THESIS

PERFORMANCE OF KENTUCKY BLUEGRASS, TALL FESCUE, AND BUFFALOGRASS UNDER LINE SOURCE IRRIGATION

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY ERIK H. ERVIN ENTITLED PERFORMANCE OF KENTUCKY BLUEGRASS, TALL FESCUE, AND BUFFALOGRASS UNDER LINE SOURCE IRRIGATION BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

PERFORMANCE OF KENTUCKY BLUEGRASS, TALL FESCUE, AND BUFFALOGRASS UNDER LINE SOURCE IRRIGATION

Increasing demand for the scarce water resources of the semi-arid western United States, coupled with the highly visible practice of landscape irrigation, has fostered increased concern regarding turfgrass water conservation. Accordingly, the objectives of this research were to determine the relative performance of Kentucky bluegrass (*Poa pratensis* L.), turf-type tall fescue (*Festuca arundinacea* Schreb.), and buffalograss [*Buchloë dactyloides* (Nutt.) Engelm.] under increasing levels of water stress; to examine the effects of differential tillage depth of a previously compacted soil at sod establishment on rooting characteristics and subsequent drought resistance; and to compare this study's findings concerning the irrigation required to maintain acceptable turfgrass quality with irrigation requirements predicted by the weather station estimated evapotranspiration (ET)-models used by Denver and other Colorado communities. The effects of irrigation amount, turfgrass type, and tillage depth at sod establishment on rooting characteristics, water use, visual quality and leaf firing, and canopy temperatures were investigated at Fort Collins, CO, on a Nunn clay loam (Aridic Argiustoll, fine, montmorillonitic, mesic) soil. A line source irrigation system was used to apply five irrigation treatments based on percent replacement of reference ET. In 1993, irrigation treatments at the following levels were applied every three days: 80%, 70%, 60%, 45%, and 20% of reference ET. In 1994, the irrigation treatments were 95%, 85%, 75%, 60%, and 35% of reference ET. Five turfgrass types and two tillage depths at sod establishment were arranged in four randomized complete blocks. The five turfgrass types were: 'Nustar' Kentucky bluegrass, a turf type tall fescue/Kentucky bluegrass mix, a turf type tall fescue blend, '609' buffalograss, and 'Prairie' buffalograss. The two tillage depths were ~2.5 cm and ~15.0 cm. In both 1993 and 1994 no effect of tillage treatment was measured for any of the parameters sampled. At the end of both years, the tall fescue blend had more total root density (down to 90 cm) than Kentucky bluegrass. Consequently, the tall fescue extracted greater amounts of soil moisture from deep in the soil (30-90 cm). These results were reflected in significantly higher quality ratings, lower leaf firing ratings, and lower canopy temperatures as irrigation level decreased for the tall fescue blend relative to the Kentucky bluegrass. Buffalograss quality was not significantly affected by any of the irrigation treatments in either year, a confirmation of its reported superior drought resistance. Results indicate that buffalograss avoids drought better than turf type tall fescue and that turf type tall fescue avoids drought better than Kentucky bluegrass. It is concluded that acceptable turfgrass quality can be maintained in Colorado by irrigating these three turfs every three days by adjusting alfalfa reference ET's with an irrigation coefficient of 0.70 for Kentucky bluegrass, 0.60 for turf type tall fescue, and 0.30 for buffalograss.

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CHAPTER 1: INTRODUCTION

Water is responsible for the maintenance of all life on earth, but only 1% of all the water present on earth is useful for agricultural and general human use (Rossillon, 1985). Unfortunately, continuing population growth, unsustainable mining of aquifers, water pollution, and salinity, have dramatically increased the demands on this 1% of useable water.

Although the rate of population increase peaked in the late 1960's at just over 2% per year and has since fallen to 1.6%, this rate implies a population "doubling time" of just 24 years in Africa, 35 years in Asia and Latin America, and 98 years in North America (Roush, 1994). As of 1992 there were 5.5 billion people on earth, an increase of 91 million people from 1991. To put this into perspective, during every month in 1992 the world population grew by nearly the equivalent of the New York City population (Starke, 1993). Such population growth translates to worldwide per capita water supplies being a third lower in 1993 than in 1970 (Postel, 1993).

The above statistics speak strongly to our need for water conservation. This is especially true in the semi-arid and arid western United States (with an approximate dividing line from the east being the 100th meridian), where evapotranspiration often greatly exceeds precipitation. In the contiguous 48 states, approximately 80% of the water resources are located in aquifers; they are the source of approximately 20% of the fresh water used (Watson, 1985). In 1975, the U.S. Water Resources Council reported that 60 of the 106 aquifer subregions were being mined in excess of recharge (Watson, 1985). More important to the western United States is the continuing depletion of the Ogallala aquifer, and aquifers in the central valley of California and southern Arizona.

The Ogallala aquifer, which stretches from southern South Dakota to northwest Texas, supplies approximately 30% of the groundwater used for irrigation in the United States (Postel, 1993). As of 1990, 24% of the Texas portion of the Ogallala had been depleted (Postel, 1993). Some predictions are that, by the turn of the century, southwest Nebraska, eastern Colorado, and western Kansas will have exhausted the recoverable underground water from the Ogallala (Watson, 1985). In Colorado, 196,000 hectares (18% of the total irrigated area) are estimated to be irrigated by the overpumping of groundwater. Large percentages of total irrigated land in Arizona (41%) and Texas (72%) also utilize aquifer water (Postel, 1989).

Of course, the above statistics pertain primarily to agricultural water use, which accounts for 47% of all water used in the United States. Industry utilizes another 43%, and domestic use (for cooking, bathing, drinking, landscape irrigation, etc.) accounts for the remaining 10% (Rossillon, 1985).

Domestic water use is often separated into indoor water use and outdoor water use, of which a large proportion is for landscape irrigation. A traditional method of estimating outdoor water use has been the winter base rate method (DiNatale, 1981). This method assumes that indoor water use remains fairly constant throughout the year and that there is relatively insignificant outside use during the winter months. The water use rate during the winter months, therefore, is used as the indoor use rate for the entire year. Outside use rate is then estimated to be that proportion greater than the winter base rate. While it is tempting to attribute excess use (over the winter base rate) entirely to landscape irrigation or even just to lawn watering, other demands for water occur during the spring and summer months, to include: increased car washing, filling and maintaining swimming pools, and more frequent bathing (and related clothes washing). Most would agree, however, that irrigation of lawns, gardens (ornamental and vegetable), and landscape ornamental plants accounts for most outdoor domestic water use, with lawn watering comprising the largest percentage of total landscape irrigation.

Using Denver Water monthly statistics for 1993 (Denver Water, 1993), with the November through February period representing the winter base rate, it can be estimated that total outdoor water use accounted for 45% of Denver's domestic water use. Outdoor water use in 1993, expressed as a percent of total monthly domestic use was as follows: March, 9.5%; April, 21.2%; May, 55.5%, June, 64.7%; July, 69.0%; August, 64.3%; September, 45.9%; and October, 30.9%. In 1989, the highest water demand year in the 1988-1993 period, the average outdoor water use for Denver was 49%

(Denver Water, 1989). For the months of June, July, and August, outdoor water use in Denver accounted for 66% of the total domestic use in 1993 and 65% in 1989. Some additional estimates of outdoor water use are reviewed below.

In the summer of 1978 it was estimated that 35% of summer water use was for landscape irrigation in Fort Collins, Colorado (Bode and Olson, 1980). Danielson et al. (1979) reported that, during the droughty summers of 1977 and 1978, outside water use accounted for over 70% of the total urban use in Northglenn, Colorado. DiNatale (1981), by summarizing a number of older studies, estimated that approximately 60% of annual Colorado residential water use occurs outdoors, where the primary use is for landscape irrigation. This estimate seems a bit high, given the outdoor water use figures reported above for Denver. If one compromised and proposed a figure of 50% as the amount of domestic water used outdoors annually, it can be estimated that 5% of all water used in Colorado is for domestic outdoor use. The statistics would indicate that outdoor water use (of which lawn watering may be the major portion), at 5%, comprises a relatively small portion of all water used in Colorado. However, because of the very visible nature of landscape irrigation, much of the public perceives landscape irrigation as accounting for a much higher percentage of total water use than it actually does. Further, wasteful irrigation practices, such as daytime watering, sidewalk irrigation, and runoff caused by overwatering, are also quite visible and draw the generally angry attention (justifiably so) of those interested in water conservation. Given these perceptions, as well as the fact that upwards of 50% of all domestic water is used outdoors, water conservation efforts in population centers are highly targeted towards landscape irrigation. From the perspective of water conservation, one is then forced to ask the question: Are Colorado lawns being overwatered?

Barnes et al. (1979) found that Kentucky bluegrass lawn water application rates were 125% of the average seasonal ET in Laramie, Wyoming and 175% of ET in Wheatland, Colorado. They found that higher lawn quality was poorly correlated with higher lawn watering rates, indicating that a high quality lawn is not solely dependent on high irrigation amounts, but is achieved through the combination of a number of proper maintenance practices.

Danielson et al. (1979) compared water application rates on selected Kentucky bluegrass lawns in unmetered Fort Collins and metered Northglenn for the summers of 1977 and 1978. They found that water application was approximately 135% of potential evapotranspiration (PET) at Fort Collins and approximately 80% of PET at Northglenn. Average quality ratings for the two seasons were 7.4 for Fort Collins and 6.5 for Northglenn, where a quality rating of 6.0 represented a lawn of minimal acceptable quality. Thus, significant water conservation was achieved through metering, while not unduly sacrificing lawn quality.

The example of metering in Northglenn (i.e., making people pay according to the amount of water they use) is an important first step in urban lawn water conservation. Two other important aspects involve research, coupled with subsequent and ongoing public education.

This study had three main objectives.

1. To determine the relative performance of Kentucky bluegrass (*Poa pratensis* L.), turf-type tall fescue (*Festuca arundinacea* Schreb.), and buffalograss [*Buchloë dactyloides* (Nutt.) Engelm.] under increasing levels of drought stress or deficit irrigation.

