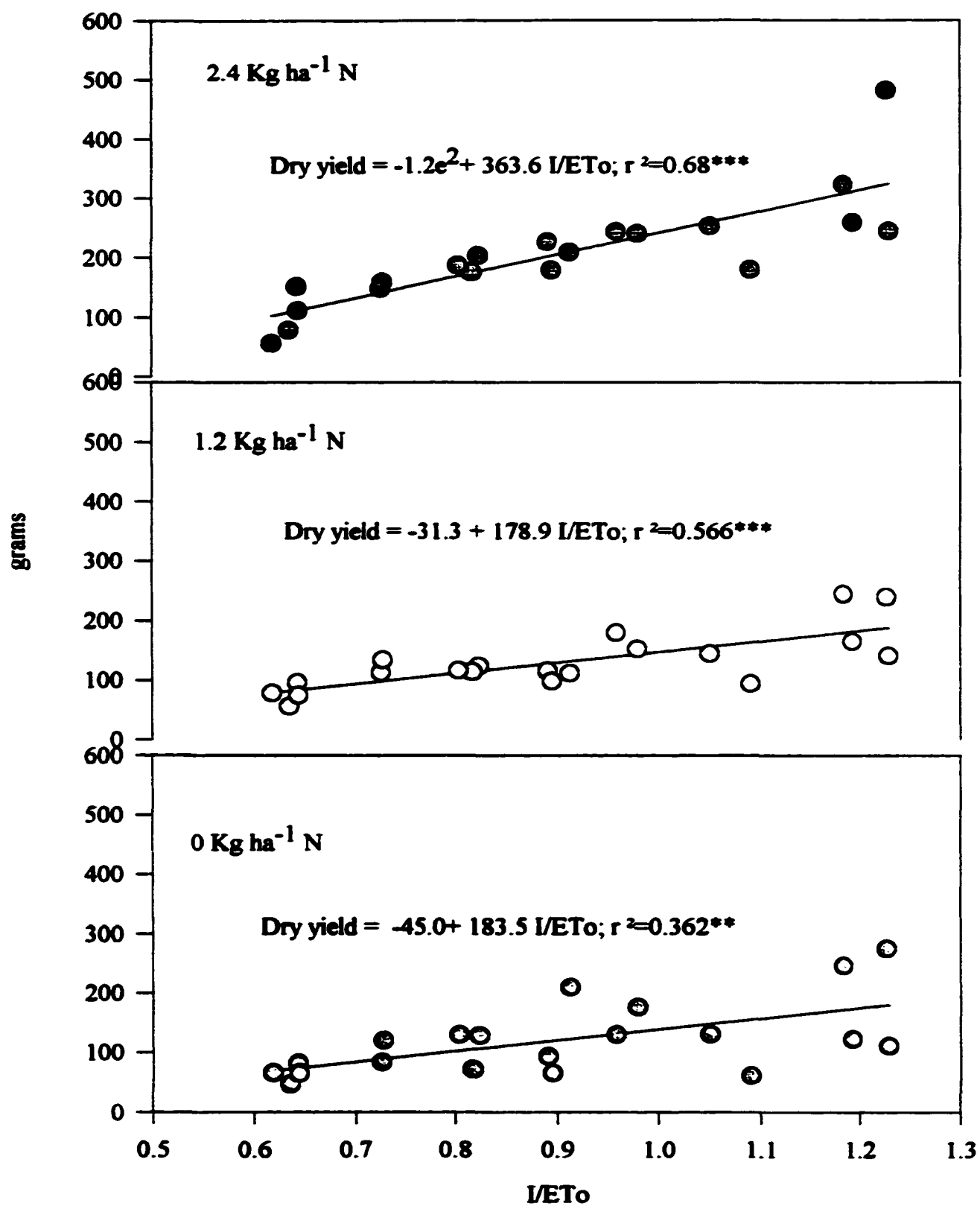
Figure 11. Turf Dry Yield by I/ET₀ by N

FIGURE 12. Daily Irrigation Color by N by LF by Time

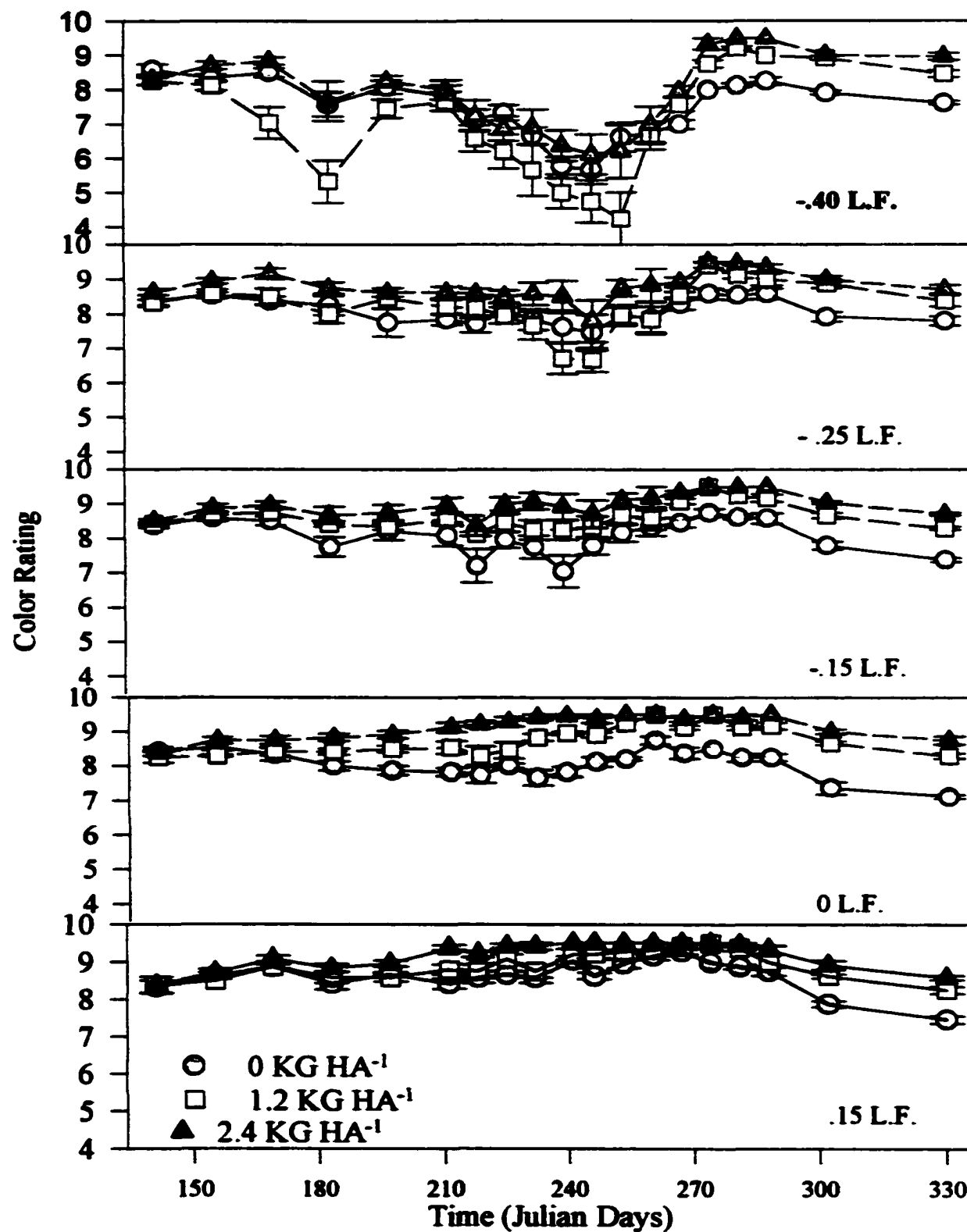