2. To examine the effects of minimal preparation (~ 2.5 cm tillage depth) of a compacted soil vs. good soil preparation (~ 15.0 cm tillage depth) at establishment on rooting characteristics and subsequent drought resistance.

3. To compare this study's findings on the irrigation required to maintain acceptable lawn quality with irrigation requirements predicted by the weather station estimated ET-models used by Denver and other Colorado communities.

The utilization of a line source irrigation system (LSIS) allowed us to irrigate all turfgrass plots at decreasing percentages of the irrigation amounts recommended by the weather station ET-model. In this way, we were able to determine if the irrigation recommendations made by Denver Water and other Front Range city agencies are too high and then define a safe range of irrigation recommendation reductions. A refinement of these programs, coupled with continuing public education, will hopefully result in more efficient private and public turfgrass irrigation.

CHAPTER 2: LITERATURE REVIEW

The focus of this study was, in the most general sense, a comparative evaluation of the drought avoidance capabilities of the three most commonly used lawn species in Colorado: Kentucky bluegrass, turf-type tall fescue, and buffalograss.

"Drought avoidance" is one component of drought resistance, which is a general term encompassing mechanisms which enable plants to survive periods of dry weather (Kneebone et al., 1992). Two other components of drought resistance are "drought tolerance" and "drought escape".

Drought tolerance, or dehydration tolerance (Kramer, 1980), involves the maintenance of a positive turgor pressure at low tissue water potential (Jones et al., 1981). Drought tolerance mechanisms include osmoregulation and dehydration tolerance achieved via protoplasm resistance (Kneebone et al., 1992). Drought escape involves the ability of a plant to complete its life cycle before soil moisture is depleted (e.g., *Poa annua* L.) or simply a plant's ability to escape death by going dormant until there is adequate addition of moisture to the soil (e.g., *Poa pratensis* L.) (Kramer, 1980). While all three turfgrass species in this study exhibit some degree of ability to tolerate and escape drought, these mechanisms are of minor importance as concerns our desire to maintain green lawns which benefit us all functionally, recreationally, and aesthetically (Beard and Green, 1994).

Drought avoidance, or dehydration postponement (Kramer, 1980), is the maintenance of a high tissue water potential during a period of high evaporative demand or a period of increasing soil water deficit (Jones et al., 1981). Plants avoid drought in two ways: by maintaining water uptake from the soil, or by restricting water loss from aboveground organs. In our study, the three species' relative abilities to avoid drought were the most significant determining factors in our measures of drought resistance. Drought avoidance is the most important factor given that it is the only drought resistance mechanism of the three which allows the turfgrass plant to resist drought while maintaining a significant amount of green, turgid tissue.

In the discussion that follows particular attention has been paid to that literature which has examined turfgrass water use and drought resistance with respect to the following variables: differences in species' evapotranspiration (ET) rates; rooting mass, depth, and distribution; moisture extraction from root zones; irrigation levels at which acceptable quality turfgrass can be maintained; the monitoring of turfgrass water stress by the calculation of a crop water stress index; and the effect of compaction at turfgrass establishment on subsequent drought resistance.

I. Turfgrass Evapotranspiration Rates and Drought Resistance

A. Potential Evapotranspiration

Turfgrass evapotranspiration rate is defined as the total amount of water needed for plant growth, including water lost by transpiration and evaporation from soil and plant surfaces. Evapotranspiration rate is expressed in terms of millimeters per day and is often referred to as ET (Kneebone et al., 1992). Evapotranspiration rates of turfgrass species are often reported as potential evapotranspiration (PET), the water use rate when soil moisture is not limiting. Some recently measured PET rates for Kentucky bluegrass, tall fescue, and buffalograss are reported in Table 2.1.

Beard (1985) proposed a seven-level classification of PET rates: very low (< 4.0 mm/day), low (4.0-4.9 mm/day), medium low (5.0-5.9 mm/day), medium (6.0-6.9 mm/day), medium high (7.0-7.9 mm/day), high (8.0-8.9 mm/day), and very high (>9.0 mm/day). Given the data summarized in Table 2.1, Kentucky bluegrass has a very low to medium-low PET rate, buffalograss has a very low to medium high PET rate, and tall fescue has a very low to very high PET rate. Much of this reported variability can be attributed to the differing environmental conditions (i.e., different temperatures, radiation levels, relative humidities, available water, and soil types) and culture (i.e., fertilizer amounts and mowing heights, leaf area indexes, etc.) that occurred in each of these studies. If the PET rates reported in Table 2.1 are averaged for each turfgrass, Kentucky bluegrass (4.9 mm/day) is classified as having a low relative PET rate, tall fescue (6.9 mm/day) possesses a medium PET rate, and buffalograss (5.0 mm/day) can be said to have a medium low PET rate.

TABLE 2.1: Summary of reported PET rates for three turfgrass species

Turfgrass species	Location	Av. PET rate mm/day	Reference
Poa pratensis 'Baron'	RI, field	3.6	Aronson et al., 1987a
Poa pratensis 'Enmundi'	RI, field	3.8	Aronson et al., 1987a
Poa pratensis 20 cultivars	NE, growth chamber	3.9 to 6.3	Shearman, 1986
Poa pratensis 'Merion'	CO, field	4.8 to 6.3	Feldhake et al., 1983
Poa pratensis 'Merion'	CO, field	4.9	Danielson et al., 1979
Poa pratensis 'Merion'	CO, field	5.0 to 5.9	Minner, 1984
Festuca arundinacea 2 cultivars	GA, field	3.6 to 3.7	Carrow, 1991
Festuca arundinacea	WV, growth chamber	4.2 to 9.5	Feldhake & Boyer, 1985
Festuca arundinacea 'Rebel'	CO, field	4.5 to 7.0	Fry & Butler, 1989
Festuca arundinacea 'Rebel'	CO, field	5.8	Feldhake, et al., 1983
Festuca arundinacea 'Kentucky 31'	TX, field	6.1	Kim & Beard, 1988
Festuca arundinacea 'Fawn'	CO, field	6.3	Minner, 1984
Festuca arundinacea 6 cultivars	NV, greenhouse	7.1 to 9.8	Bowman & Macaulay, 1991
Festuca arundinacea 20 cultivars	NV, greenhouse	8.6 to 10.0	Bowman & Macaulay, 1991
Buchloë dactyloides	WV, growth chamber	2.5 to 5.7	Feldhake & Boyer, 1985
Buchloë dactyloides 'Common'	CO, field	4.5	Feldhake et al., 1983
Buchloë dactyloides 'Texas Common'	TX, field	4.8	Kim, 1983
Buchloë dactyloides 'Texas Common'	TX, field	5.3	Kim & Beard, 1988
Buchloë dactyloides 'Texas Common'	TX, field	7.3	Kim & Beard, 1988

B. Evapotranspiration Rates and Drought Resistance

The data above should warn against the conflation of PET-rate with drought resistance, and more particularly, with drought avoidance. The comparative PET-rates of turfgrass species are distinct from their relative drought avoidance because each is a distinct physiological phenomenon (Beard, 1985). Recall that drought avoidance involves the maintenance of a high tissue water potential during a period of high evaporative demand or a period of increasing soil water deficit. Plants avoid drought in two ways: by maintaining water uptake from the soil or by restricting water loss from aboveground organs. Thus, the ability of a turfgrass to avoid drought may, in large part, depend on its ability to reduce its ET-rate (physiologically or morphologically) when water is limiting.

In a greenhouse lysimeter (30 cm deep) study, Aronson et al. (1987b) showed that the transpiration of four cool-season turfgrass species (Kentucky bluegrass, perennial ryegrass, hard fescue, and Chewings fescue) was governed mainly by meteorological factors when soil water was not limiting, but that their transpiration declined linearly with soil water potential after a critical soil water level was reached. In particular, 'Baron' Kentucky bluegrass maintained 100% of PET until a soil water potential of -0.04 MPa was reached. When the soil water potential had fallen to -0.06 MPa, the bluegrass no longer was of acceptable visual quality (<6.5). From -0.04 MPa, transpiration decreased linearly with decreasing soil water potential until the turf appeared dead; a point at which its water use rate was only 20% of PET at -0.40 MPa. In contrast, the quality of the hard and Chewings fescues did not fall below an acceptable level (<6.5) until a soil water potential of -0.40 MPa had been reached. The superior ability of the fescue species to avoid drought relative to the bluegrass was significantly correlated with two physiological factors. The fine fescues maintained leaf growth to a soil water potential of -0.40 MPa, while bluegrass leaf growth ceased at -0.13 MPa; and while the relative leaf water potentials of the fescues remained relatively constant down to a soil water potential of -0.40 MPa, bluegrass relative leaf water potential had declined by as much as 50% at -0.13 MPa. The authors concluded that these differences in sensitivity to low soil water potential could give these fine fescue species a substantial additional period of acceptable quality during an episode of drought.

This research suggests that the fescue species have a greater ability to maintain high tissue water potentials (i.e., avoid drought) relative to Kentucky bluegrass, but since no similar research has compared tall fescue with Kentucky bluegrass it is an open question as to whether tall fescue has a greater physiological sensitivity (or a greater ability to maintain its ET-rate) when faced with declining soil water potentials.

Although no studies were found which compared Kentucky bluegrass and tall fescue ET-rates at continually decreasing soil water potentials, Younger et al., (1981) reported that, when these two turfs were irrigated when soil water potential reached a (moderately stressful) level of -0.06 MPa in California, their summer average ET-rates were nearly identical: 4.4 mm/day for Kentucky bluegrass and 4.5 mm/day for tall fescue. In comparison, when 'Rebel II' tall fescue growing in Georgia was irrigated at the much more stressful level of -

0.40 MPa, its summer average ET-rate was only 3.6 mm/day (Carrow, 1991).

C. Osmotic Adjustment and Drought Resistance

White et al. (1992) compared the turgor maintenance of three experimental tall fescue selections under severe water-deficit stress (leaf water potentials down to -3.5 MPa) and found that the primary mechanism of turgor maintenance in tall fescue is low basal leaf osmotic potential and osmotic adjustment. They found that tall fescue osmotic adjustment ranged from 0.20 to 0.27 MPa. In another study, West et al. (1990) reported osmotic adjustments of 0.49 MPa for tall fescue. Working with Kentucky bluegrass, Nus and Hodges (1985) reported osmotic adjustment of 1.39 MPa during water-deficit stress (leaf water potentials down to -3.5 MPa). No studies concerning osmotic adjustment of buffalograss were found.

These limited data would indicate that, under severe water stress (equivalent to zero turgor), Kentucky bluegrass has a greater ability than tall fescue to tolerate or even escape drought by protecting the membranes in its crowns through greater osmoregulation. This statement is supported by field observations which have revealed that tall fescue turfs can be severely thinned after severe drought, while Kentucky bluegrass recovers more fully.

If these observations are related to the Aronson et al. (1987b) study reviewed above, one may speculate that Kentucky bluegrass ceases growth (i.e., goes dormant) sooner than tall fescue when soil moisture becomes limiting. In this way, it is able to direct its limited resources toward osmotically protecting its meristematic cells (or growing point tissues, particularly, its crowns) so that each plant can recover once there is adequate soil moisture. Tall fescue may instead direct more of its resources towards maintaining positive leaf turgor rather than towards osmotically protecting its meristimatic tissues. Thus, while it may be that tall fescue avoids drought longer than Kentucky bluegrass, it may not tolerate it as well.

Such information, if confirmed, would play a major role, depending on the level of projected maintenance, in determining which species to plant. If the plan is to have a cool-season species lawn in Colorado, following establishment, which will almost never be irrigated, the sensible choice would be Kentucky bluegrass. If the plan is to have a cool-season species lawn which will be irrigated at 50-75% of PET (or, as is more often the case, when moderate to severe wilting occurs), the better choice would be tall fescue.

D. Morphological Characteristics and Other Factors Influencing Drought Resistance

Buffalograss possesses a number of morphological features which function to minimize transpiration. It has been reported that, during drought, buffalograss can reduce its epidermal and stomatal conductance or water loss by an added growth of wax which partially covers its stomates. Kim (1987) indicated that 'Texas Common' buffalograss possessed a heavy wax accumulation on both sides of its leaf blades which increased during water stress and almost completely blocked stomatal openings. This wax accumulation was also visually greater than on any of the nine other warm-season turfgrasses examined. A waxy leaf surface also aids in reflecting radiation, thereby keeping the leaf surface cooler and reducing transpiration (Jones, 1992). Additionally, many varieties of buffalograss have pubescent leaf blades which increase radiative reflectance and cause greater resistance to the normal upward movement of water vapor through the canopy (Kim and Beard, 1988).

Kim (1987) also reported that 'Texas Common' buffalograss had significantly lower stomatal density (on both sides of the leaf blade) compared to 'Meyer' and 'Emerald' zoysiagrass and 'Tifway' and 'Tifgreen' bermudagrass. This buffalograss had an average of 324 adaxial stomates/mm^2 and 224 abaxial stomates/mm^2. Kentucky bluegrass stomatal densities have been reported in the range of 73 to 125/mm^2 adaxially and 24 to 41/mm^2 abaxially (Green et al., 1990). Tall fescue stomatal densities have been reported in the range of 68 to 88/mm^2 adaxially and 46 to 55/mm^2 abaxially (Green et al., 1990). These numbers do not seem to indicate a large difference between the two cool-season species as far as potential transpiration is concerned. The interesting comparison is between the warm-season and cool-season species.

How can warm-season turfgrass species possess higher stomatal densities yet consistently have lower ET's? The answer, of course, involves their different CO_2-fixation pathways. Warm season (C-4) species have virtually no CO_2 compensation point, allowing them to utilize water more efficiently in comparison to cool-season (C-3) species. Jones (1992) reports transpiration ratios (g H_2O lost per g CO_2 fixed), of 450-950 for C-3 species and 250-350 for C-4 species. The stomates of warm season species are also more sensitive to environmental changes than cool-season species, closing faster under high temperature stress and drought (Jones, 1992). These factors, coupled with buffalograss' waxy and pubescent nature, serve to explain how it can have higher stomatal density while possessing a lower transpiration rate.

Kim and Beard (1988) reported that 'Texas Common' buffalograss had an average blade width of 1.7 mm versus a value of 3.6 mm for 'Kentucky 31' tall fescue. It has been reported that buffalograss and tall fescue can reduce water loss by rolling their blades during drought, which decreases the evaporative surface area (Savage and Jacobsen, 1935; Kim, 1987). Although they both may roll their leaves during drought, the difference in blade width indicates a competitive advantage for buffalograss.

E. Heat Tolerance and Drought Resistance

Another partial indicator of drought resistance is heat tolerance. Wallner et al. (1982) ranked the heat tolerance of buffalograss, tall fescue, and Kentucky bluegrass by measuring their respective killing temperatures and times as determined by electrolyte leakage. They found that buffalograss was killed much more slowly (>600 minutes) and at a higher temperature (61 C) than both tall fescue (55 C, 166 minutes) or Kentucky bluegrass (55 C, 176 minutes), which exhibited statistically equivalent levels of heat tolerance. These results, coupled with the osmotic adjustment results reviewed above, provide more support for the supposition that tall fescue's greater ability to remain green longer than Kentucky bluegrass, when observed, is due neither to greater heat or drought tolerance but to greater drought avoidance provided by deep rooting (DiPaola and Beard, 1992), and its (proposed) greater ability to physiologically adjust its ET-rate.

F. Rooting Activity, Soil Moisture Extraction, and Drought Avoidance

At the end of a three year water-use study in California (on a sandy-loam), Younger et al. (1981), reported that maximum root depth was significantly greater for tall fescue (61 cm) than for Kentucky bluegrass (46 cm). At their lowest irrigation level, automatic irrigation when soil tension fell to -0.55 MPa or approximately 75% of pan evaporation, tall fescue maintained significantly greater quality than Kentucky bluegrass; a result, although no soil moisture data were taken, which the authors attributed to tall fescue's greater ability to extract deep soil moisture because of a deeper root system.

In a classic study, Madison and Hagan (1962), reported that during a 27-day dry-down cycle, three and four year old 'Merion' Kentucky bluegrass, grown in a clay-loam in California and mowed at 5 cm, extracted 62% of the water it used from the 0-20 cm depth, 33% from the 20-50 cm depth, and 5% from the 50-90 cm depth in 1954. In 1955, its pattern of water extraction remained very similar, extracting 64% from 0-20 cm, 32% from 20-50 cm, and 4% from 50-90 cm. They unfortunately did not measure root mass at these depths, but instead stated that in interpreting their results they assumed that plant water extraction was directly proportional to the number of absorbing roots (when soil moisture was not limiting). One might further add the caveat that when the amount of available water in the soil around the roots in the upper soil layers becomes limiting, the proportion of moisture extracted by the roots in the deeper, more moist soil, will increase.

More recently, Carrow (1991) reported water extraction patterns and root densities for 'Rebel II' tall fescue grown on a sandy loam in Georgia under a number of different irrigation regimes. After 14 months of growth, this turf, under non-limiting soil moisture conditions, extracted 67% of the water it used from the top 20 cm of soil and the remaining 33% from the 20-60 cm depth, on average, over a four day period. Two weeks later, over a three day period, this water extraction pattern was very similar: 64% from the top 20 cm and 36% from the 20-60 cm depth. When this turf was subjected to a number of short dry-down cycles (18 days in June, 13 days in August, and 11 days in September) its water extraction pattern by depth shifted to an average of 46% from the top 20 cm and 54% from 20-60 cm. In September of 1990, after 17 months of growth, this turf had 81% of its roots in the top 20 cm and 19% from 20-60 cm deep. From these root data, one can see that when water became limited in the upper 20 cm of soil, a greater proportion of water was taken up by the relatively small proportion of roots at the 20-60 cm depth. This data clearly provides evidence for the hypothesis that small amounts of roots deep in the soil contribute substantially to a plant's ability to avoid drought.

If we compare this pattern of tall fescue water extraction during limited soil moisture conditions with those reported above by Madison and Hagan (1962) for Kentucky bluegrass, we see that while the tall fescue extracted 54% of its water from deeper than 20 cm, the Kentucky bluegrass only extracted 36% from deeper than 20 cm. If Madison and Hagan (1962) had taken root samples they probably would have shown that their proportionality assumption was correct. Namely, that Kentucky bluegrass proportions a relatively small amount of its roots deep in the soil (> 30 cm); thereby confirming their data which indicated that only a small proportion of water was extracted from deep in the soil.

While no soil-water extraction data are available for buffalograss, there are some elegant water-extraction data available for hybrid bermudagrass (*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Davy cv. 'Tifgreen' and 'Midiron') which may serve to indicate possible buffalograss water extraction patterns.

Working in Arizona, Garrot, Jr. and Mancino (1994) monitored fairway-maintained bermudagrass water extraction under successive dry down cycles with neutron probes. In the summer of 1990, during two successive dry-down cycles, they reported the following bermudagrass water extraction patterns. At the beginning of the first cycle, when water was not limiting (field capacity), the bermudagrass extracted approximately 75% of its water from the top 30 cm, 20% from 30-60 cm, and 5% from 60-90 cm. In the middle of the first cycle, the bermudagrass extracted 55% from the top 30 cm, 30% from 30-60 cm, and 15% from 60-90 cm. By the end of the first cycle, when water was severely limiting (i.e., soil water contents at all three depths were below the measured wilting point estimated at -1.5 MPa) and just prior to an irrigation event, the bermudagrass extracted only 20% from the top 30 cm, 20% from 30-60 cm, and 60% from 60-90 cm. Following an irrigation event, which was applied with the intent of restoring the top 90 cm of soil to field capacity, the bermudagrass water extraction pattern was 60% from the top 30 cm, 20% from 30-60 cm, and 20% from 60-90 cm. Mid-way through this second cycle, the bermudagrass water extraction pattern had again shifted so that 40% of the extracted water was from the top 30 cm, 40% from 30-60 cm, and 20% from 60-90 cm. And again, by the end of the second dry-down cycle, when all three depths had almost reached the wilting point, the water extraction pattern was 30% in the top 30 cm, 30% from 30-60 cm, and 40% from 60-90 cm.