Figure 13. Twice Weekly Irrigation Color by Nitrogen by Leaching Fraction

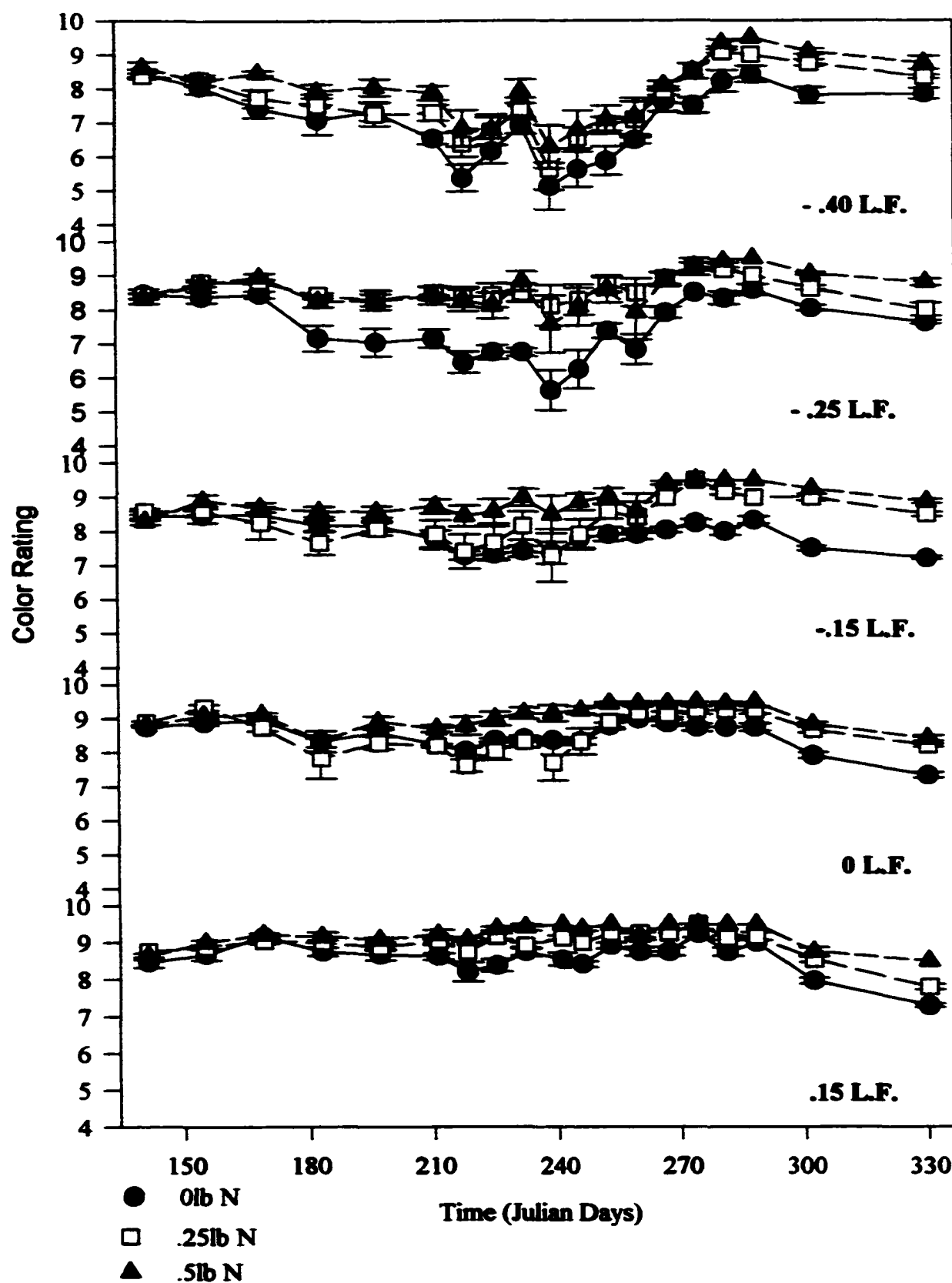


FIGURE 14. TURFGRASS COLOR RATINGS AS A FUNCTION OF LEAF XYLEM WATER POTENTIAL AND WATER SAVINGS.