Although Garrot, Jr. and Mancino (1994) did not report any rooting data, the above stated assumption (or hypothesis) is also supported by this data. Namely, it supports the hypothesis that plant water extraction is directly proportional to the number of absorbing roots when soil moisture is not limiting. Additionally, it shows that when the amount of available water in the upper root zone becomes limiting, the proportion of moisture extracted by the proportionately smaller number of roots in the deeper, more moist soil, will increase.

At the end of a two year rooting depth study in Missouri (on a silty clay), Sheffer et al. (1987) reported that unirrigated 'Fylking' Kentucky bluegrass had significantly greater root mass at the 0 to 12 cm depth than unirrigated 'Kentucky 31' tall fescue, but that from 12 to 84 cm, tall fescue had significantly more root mass. While the Kentucky bluegrass had 75% of its root mass in the top 12 cm, the tall fescue had only 50% in the same zone. These differences in root distribution were significantly correlated with a higher soil moisture content in the top 6 cm and significantly lower soil moisture contents at depths of 54 and 78 cm for tall fescue, relative to Kentucky bluegrass. Also, while the Kentucky bluegrass went dormant in August, the tall fescue remained 100% green and viable, an observation which the authors attributed to tall fescue's much deeper rooting.

At the end of a three year rooting study employing a rhizotron in Ohio (on a sand), Koski (1983), reported a maximum rooting depth, under well-watered conditions, of 81 cm for 'Rebel' tall fescue, while 'Baron' Kentucky bluegrass' maximum rooting depth was merely 29 cm. Similar to the data reported by Sheffer et al. (1987), Koski found that the Kentucky bluegrass had 96% of its roots in the top 30 cm of soil, while the tall fescue had only 87%. No soil moisture distribution data were reported.

A number of other studies have also demonstrated tall fescue's greater rooting character relative to Kentucky bluegrass. After one year's growth on a silt loam in Kansas, Carrow (1980) reported that 'Kentucky 31' tall fescue had significantly more root mass in the 0 to 20 cm root zone than 'Baron' Kentucky bluegrass. Garwood and Sinclair (1979) showed that unirrigated tall fescue, grown for three years as a forage on a sandy loam in England, grew roots and extracted significant amounts of soil moisture at depths greater than 100 cm. Bennett and Doss (1960) showed that irrigated tall fescue, grown for four years as a forage on a sandy loam in Alabama, grew roots and extracted soil moisture to a depth of 115 cm. Gist and Smith (1948) reported that a mature (> 5 year old) stand of Kentucky bluegrass on a silt loam in West Virginia, formed some root mass (0.3%) down to a depth of 30 to 46 cm, but that most roots (95%) were in the top 15 cm. O'Donnell and Love (1970) reported that a three year old stand of 'Merion' Kentucky bluegrass, on a silt loam in Wisconsin, had approximately 1% of its root mass to a depth of 66 to 76 cm, while 85% of its root mass was in the top 15 cm.

Weaver (1958) reported that buffalograss in a natural grassland community had 79% of its roots distributed in the top 15 cm of soil, and 10% in the 15-31 cm root zone. Hopkins (1953) reported that a stand of native buffalograss in Kansas on a silty loam had roots to a depth of 213 cm. When the root mass was sampled to a depth of 122 cm it was found that 72% of the root mass was in the upper 30 cm of soil. Rooting data for a ten-year-old seeded buffalograss stand revealed maximum rooting depth to 198 cm; 80% of the root mass sampled to 122 cm occurred in the top 30 cm. A seven-year-old stand of Kentucky bluegrass in this Kansas study displayed maximum rooting depth to 122 cm, with 95% of its root mass in the surface 30 cm. Lastly, Kim (1987) found maximum rooting depth for 'Texas Common' buffalograss to be 88 cm when grown in sand-filled columns in the greenhouse for six months; rooting distribution by depth was not reported.

Past research would allow one to safely conclude that tall fescue, though possessing a relatively high ET rate, avoids drought by extracting water from a greater volume/depth of soil. Thus, tall fescue maintains a high tissue water potential relative to other cool-season species when faced with soil moisture deficits. It is therefore not surprising that a number of researchers have demonstrated tall fescue's superior ability to avoid drought relative to Kentucky bluegrass when irrigated at less than optimum levels, while no such comparison has included buffalograss.

II. Irrigation Requirements to Avoid Drought

Over a two year period in California, Meyer and Gibeault (1987) demonstrated that tall fescue performance, when irrigated at 60% of wind-modified pan-evaporation, was not significantly different from its performance when irrigated at 100% of pan evaporation. The same was not true of Kentucky bluegrass, where its performance was significantly decreased (relative to the 100% treatment) at the 60% level. Kentucky bluegrass quality, however, was not significantly decreased when irrigated at an 80% level. It also should be noted, even though rooting data were not taken, that these turfs were grown in a deep soil (> 180 cm) which did not restrict depth of rooting.

Over a period of three years in Fort Collins, Colorado, Feldhake et al. (1985) performed a deficit irrigation study comparing the drought resistance of 'Merion' Kentucky bluegrass and 'Rebel' tall fescue grown in 23 cm deep sand-filled lysimeters. Both Kentucky bluegrass and tall fescue maintained acceptable quality at an irrigation replacement level of 73% of PET or greater. Given the shallow lysimeters used in this study, it is not unreasonable to assume that tall fescue failed to outperform Kentucky bluegrass because it was not allowed sufficient soil volume from which to extract moisture when deficits occurred. In fact, given tall fescue's higher relative PET-rate, it is surprising that it maintained quality comparable to Kentucky bluegrass with such a shallow root zone. This result might indicate a greater ability on the part of tall fescue to regulate its water use in proportion to the amount of available soil water.

Over a period of two years in Fort Collins, Colorado, Minner (1984), using lysimeters with the same specifications as Feldhake et al. (1985), found that 'Merion' Kentucky bluegrass and 'Fawn' tall fescue maintained acceptable quality when irrigated at 75% or greater of Kentucky bluegrass PET. In this study, Minner pointed out the unfortunate use of such a shallow lysimeter for comparing the relative drought avoidance capabilities of these two species.

Finally, in another two-year study in Fort Collins, Colorado, Fry and Butler (1989) demonstrated that 'Rebel' tall fescue, grown in the field on a sandy clay loam, maintained acceptable quality when watered every two days at 50% of (tall fescue) PET or when watered every seven days at 75% of PET. They concluded that tall fescue's inherent ability to root deeply contributes to its drought resistance. Further, they concluded that, in Colorado, tall fescue is a better turfgrass choice over Kentucky bluegrass if the objective is to conserve water because previous research (Minner, 1984) had shown that Kentucky bluegrass was not able to maintain acceptable summer-long quality when irrigated at 50% of PET regardless of irrigation frequency.

III. Use of Infrared Thermometry to Monitor Turfgrass Stress

A fairly recent development in plant water stress research and irrigation scheduling is the determination of crop water stress indices (CWSI). Their determination is based on canopy temperature minus air temperature (Tc-Ta) differentials, as measured by infrared thermometry, and other significant microenvironmental factors such as air vapor pressure deficit (VPD), solar radiation, and wind speed. Idso et al. (1981) introduced the CWSI based on the empirical observation that the relationship between the Tc-Ta of well-watered plants and the VPD appeared to produce species-specific linear relationships on cloud-free days (Jalali-Farahani et al., 1993). They referred to this linear relationship as the non-water-stressed baseline, commonly called the lower baseline, which they expressed as

$$(Tc\text{-}Ta)p = a + b \times \text{VPD},$$

where $(Tc\text{-}Ta)p$ is the canopy temperature minus air temperature of a plant transpiring at maximum potential, and a (intercept) and b (slope) are the linear regression parameters of $(Tc\text{-}Ta)p$ on VPD.

A second baseline, the zero transpiration baseline or upper baseline, also needs to be calculated. This baseline represents the theoretical Tc-Ta that would be reached by a plant with no cooling transpiration (i.e., its stomates completely closed). This baseline has been defined by Jalali-Farahani et al. (1993) as

$$(Tc\text{-}Ta)p = a + b \times \text{VPG},$$

where a and b are the intercept and slope and VPG is the difference between the saturation vapor pressure at Ta and a temperature equal to $Ta + a$.

The CWSI is calculated by

$$\text{CWSI} = (\text{Tc-Ta})\text{m} - (\text{Tc-Ta})\text{l} / (\text{Tc-Ta})\text{u} - (\text{Tc-Ta})\text{l},$$

where (Tc-Ta)m is the measured canopy/air temperature differential, (Tc-Ta)l is the minimum potential canopy/air temperature differential at the measured VPD, and (Tc-Ta)u is the maximum potential temperature the canopy/air temperature differential can reach at the measured ambient air temperature (Idso et al., 1981; Throssell et al., 1987; Jalali-Farahani et al., 1993). As the crop goes from a state of maximum transpiration to zero transpiration, the CWSI will range from zero to one. The need for irrigation is indicated when the

CWSI approaches or exceeds a specific value that has been determined by experimental observation or experience (Throssell et al., 1987; Carrow, 1994).

Irrigation scheduling based on CWSI's has a number of practical advantages. First, because they provide nearly direct monitoring of turfgrass transpirative-cooling status, the turf manager is able to schedule irrigations which more closely match the plant's needs. In this way, the turf manager is able to predict that his or her turfgrass is undergoing significant water stress much earlier than would be apparent visually. Irrigating in such a manner should promote greater overall turfgrass health. Watering that is more "in tune" with the plant's needs will result in a turf that is more wear tolerant and less prone to weed invasion and pest damage. It would also promote and conserve deep rooting, making the plant more water and nutrient efficient.

Throssell et al. (1987) irrigated 'Sydsport' Kentucky bluegrass for one summer in Kansas at soil water potentials of -0.04 MPa (well-watered), -0.07 MPa (slightly stressed), and -0.40 MPa (moderately stressed) and reported seasonal average CWSI's of 0.10, 0.25, and 0.50, respectively. They reported a non-water-stressed baseline of

$$(Tc\text{-}Ta)l = 7.7 - 2.2 \times VPD; \ (R^2 = 0.67, n = 80).$$

The following year they compared the quality of 'Ram I' Kentucky bluegrass with two irrigation treatments: i) tensiometer scheduled irrigation at -0.07 MPa or ii) when its CWSI reached 0.25. For the tensiometer treatment, 98 mm of water was applied and for the CWSI treatment, 140 mm of water was applied.

While visual quality was above 7.0 (1-9 scale) at the end of the 30 day study for the CWSI schedule, visual quality for the tensiometer schedule finished the study at about 6.0, a rating significantly lower ($p = 0.05$) than the CWSI treatment.

Horst et al. (1989) developed non-water-stressed baselines for 'Falcon' tall fescue and 'Texoka' buffalograss. These baselines were developed from the Tc-Ta differentials for the plots which received 100% of lysimeter ET from a line source irrigation system. In 1986, irrigation was applied to replace accumulated lysimeter ET every two days and in 1987, the same was done every three days. The reported tall fescue non-water stressed baselines for 1986 and 1987 were:

$$(Tc\text{-}Ta)l = 6.4 - 2.1 \times VPD; \ (R^2 = 0.50, n = 299); \text{ and}$$

$$(Tc\text{-}Ta)l = 6.5 - 2.7 \times VPD; \ (R^2 = 0.37, n = 327).$$

The reported buffalograss non-water-stressed baselines for 1986 and 1987 were:

$$(Tc\text{-}Ta)l = 9.3 - 2.3 \times VPD; \ (R^2 = 0.70, n = 299); \text{ and}$$

$$(Tc\text{-}Ta)l = 9.4 - 3.0 \times VPD; \ (R^2 = 0.54, n = 305).$$

In comparing the baselines for each species an interesting trend is apparent. Tall fescue has the lowest Tc-Ta intercept, followed by Kentucky bluegrass, with buffalograss having the highest Tc-Ta intercept. This trend seems to indicate that when water is not limiting tall fescue is able to transpire at a higher rate, thus cooling its leaves more readily than Kentucky bluegrass and buffalograss. This statement agrees well with tall fescue's reportedly higher PET-rate relative to Kentucky bluegrass and buffalograss. It also agrees with the growth chamber study of Feldhake and Boyer (1985) who found that well-watered buffalograss, and warm-season grass species in general, had higher internal resistances (i.e., greater stomatal sensitivity to small changes in vapor pressure deficit) to water loss when compared to well-watered cool-season grasses such as tall fescue. This resulted in lower PET-rates and warmer canopy temperatures at any given air temperature and vapor pressure deficit for the warm-season grasses. In the literature it is well-established that these differences are most likely due to the fact that warm-season grasses (or plants) in general have significantly lower transpiration ratios (mol H_2O transpired/mol CO_2 fixed) than cool-season grasses (or plants) (Noble, 1991; Jones, 1992). This information and the Feldhake and Boyer (1985) study provide further evidence for the supposition that buffalograss possesses morphological and physiological drought resistance advantages in relation to Kentucky bluegrass and tall fescue.

IV. Soil Compaction at Establishment and Drought Resistance

A final factor investigated in this study which may influence drought resistance is soil compaction at turfgrass establishment. Soil compaction results in increased bulk density, increased moisture retention at higher matric potentials, and increased penetrometer resistance (i.e., mechanical impedance to root growth), while total pore space, aeration porosity, and hydraulic conductivity decrease (Carrow and Petrovic, 1992). In turn, these factors affect plant growth by altering root growth, shoot growth, and water use.

Carrow and Petrovic (1992) hold that the most conspicuous rooting response to soil compaction is altered root distribution. Agnew and Carrow (1985) reported increased surface rooting and decreased deep rooting for well-watered (0 to -0.04 MPa soil water potential) and compacted (720 Joules of energy over 99 days) Kentucky bluegrass turf, grown in a greenhouse, when compared to uncompacted turf. The compacted turf had significantly more root mass in the surface 5 cm, while it had significantly less root mass from 10 to 20 cm. When the soil was allowed to become drier (down to -0.40 MPa), surface rooting still increased and deeper rooting decreased under compaction. Total root growth from 0 to 20 cm decreased by 10% relative to the uncompacted treatment. Obviously, such a reduction in deep rooting caused by continuous surface soil compaction will decrease a plant's ability to explore the soil profile for water and nutrients. Such a reduction in deep rooting potential will result in a plant more susceptible to high temperature stress and drought.

Lee and Rieke (1993) performed a study at Michigan State which included compaction and tillage treatments similar to those imposed in our study. In their study, they compared the rooting strength of well-watered Kentucky bluegrass sod that was established on equally compacted plots which, prior to sod planting, were either rototilled to a depth of 4.5 cm or not rototilled. They gauged each sod's subsequent rooting strength by the force needed to lift sod rooting boxes out of the ground. One month after sodding, the rototilled plots had significantly greater rooting strength. The same was true after two and a half months, but after 10 months there were no significant differences in rooting strength between the tilled and the untilled plots. Essentially the same experiment was run two more times with the same ten-month transitory result. In all three experiments the same pattern was observed. Sod that was laid in August had greater sod strength through the fall in the tilled plots, with the effect no longer being measurable by the next summer. The transitory nature of the compaction treatment was confirmed by showing that the bulk densities, which at the beginning of the experiment were significantly higher for the untilled plots, were no longer different after ten months.

CHAPTER 3: MATERIALS AND METHODS

This study was conducted during 1993 and 1994 at the Colorado State University Horticulture Field Research Center. It is located a few kilometers northeast of Fort Collins, Colorado and is at 1500 m above sea level. The climate is semi-arid with average annual maximum temperatures of 16.8 C, minimum of 1.2 C, and average annual precipitation of 365 mm. The soil is a Nunn clay loam (Aridic Argiustoll, fine, montmorillonitic, mesic).

The experiment had three factors arranged in four randomized complete blocks. Each block contained 50 experimental units that were 1.8 meters wide and 2.4 meters long. The three factors were turfgrass type, establishment tillage depth, and irrigation level. Each of the five turfgrass types were sodded over two establishment tillage depths. These two factors represented ten main plots which measured 1.8 meters wide by 12.0 meters long. The main plots were split into five 1.8 meter wide by 2.4 meter long plots according to irrigation level.

I. Turfgrass Types

The following turfgrass types were sodded onto the prepared study site on September 22 and 23, 1992.

1) 'NuStar' Kentucky bluegrass (*Poa pratensis* L.), an improved cultivar which was released in 1992, with a reputation for being very drought resistant.

Under medium-high maintenance conditions in the 1993 National Turfgrass Evaluation Program (NTEP), its quality ranking was 88 out of 125 cultivars at Colorado State University (CSU) and 30 out of 125 nationwide (Morris, 1993a). In the low maintenance 1993 NTEP trials, the quality ranking of NuStar was 20 out of 62 cultivars at CSU and 13 out of 62 nationwide (Morris, 1993b). Also, in the low maintenance 1993 NTEP trials, the ability of NuStar to tolerate drought was evaluated by rating its ability to postpone dormancy and its ability to recover from drought. Dormancy postponement ratings were conducted at CSU and two locations in Maryland. At CSU and across all three sites, none of the 62 cultivars tested had a significantly greater ability to postpone dormancy than NuStar. Drought recovery ratings were conducted at only two locations, CSU and North Brunswick, New Jersey. At CSU, 27 of the 62 cultivars tested had a significantly greater ability to recover from drought than NuStar (Morris, 1993b). We chose to use NuStar because of its reputation for drought resistance, as well as the fact that it was being widely planted by sod producers in Colorado.

2) Turf-type tall fescue (*Festuca arundinacea* Schreb.) blend: 38% 'Rebel Jr.', 38% 'Crewcut', 24% 'Monarch'.

These three cultivars are known as lower growing "dwarf-types". These new dwarf-type cultivars have a more prostrate growth habit, a reduced vertical growth rate, a finer leaf texture, and higher tiller density relative to the older turf and forage type tall fescues (Meyer and Fricker, 1989; Funk and Clarke, 1989). Rebel Jr. also contains some level of endophytes, while the other two do not. Data from greenhouse studies in Nebraska (Kinbacher et al., 1988) and New Jersey (Suichang and Funk, 1988) have indicated that these new dwarf-type cultivars produce fewer clippings and more verdure than the original turf and forage types (Meyer and Fricker, 1989). There are conflicting thoughts about the rooting characteristics of these dwarf-types relative to the older turf and forage types. The Kinbacher et al. (1988) study at Nebraska indicated that there were not distinct differences between dwarf, original turf-type, and forage types for rooting responses. Dr. Leah Brilman (personal communication, 1994) has observed a tendency for these dwarf-types to produce less roots than the original improved turf-types such as 'Rebel', 'Rebel II', and 'Arid', possibly due to some inbreeding depression.

3) Turf-type tall fescue blend and Kentucky bluegrass mix: 25% each 'Rebel II', 'Apache', 'Arid', and 'Trident'. In addition, 'Freedom' Kentucky bluegrass was mixed in at 5% of the total seed weight. This translates into a seed mix ratio of 65 turf-type tall fescue seeds to 35 'Freedom' Kentucky bluegrass seeds at seeding.

This mix was included in this study for two reasons. First, because it is a common sod sold for home lawns in Colorado. Second, it was desired to observe (and eventually quantify) its long-term population dynamics under differing irrigation regimes.