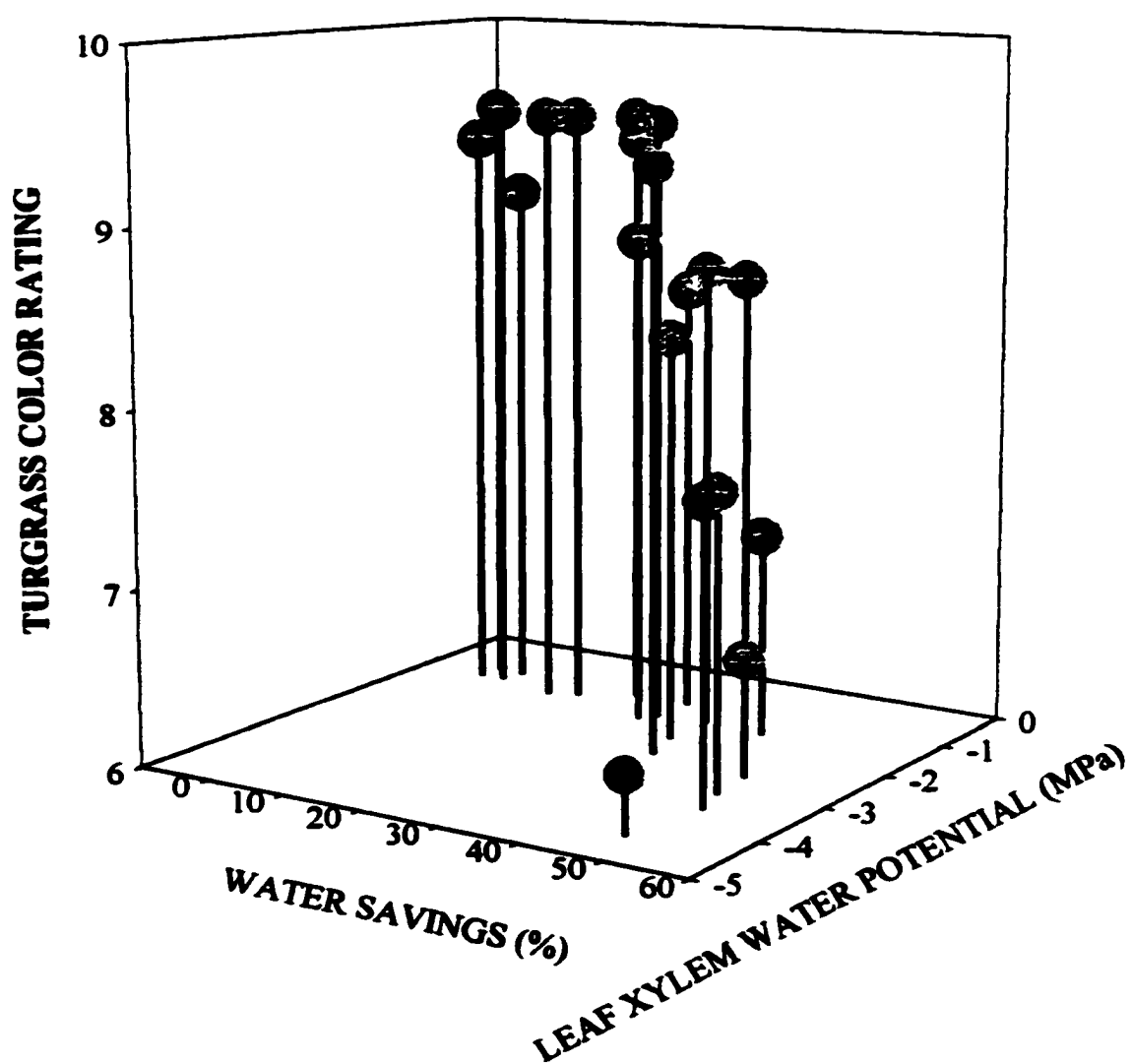


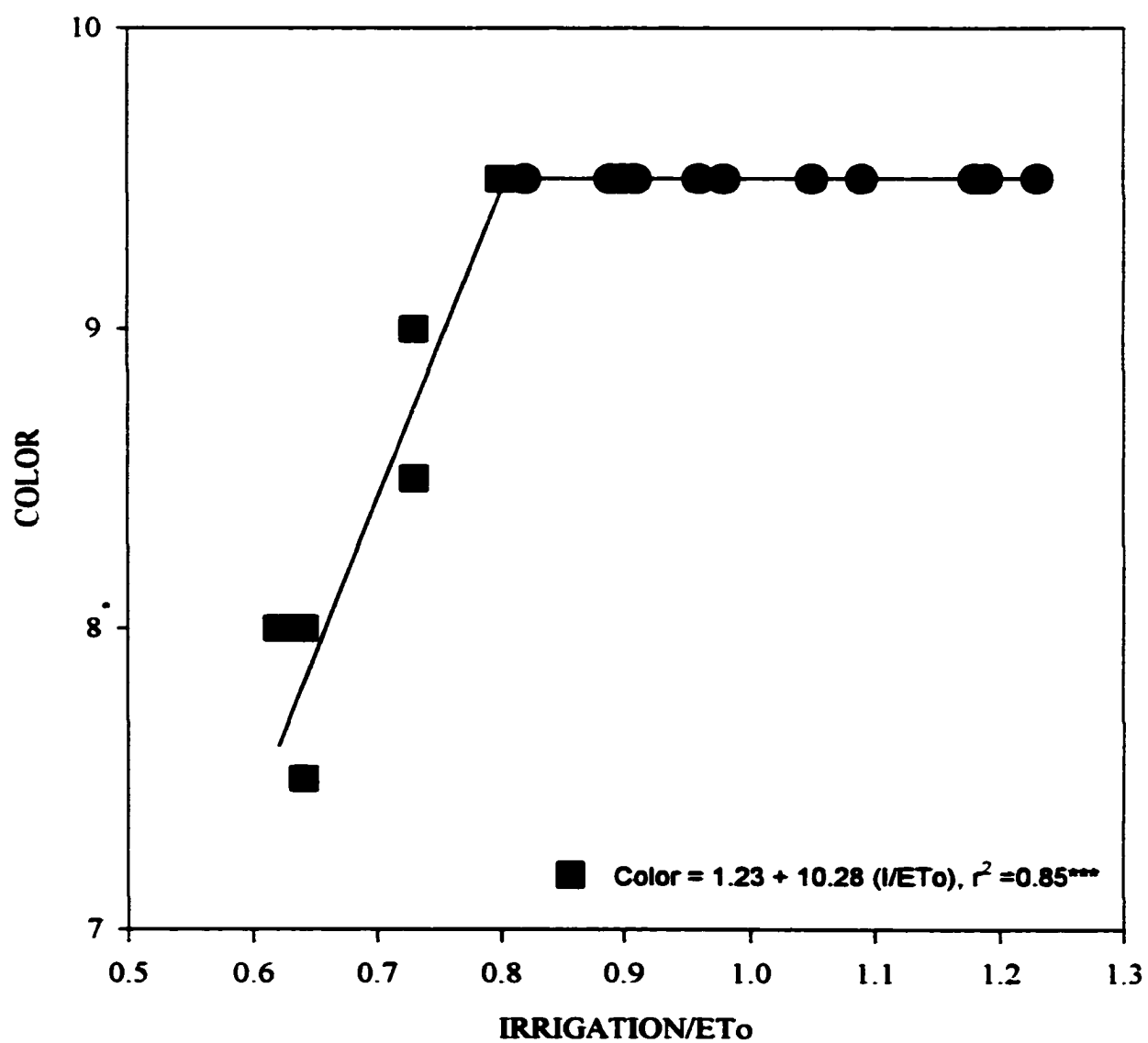
Figure 15. Color by I/ET_o (Julian Day 260)

Figure 16. Percent cover by I/ET_o (Julian Day 260)

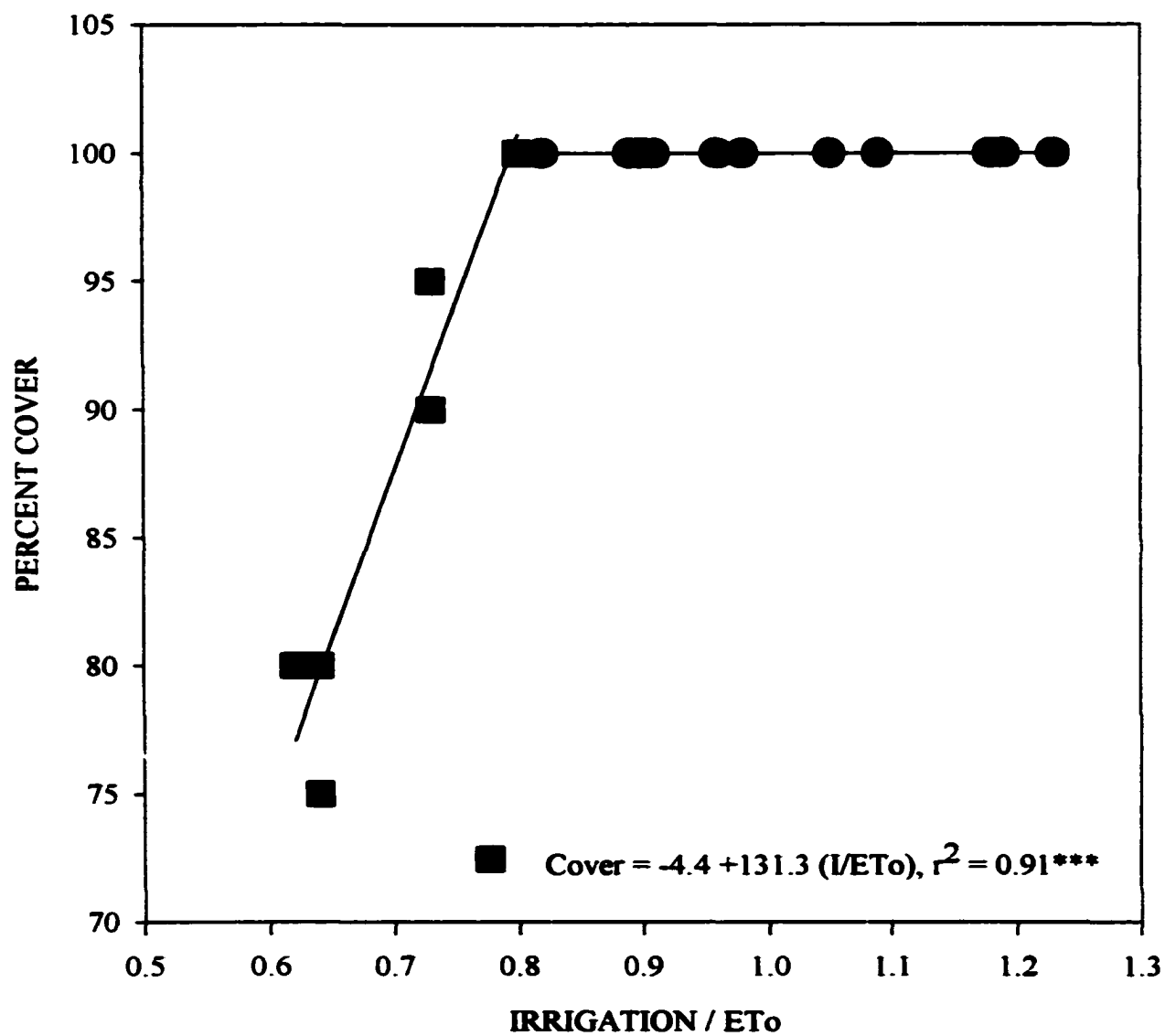


Figure 17. Turf canopy temperature differential by tissue moisture content (percent).