4) '609' buffalograss (*Buchloë dactyloides* Nutt. Engelm.)

609 is an improved turf-type buffalograss which was developed by the University of Nebraska and released in 1991. It is a female clone and therefore can only be established vegetatively. This cultivar is currently available from a limited number of Colorado sod producers.

5) 'Prairie' buffalograss (*Buchloë dactyloides* Nutt. Engelm.)

Prairie is also an improved turf-type buffalograss which was developed by Texas A & M and released in 1991. It is a female clone and therefore can only be established vegetatively.

All of the cool-season turfgrass types were obtained from Turfmaster Sod, Fort Collins, CO. The Nustar Kentucky bluegrass and tall fescue blend were approximately one year old at harvest and the tall fescue/Kentucky bluegrass mix was approximately two years old at harvest. Both buffalograss cultivars were obtained from Crenshaw and Douget Turfgrass, Austin, TX. The 609 was approximately seven month old regrowth and the Prairie was approximately twelve month old regrowth.

(Note: In the rest of the text these turfgrass types will be referred to as KBG, TF, TF/KBG, 609, and Prairie, respectively.)

II. Establishment Tillage Depths

Two tillage depths were used at the time of sod establishment over a previously compacted Nunn clay loam. (See Appendix A for soil analysis details.) The soil was intentionally compacted prior to establishment in an attempt to mimic compaction conditions on a new home lawn following house construction. Approximately 2.5 cm of irrigation was applied to the soil, followed by driving a heavy tractor over the area for approximately thirty minutes. While no quantitative measures of compaction were taken, there was a definite indication of surface compaction when tillage treatments were first attempted. The first attempt at tilling the compacted soil surface with a 1.8 meter wide tractor-mounted rototiller was unsuccessful. The rototiller would not initially penetrate the soil surface. After an additional 2.5 cm of irrigation was applied and the soil allowed to dry and drain overnight, the tillage operation was successful.

Two tillage treatments were applied, one representing very poor soil preparation (2.5 cm tillage depth), and the other representing adequate soil preparation (15.0 cm tillage depth).

III. Irrigation Levels

Environmental parameters were monitored throughout the 1993 and 1994 summer seasons by a Northern Colorado Water Conservancy District (NCWCD) managed weather station over a field of actively growing (well-watered) alfalfa maintained at 30.0 cm. This weather station is located approximately 200 meters east of the study site. The weather station reported daily alfalfa reference evapotranspiration estimates based on the 1982 Kimberly-Penman combination equation (ASCE, 1990):

$$\lambda ETr = (\Delta/(\Delta + \gamma))(Rn - G) + (\Delta/(\Delta + \gamma))(6.43)Wf(e^{o}_{z} - e_{z})$$

where λ is the latent heat of vaporization in MJ/kg; ETr is evapotranspiration from a well-watered alfalfa reference crop in mm/day; Δ is the slope of the saturation vapor pressure/temperature curve in kPa/C; γ is the psychometric constant in kPa/C; Rn is net radiation in MJ/m^2 day; G is soil heat flux in MJ/m^2 day; Wf is a wind function developed in Kimberly, Idaho for the semi-arid West, where

$$Wf = a_w + b_w(u_2)$$

$$a_w = 0.4 + 1.4 \exp\{-[(D - 173)/58]^2\}$$

$$b_w = 0.605 + 0.345 \exp\{-[(D-243)80]^2\}; \text{ and}$$

u_2 is horizontal wind speed at 2.0 m above the ground in m/s, with D being the calendar day. Finally, $e^{o}_{z} - e_{z}$ is the saturation vapor pressure of air minus the water pressure of air at height z in kPa where,

$$e^{o}_{z} - e_{z} = [e^{o}(Tmax) + e^{o}(Tmin)/2] - e^{o}(Tdew)$$

These estimates were summed every three days during the irrigation treatment cycle and multiplied by a Kentucky bluegrass crop coefficient of 0.80. The resulting number, minus any precipitation that had occurred, represented the estimated amount of irrigation needed to totally replace Kentucky bluegrass evapotranspiration. The crop coefficient (Kc) of 0.80 for Kentucky bluegrass is the most common average value recommended by the relevant research (Feldhake et al., 1985; Minner, 1984; Meyer and Gibeault, 1987; Carrow, 1991), all of which were based on a grass cover as the reference crop (not alfalfa); it is the value recommended by Allen (1990) for use in Utah State University's "Reference ET-calculator" computer program; and is the value used by Denver and other Front Range city agencies in their turfgrass irrigation recommendation programs (Ball 1993, personal communication; Clark 1993, personal communication). Also, recent research with bucket lysimeters in Kentucky bluegrass, conducted by the NCWCD in Loveland, Colorado, resulted in a two-year average Kc (Actual ET/Kimberly-Penman reference ET) of 0.75 (NCWCD, 1993, 1994, unpublished manuscripts). Since a major objective of this study was to determine whether turf-type tall fescue and buffalograss are water-saving grasses relative to Kentucky bluegrass, there was no need to adjust estimated alfalfa-reference ET's with separate crop coefficients for tall fescue and buffalograss. A line source irrigation system (LSIS) was used to replace the three-day Kentucky bluegrass ET-estimates.

The LSIS consists of a single row of in-ground irrigation heads (Rainbird R-50 heads; 4 gal/min nozzles) located down the middle of the study area, spaced four meters apart. This spacing is equivalent to one-third of the radius of each sprinkler's maximum throw (12 meters). This sprinkler arrangement is designed to apply a linearly decreasing amount of water as perpendicular distance from the row of irrigation heads increases. Thus, the greatest amount of water is applied adjacent to the heads and the least amount of water 12 meters away, along a line parallel to the irrigation line. Ideally, this irrigation system was designed to allow the replacement of 100% of Kentucky bluegrass ET to those plots immediately adjacent to the irrigation line, and (linearly) less water to the remaining plots as distance from the irrigation line increased. Experimentally, we applied five irrigation levels, representing decreasing levels of Kimberly-Penman estimated KBG-ET, every third day during each season's irrigation cycle. These levels are represented in Figure 3.1 for 1993 and Figure 3.2 for 1994. See Appendix B for irrigation data details.

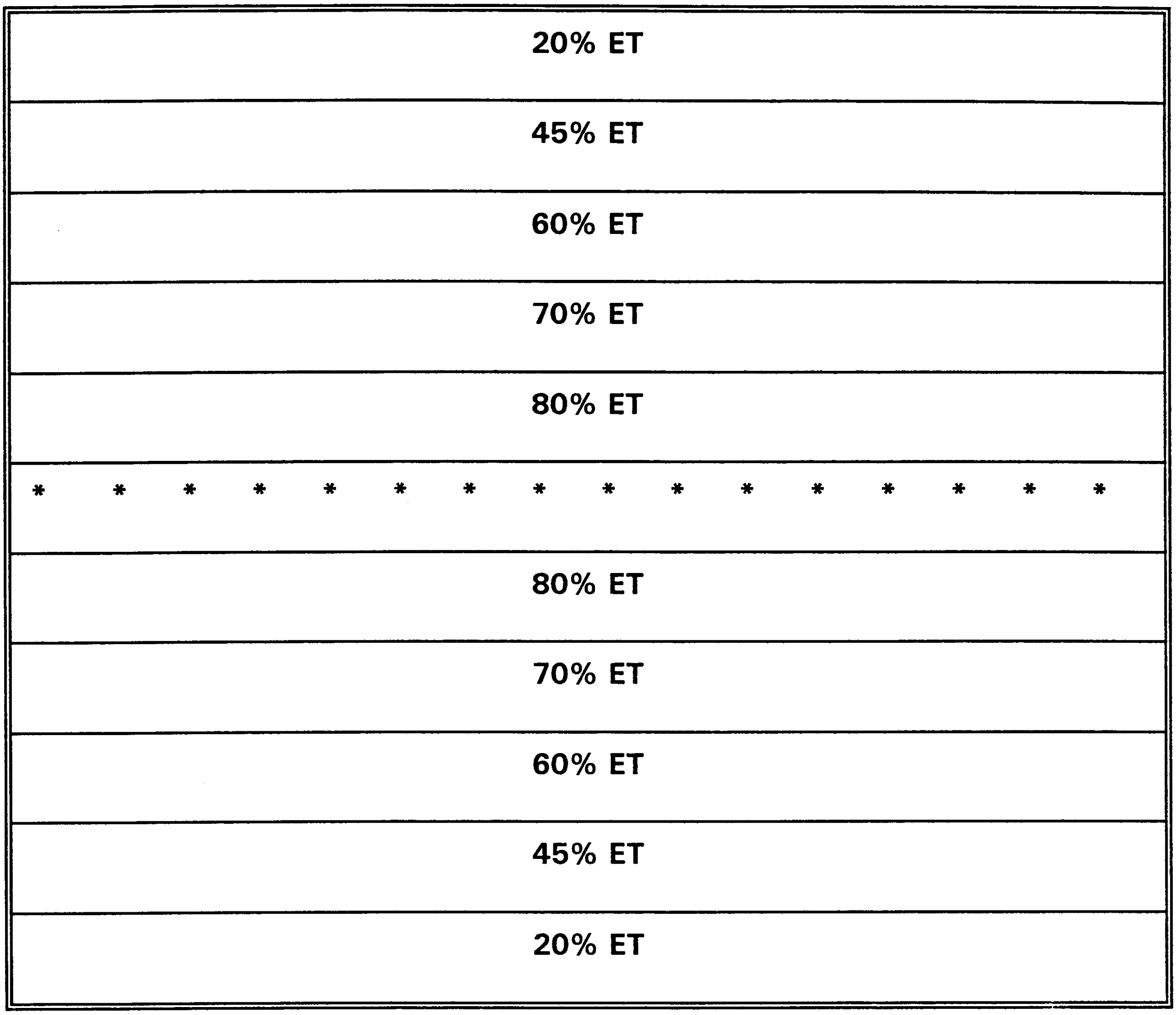


Figure 3.1: 1993 Irrigation Levels; irrigation was applied every three days from 7-1 to 9-8. (* = irrigation heads).