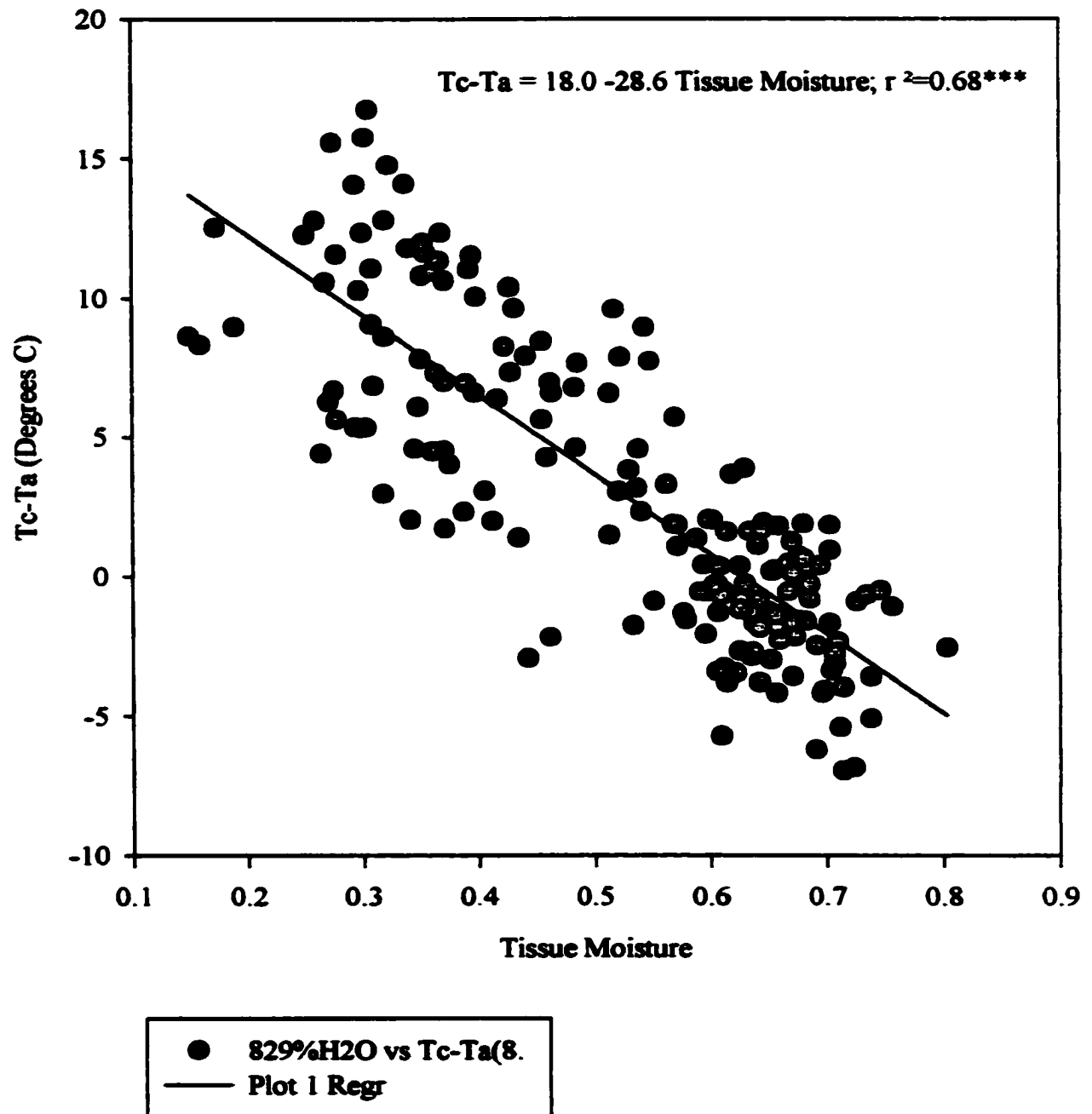


Figure 18. Color by Tissue Moisture (Day 241)

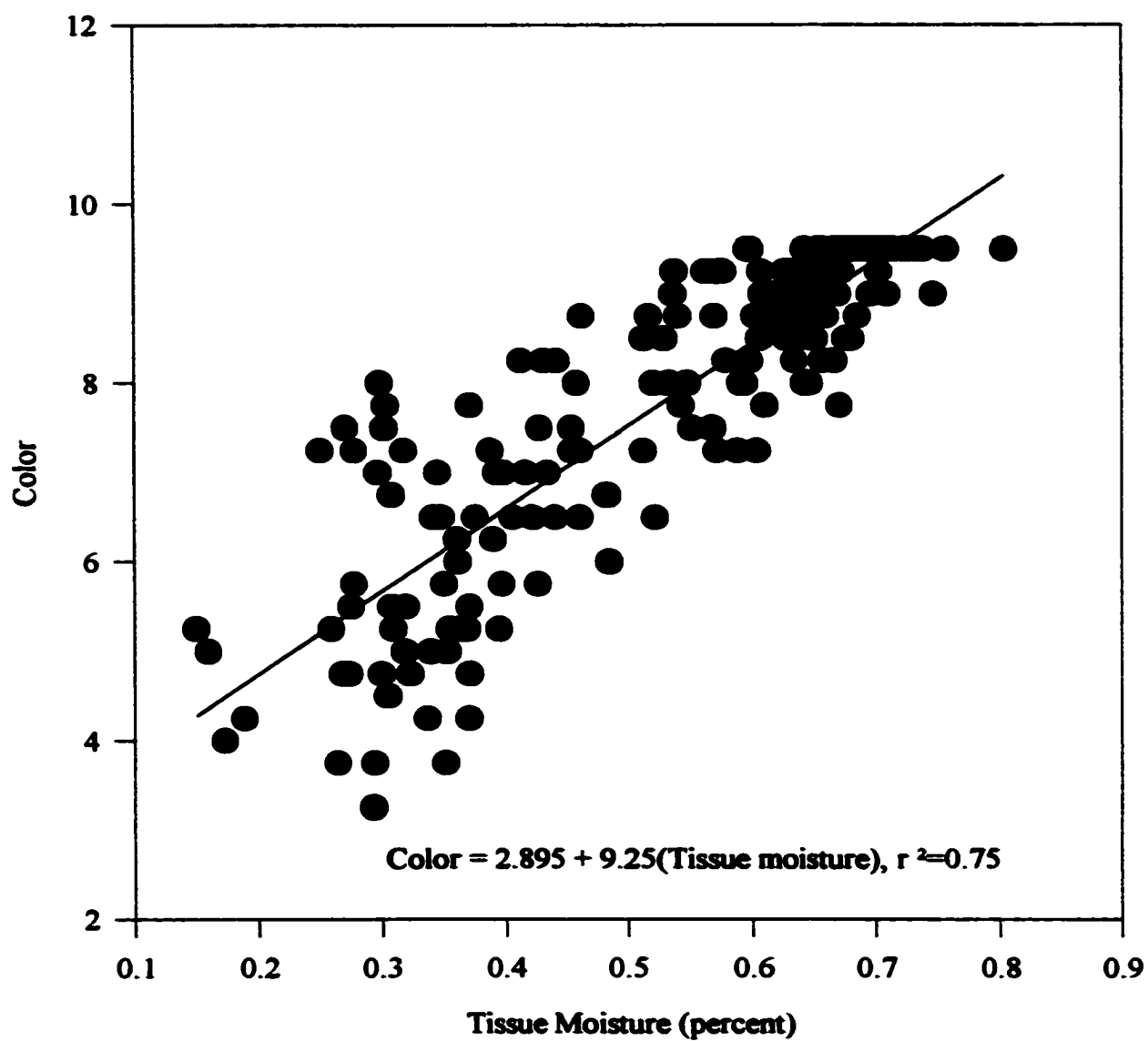


Figure 19. Color by TKN by T Mois separated by Leaching Fraction

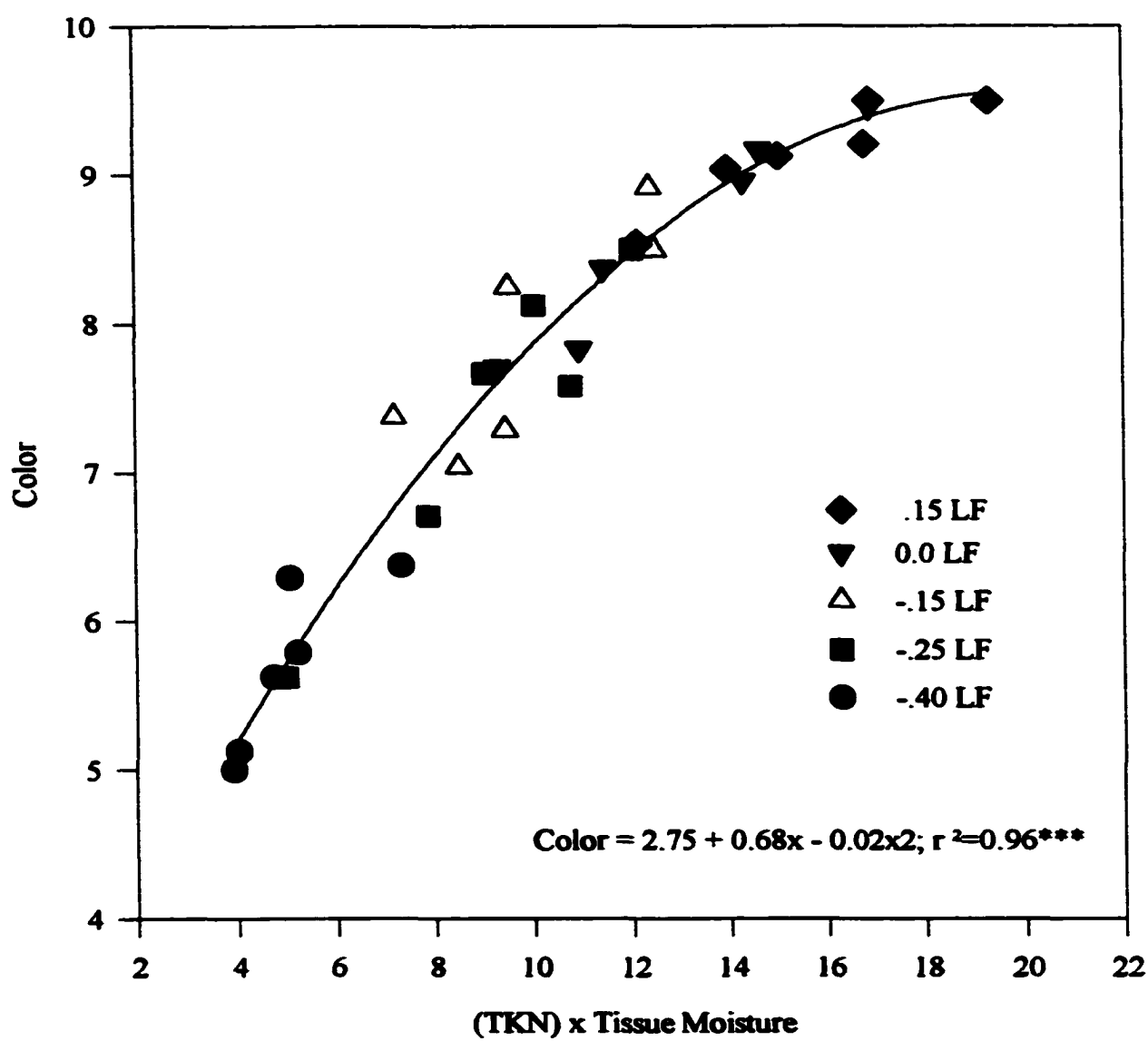


Figure 20. Storage/Storage^{Max} for -.40 L.F. Plots for Stress Period

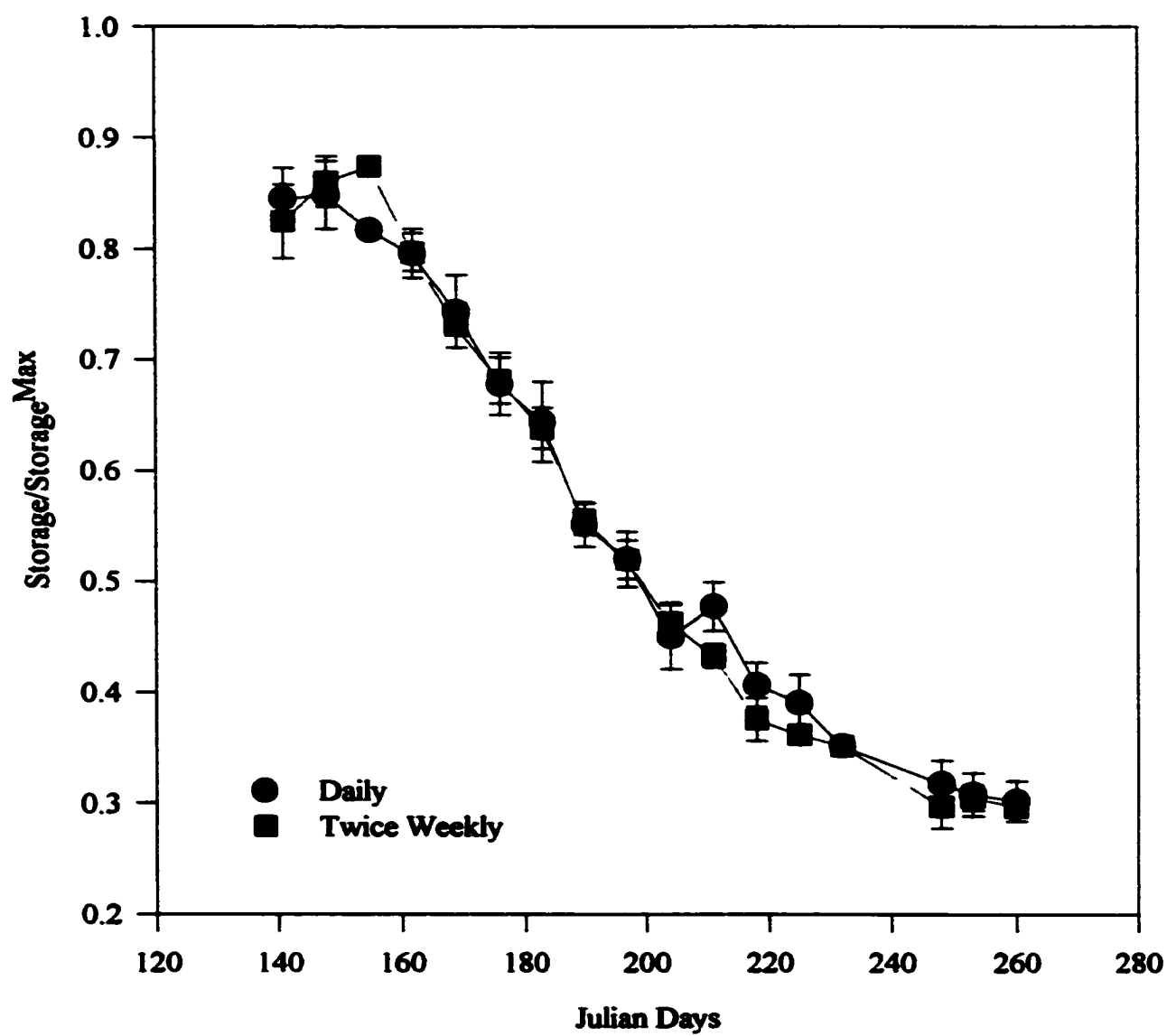