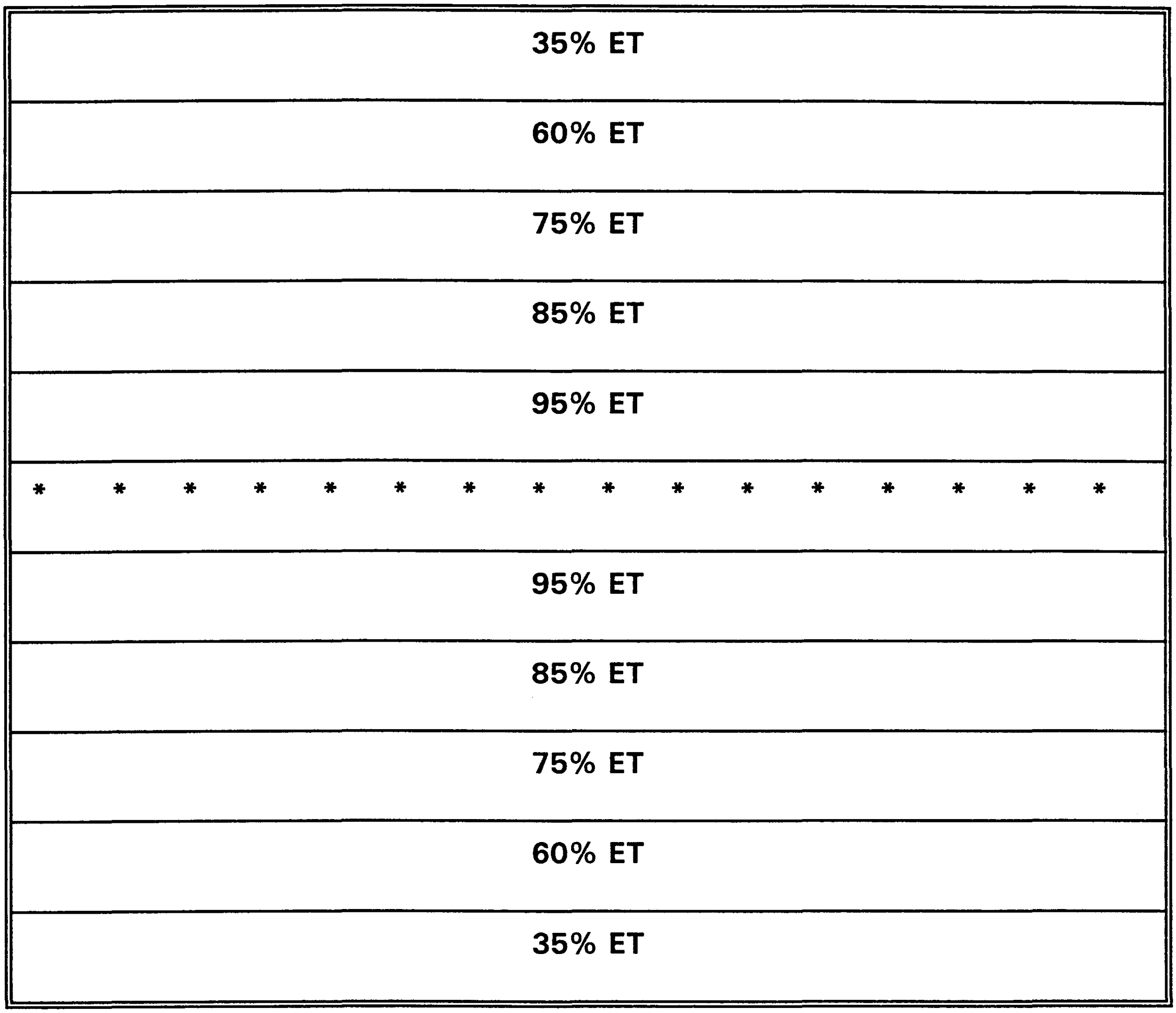


Figure 3.2: 1994 Irrigation Levels; irrigation was applied every three days from 6-9 to 9-3. (* = irrigation heads).

The irrigation level differences between 1993 and 1994 are a result of a change in pump size from the 1993 (40 psi) to the 1994 (60 psi) season and the resultant change in operating pressure. Some of the difference could also be attributed to different wind conditions between seasons.

Irrigation treatments were applied between 8 PM and 7 AM every third day to follow recommendations of the Denver Water Department with respect to interval and time of day.

IV. Cultural Practices

All plots were mowed twice weekly at 6.4 cm (2.5 inches), as recommended by Colorado State University Cooperative Extension for home lawns (Koski and Skinner, 1992). Each turf species was fertilized according to recommendations for a typical home lawn. A detailed breakdown of fertilizer and herbicide applications is shown in Table 3.1.

Table 3.1: 1993 and 1994 Fertilizer and Herbicide Applications

DATE	Turfgrass Type	N-amount (kg/ha)	P-amount (kg/ha)	Herbicide used	Herbicide rate (kg ai/ha)
4-18-93	BUFFs			Glyphosate	0.35
4-18-93	ALL			Dithiopyr	0.39
7-10-93	BUFFs		spot spray	Atrazine	2.24
7-19-93	BUFFs	49.0			
7-20-93	ALL			Bromoxynil	1.12
8-17-93	BUFFs	49.0			
9-30-93	COOLs	98.0			
10-21-93	BUFFs			Glyphosate	0.35
4-18-94	ALL			Dithiopyr	0.56
4-19-94	ALL	39.2	98.0		
5-9-94	BUFFs		spot-spray	Glyphosate	0.35
7-1-94	BUFFs	49.0			
9-4-94	COOLs	49.0			
9-29-94	COOLs	49.0			

An important deleterious herbicidal effect of dithiopyr (Dimension) application on buffalograss growth in 1994, and possibly 1993, warrant comment. Both years, dithiopyr was applied on 18 April on the dormant buffalograss as a preemergent crabgrass control. In 1993, a low labeled rate of 0.39 kg ai/ha was applied, while in 1994 the maximum labeled rate of 0.56 kg ai/ha was applied. Dithiopyr is a recently released product which has characteristics similar to the dinitroaniline herbicide group. It is relatively immobile in the soil and its mode of herbicidal action is a disruption of microtubule formation resulting in the loss of root-tip cell division and the subsequent appearance of short and swollen root-tips (Devine et al., 1993; Fishel and Coats, 1994).

A study investigating dithiopyr affects on common bermudagrass [*Cynodon dactylon* (L.) Pers.] sod rooting revealed that it had a number of deleterious effects when applied at 0.56 and 1.12 kg ai/ha (Fishel and Coats, 1994). Dithiopyr reduced the number of normal roots by 90-97%, compared to a control, two weeks following application at the maximum labeled rate of 0.56 kg ai/ha. Eight weeks following application, the number of normal roots was still 37-40% less than the number of normal roots in the control. Also, the number of abnormal roots compared to the control was significantly greater two and four weeks following application at 0.56 kg ai/ha, but there were no significant differences after eight weeks. These results corresponded to significant reductions in root fresh weight two and four weeks following application, but not at eight weeks. The authors concluded that the use of the labeled rate of dithiopyr on bermudagrass sod severely impacted rooting and therefore should be used only if a long time period (> two months) between application and sod harvest was foreseen.

The Fishel and Coats (1994) bermudagrass study seems to be very telling as concerns the effects of dithiopyr application on 609 and Prairie buffalograss growth in this study. In 1993, the irrigation treatments were not initiated until 1 July because of slow buffalograss May and June re-growth. At that time, the slow spring/summer growth was wholly attributed to poor establishment rooting due to the late sodding date of September 23, 1992, which may have contributed to some freezing damage and subsequent slow re-growth in the spring/summer of 1993. Given the above study results, much of this slow re-growth may have been caused by dithiopyr rhizotoxicity.

In 1994, with the higher rate of 0.56 kg ai/ha of dithiopyr being applied on 18 April, both 609 and Prairie buffalograss failed to re-grow a uniform canopy until approximately three and a half to four months following application. A non-replicated activated charcoal bioassay conducted in the greenhouse with some of the dithiopyr affected soil revealed severe perennial ryegrass (*Lolium perenne* L.) rooting inhibition.

V. Weather During the Study Period

Weather station data for the 1993 and 1994 treatment periods are contained in Appendix D.

During the 1993 treatment period (7-1 to 9-8), air temperatures were below normal and precipitation was above normal. The average daily high temperature for this period was 25.7 C, while the 88-year average for approximately the same time period is 28.6 C (SCS, 1989). The total precipitation was 130.6 mm, while the 88-year average is 89.8 mm (SCS, 1989). The average daily ET-demand adjusted with a 0.80 crop coefficient was 4.1 mm/day.

During the 1994 treatment period (6-9 to 9-3), air temperatures were above normal (with the hottest June ever recorded) and precipitation was below normal. The average daily high temperature for this period was 29.0 C, while the 88-year average for June, July, and August is 27.9 C (SCS, 1989). The total precipitation was 88.1 mm, while the 88-year average is 118.4 mm (SCS, 1989). The average daily ET-demand adjusted with a 0.80 crop coefficient was 4.7 mm/day.

VI. Data Collection Methods of Dependent Variables

Data was collected over the course of the two summer seasons on the possible effects of the three independent treatment variables. The five dependent variables sampled were: quality, leaf firing, crop water stress index (CWSI), root mass, and gravimetric soil moisture content.

Turfgrass quality was visually rated every three to four days at 1400 hours during each year's study period. In visually rating the quality of turfgrass, the color, density, and uniformity, or overall appeal of each plot were taken into consideration. Quality was rated on a scale of one to nine, where nine is an ideal turf area or lawn, six corresponds to a lawn of minimum acceptable quality, and one indicates a turf that is completely dormant or dead. Skogley and Sawyer (1992) have pointed out that Northeastern Turfgrass Research Committee members, meeting once or twice annually since 1962, have demonstrated and agreed that subjective quality ratings are valid when taken by experienced researchers. In comparing a number of different turfgrass types, there is a need on the part of the researcher to have a top quality rating for each type firmly set in his or her mind (Skogley and Sawyer, 1992). The following were the top quality levels possible for each turfgrass type in this study: KBG = 8.5; TF/KBG = 8.5; TF = 8.0; 609 = 7.0; Prairie = 7.0.