Figure 21. LXWP

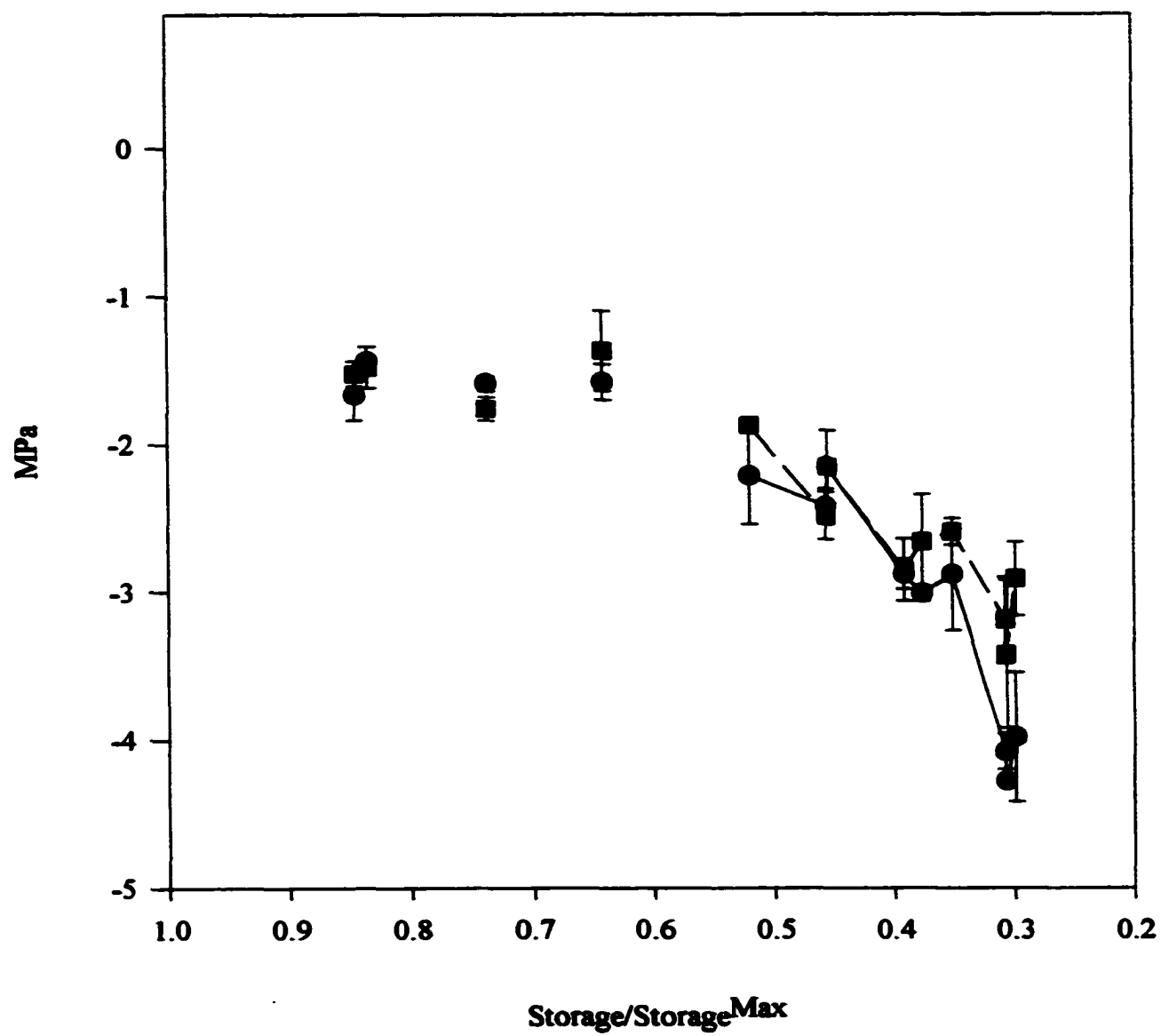


Figure 22. Total Soil Water Potential

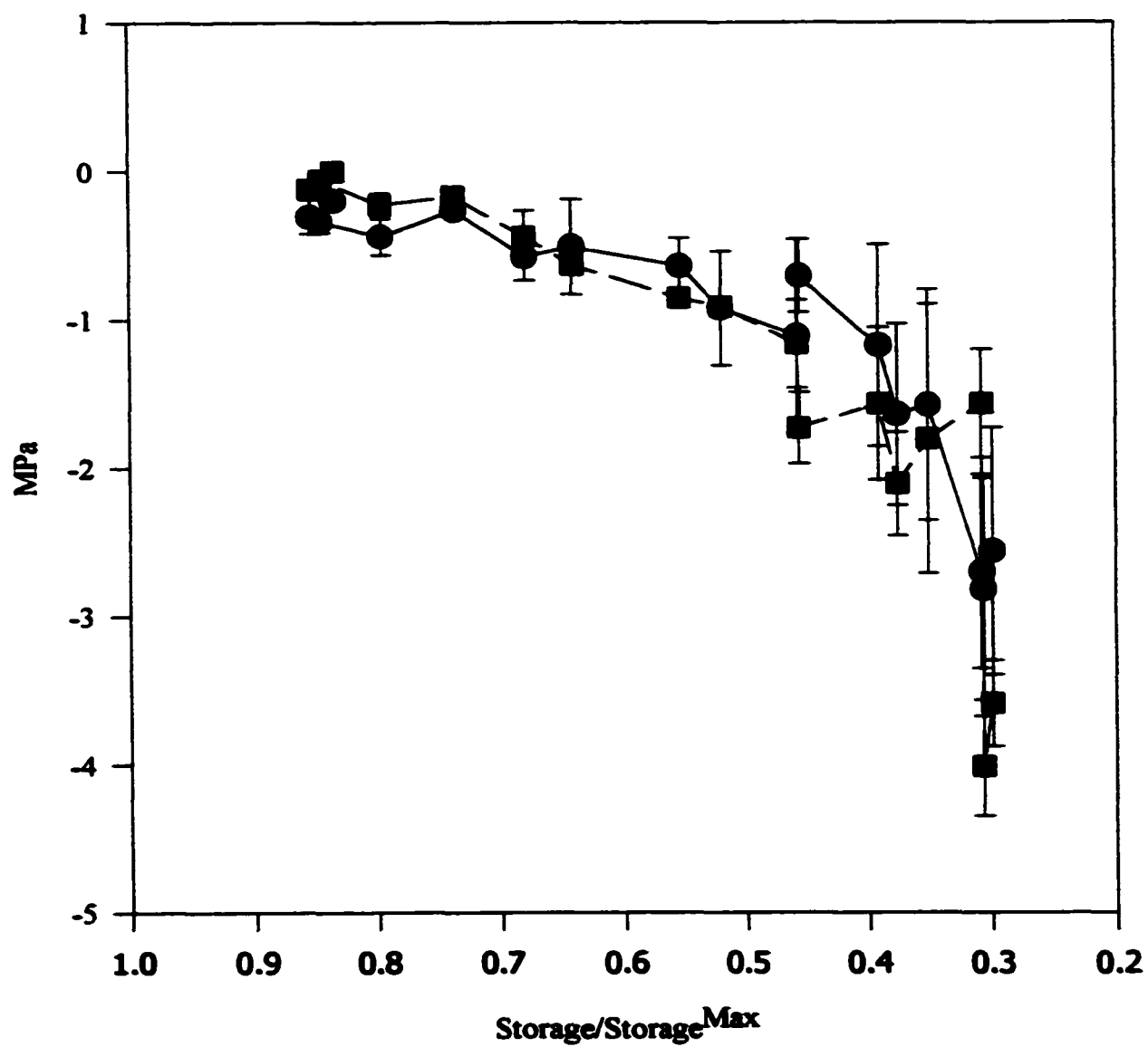


Figure 23. Tissue Moisture Content for -.40 L.F. by Irrigation Frequency

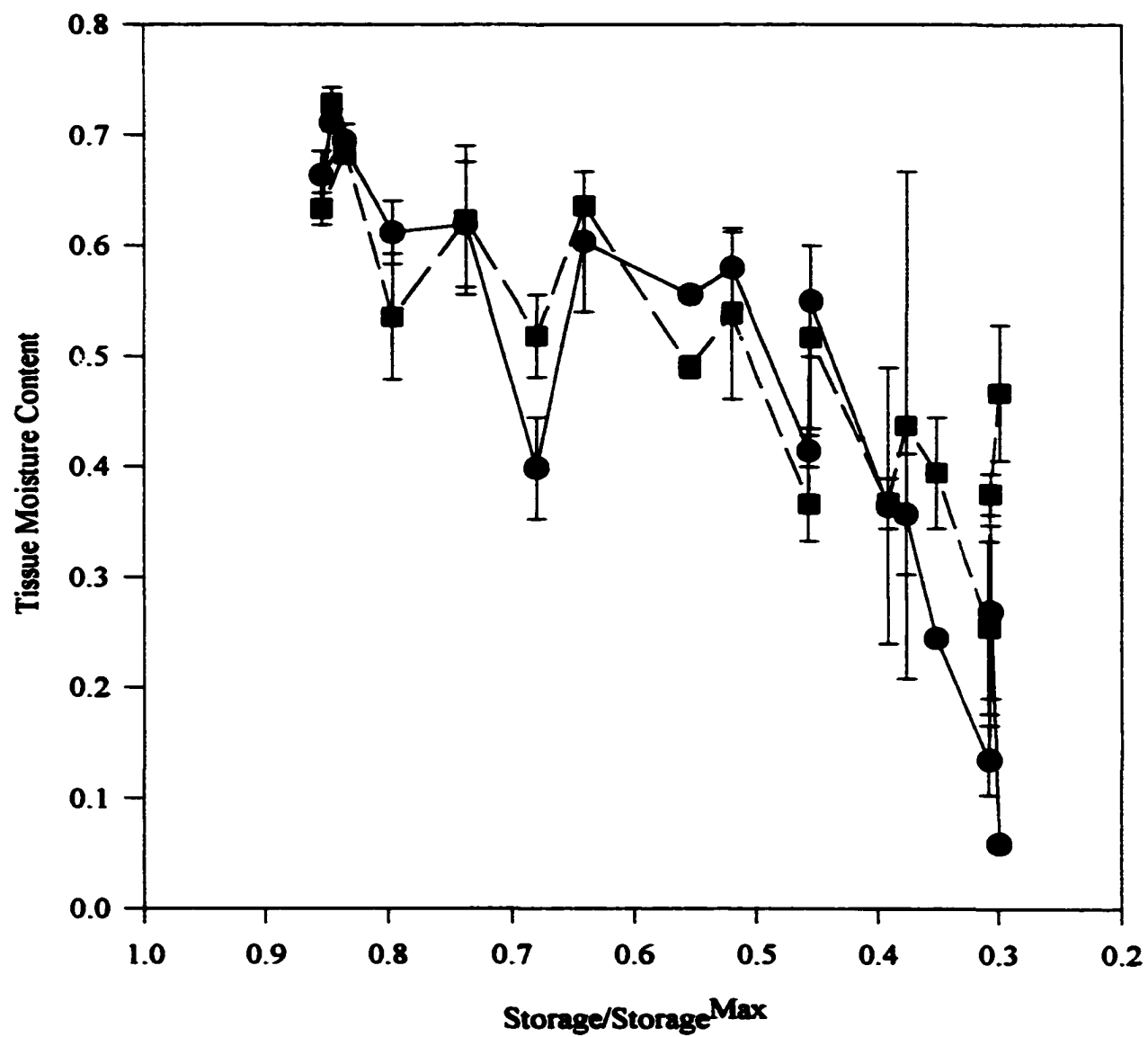


Figure 24. Evapotranspiration for -.40 L.F. by Irrigation Frequency

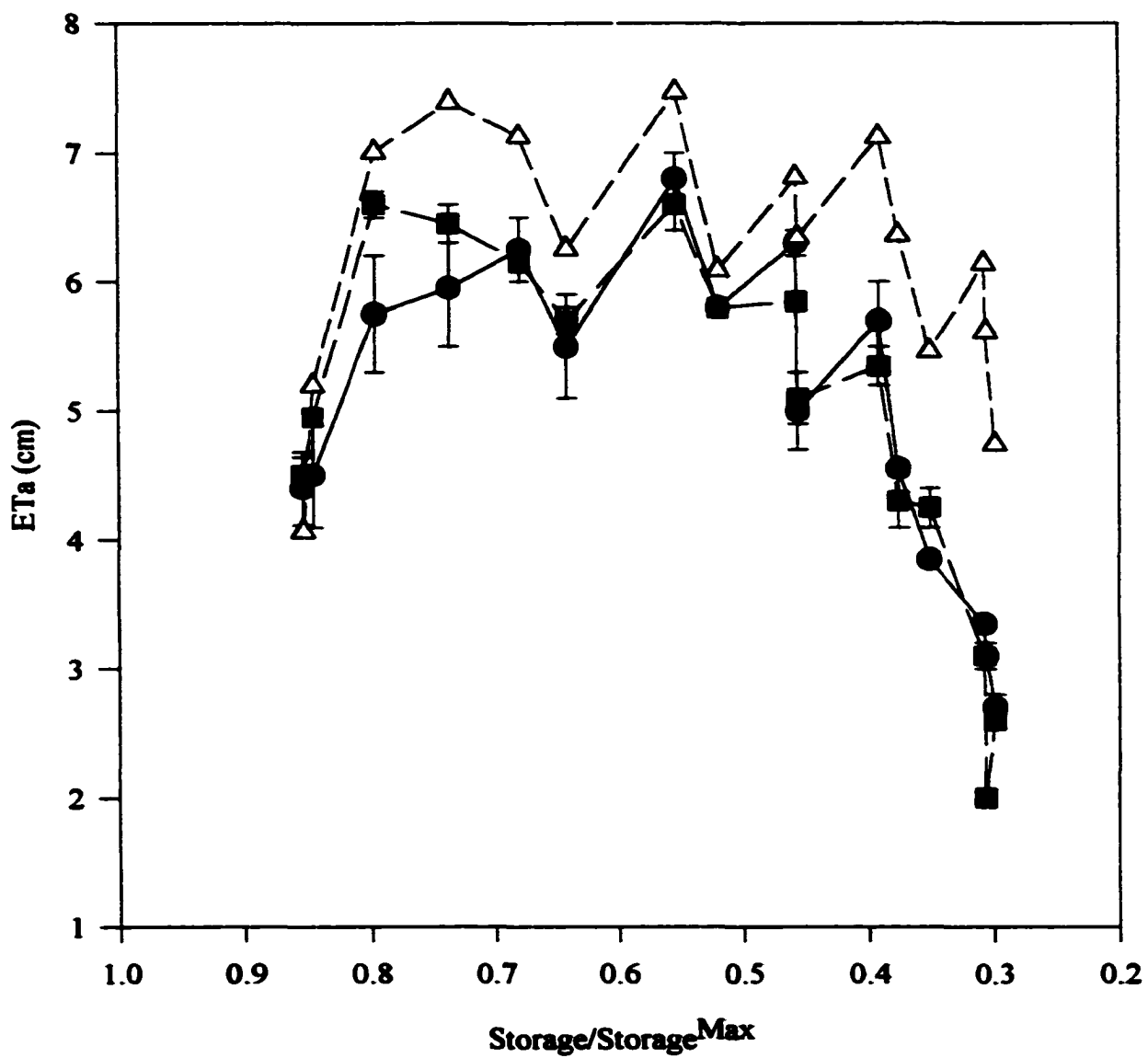


Figure 25. Color for -.40 L.F. by Irrigation Frequency

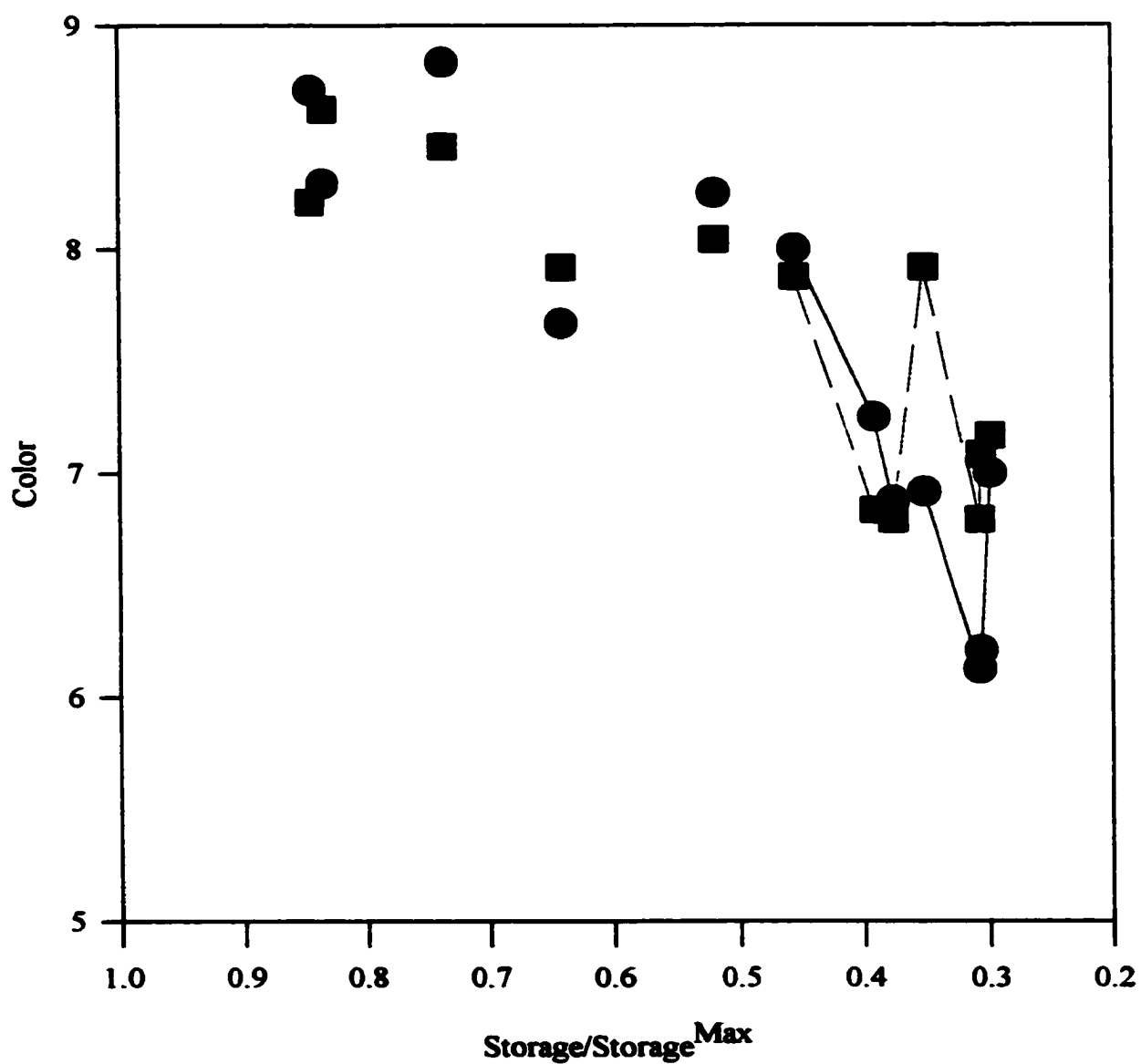
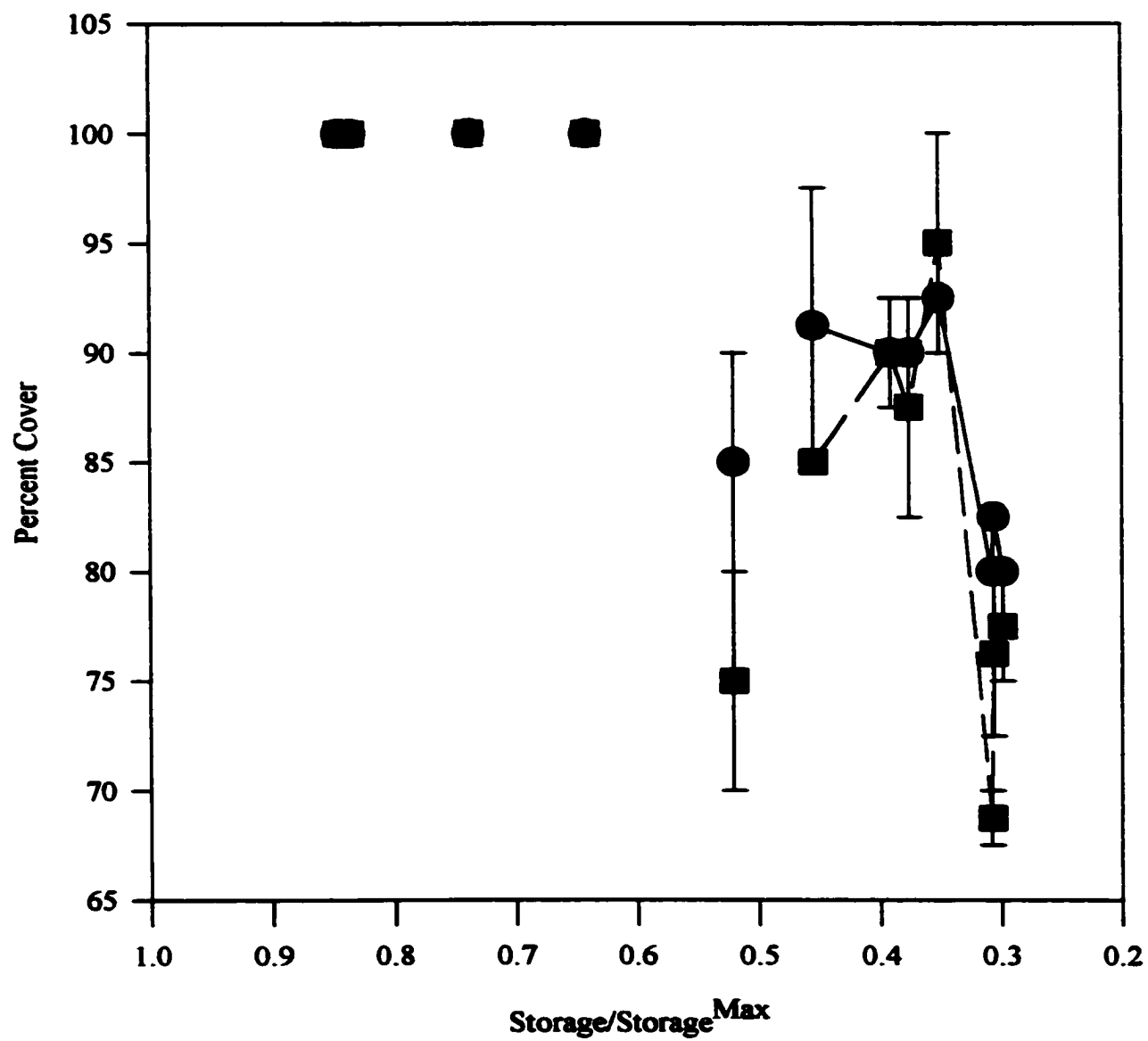


Figure 26. Cover for -.40 L.F. by Irrigation Frequency



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Thesis Title: The Effects of Varying Irrigation Frequency, Irrigation Volume, and Nitrogen Levels on the Water Use of Tall Fescue (*Festuca arundinacea*)

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