Turfgrass leaf firing was visually rated at the same time as quality. In visually rating the leaf firing of a turfgrass plot, the researcher recorded an estimate of the percent of leaves fired or browned in order to estimate the amount of turfgrass tissue injury that was occurring, with no differentiation as to whether the stress was a result of drought and/or high temperature. Under the deficit irrigation conditions of this study, leaf firing was regarded as a good overall measure of the relative drought resistance of each turf type. Leaf firing was rated using a scale of one to nine, where nine indicated no visible leaf firing and one indicated that all leaves were fired.

Canopy temperatures of each turfgrass type were measured with an infrared thermometer (Model 4000A, Everest Interscience, Tustin, CA) with a four-degree field of view and a factory-set emissivity setting of 0.98. Infrared thermometers measure the energy emitted by a plant canopy rather than surface temperature as such. The infrared thermometer is filtered to allow only a specific waveband, typically 8 to 14 microns, onto the detector. The energy captured by the detector is converted to temperature using Stefan's Law, which states that energy emitted is proportional to the fourth power of temperature and the emissivity of the surface (Hatfield, 1990).

Canopy temperatures were taken every third day during each summer's irrigation cycle between 11:30 and 14:00 hours if clear-sky conditions permitted. The infrared thermometer was held approximately one meter above the turfgrass canopy at an angle of 45 degrees from horizontal providing a target area of approximately 0.10 square meters. Canopy temperatures for 1993 are an average of 4 readings per experimental unit (2 facing east and 2 facing west). Canopy temperatures for 1994 are an average of an approximately 20 second scan of each experimental unit (a 10 second scan walking while facing east and a 10 second scan walking while facing west) logged into an Omega 160 data-logger (Omega Engineering, Inc.). Wet and dry bulb temperatures were measured with an aspirated psychrometer four times on each sampling date (once after each replication was sampled) and this average was then used to calculate each day's vapor pressure deficit.

Following the Idso et al. (1981) empirical method and using the turfgrass plots receiving the highest amount of irrigation to represent non-water stressed turfgrass plots (Horst et al., 1989), turfgrass-type upper and lower baselines were developed for the 1994 season (see Appendix C). These turfgrass type-specific baselines were then used to calculate crop water stress indices for each day sampled.

Another method which is based on a measure of net radiation and an estimate of aerodynamic resistance and foliage resistance in addition to VPD and temperature, has become known as the Jackson et al. (1981) theoretical method. Although a number of recent studies have shown the Jackson theoretical method to be superior in predicting turfgrass water stress (Horst et al., 1989; Jalali-Farahani et al., 1993; Martin et al., 1994), the Idso empirical approach was used in this study for two reasons. First, we did not have the proper equipment at our disposal to monitor the solar radiation and wind speed right on the research area. Second, the Idso empirical method is much more applicable to use in the field by turfgrass managers.

It was not possible to develop non-water stressed baselines for 1993 given that the highest resulting irrigation level was 80% ET-a level which did not represent a non-water limiting situation. Therefore, 1993 canopy temperature results are presented as the canopy temperature minus the air temperature with the vapor pressure deficit reported at the bottom of each table.

Root mass and gravimetric soil moisture content samples were obtained using a truck-mounted Gidding's hydraulic soil probe (Gidding's Manufacturing, Fort Collins, CO) on four dates in the study: two samples immediately prior to initiation of the two season's irrigation cycles (7-1-93 and 6-10-94) and two samples immediately following the two season's irrigation cycles (9-10-93 and 9-10-94). On all four dates, three depths were sampled: 0-30.5 cm, 30.5-61 cm, and 61-91.5 cm. On the first three sample dates, the soil probe diameter used was 3.81 cm; on the last sample date, the soil probe diameter used was 3.18 cm. Only 120 out of 200 experimental units were actually sampled corresponding to three of the five irrigation levels: 0-2.4 m, 4.8-7.2 m, and 9.6-12.0 m away from the irrigation line.

Two samples per unit depth were taken on each experimental unit and mixed together in one bag. These wet samples were immediately weighed and then oven-dried at 105 C for a minimum of 24 hours and then re-weighed. The difference between the wet weight and the dry weight divided by the wet weight corresponds to the gravimetric soil moisture content. Roots were then washed from the soil with a hydropneumatic elutriation system (Smucker et al., 1982), dried and weighed to obtain root mass.

VII. Statistical Analyses

Following Fernandez (1991), all data were subjected to a repeated measures analysis using the Statistical Analysis System (SAS) general linear models and analysis of variance procedures (SAS, 1988). In this analysis, the systematically arranged irrigation treatments were treated as repeated measures over space. Owing to the non-randomization of the irrigation treatments in this study, no valid conclusions can be made regarding the main effect of irrigation and associated interactions, unless a test of sphericity is satisfied. The SAS uses Mauchley's sphericity test, which states that the repeated measures (or within-subjects) model consists of independent (or orthogonal) components. If the data violate Mauchley's sphericity test ($P < 0.05$), a deflation of the numerator and denominator degrees of freedom for the F tests involving repeated measures is recommended before determining the significance levels for the univariate F tests (Fernandez, 1991). This adjustment is accomplished by calculating an H-F epsilon (Huynh and Feldt, 1976). By multiplying the numerator degrees of freedom and the denominator degrees of freedom by the H-F epsilon, the significance level of the F test is determined.

Univariate analysis of variance (ANOVA) tests were determined using the MSTAT microcomputer statistical program (Michigan State University, 1987). Where the sphericity assumption was violated as determined using SAS, the H-F adjusted F test significance was used. Mean separation tests of significance were calculated using either least significant difference (LSD) or Tukey's honest significant difference (HSD) tests, where appropriate.

CHAPTER 4: COMPACTION AND TILLAGE TREATMENTS

In the chapters that follow no discussion of the soil compaction and establishment tillage treatments will be presented because there were no effects observed or measured during either year. That is, there were no significant quality or leaf firing differences observed between the establishment tillage depths of 2.5 cm and 15.0 cm; nor were there any significant canopy temperature, root mass, or soil moisture differences measured. A number of reasons for this result may be proposed. First, it cannot be ruled out that the compaction treatment itself may not have been sufficient. Second, and more likely, the compaction applied to the soil in early September of 1992 was probably transient. That is, there probably was no significant difference in soil compaction between the soil that was rototilled to a depth of 2.5 cm and the soil that was rototilled to a 15.0 cm depth by the time irrigation treatments began on July 1, 1993-almost ten months after the compaction treatment was applied. This may have happened due to the high occurrence of shrinking and swelling during freezing and thawing which is common with soils composed mainly of the 2:1 clay, montmorillonite (USDA, 1980).

Mid-winter and early spring observations at the CSU Horticulture Research Center often reveal large cracks (1.0-2.0 cm wide) in the bare (clay-loam) soil around turfgrass areas. Unger (1991), working with a no-till clay loam soil in northern Texas, reported that the primary effect of soil freezing and thawing was loosening of the soil during the overwinter period which was reflected in decreased soil bulk density and penetration resistance in the surface 15.0 cm. Kay et al. (1985), working with a clay loam in Ontario, showed that ground freezing caused a 40% reduction in the bulk density of the surface 15.0 cm in both zero-tilled (from 1.35 to 0.70 Mg/m^3) and 18.0 cm deep fall-plowed soil (from 1.30 to 0.70 Mg/m^3). With subsequent spring thawing, almost all of this 40% bulk density decrease had disappeared and the bulk density of both soils increased to approximately 1.30 and 1.20 Mg/m^3, respectively. In this location there was only one freeze-thaw cycle. In locations such as Colorado, where many freeze-thaw cycles may occur during the winter, the authors predicted that much of the subsequent difference in spring bulk density (or porosity) between tilled and untilled soil would be lost.

This prediction seems to have been quite accurate in the case of the present study. Bulk density values from 0 to 30 cm, for those plots that were compacted and then rototilled on September 20, 1992 to depths of 2.5 cm and 15.0 cm, were nearly the same when measured on July 1, 1993. This parallels results reported by Lee and Rieke (1985) who found bulk density values, which were initially significantly different, to be transient ten months following compaction treatments in Michigan. Given this evidence, our position is that, owing to winter freezing and thawing cycles, no significant difference in compaction was apparent between the two tillage treatments when the irrigation treatments officially began on July 1, 1993.

CHAPTER 5: ROOT MASS AND DISTRIBUTION AND GRAVIMETRIC SOIL MOISTURE CONTENT

I. Results and Summary

A major objective of this study was to compare the relative drought avoidance abilities of Kentucky bluegrass, tall fescue, and buffalograss. Plants avoid drought in two ways: by maintaining water uptake from the soil or by restricting water loss from aboveground organs (Jones et al., 1981). Thus, the ability of some turfgrasses to avoid drought may, in large part, depend on its ability to reduce (but not completely) its ET-rate when water becomes limiting. Buffalograss, for example, is noted both for its ability to restrict water loss from its leaves (low ET-rate) (Table 2.1) and its deep rooting (to maintain its low ET-rate) (Hopkins, 1953; Kim, 1987). Tall fescue, however, which is noted for having a higher PET-rate relative to Kentucky bluegrass and buffalograss (Table 2.1), is noted for its deep rooting (Bennett and Doss, 1960; O'Donnell and Love, 1970; Garwood and Sinclair, 1979; Carrow, 1980; Younger et al., 1981; Koski, 1983; Sheffer et al., 1987) and subsequent greater ability to avoid drought by (supposedly) mining a greater volume of soil for available water (i.e., maintaining a low ET-rate at low soil moisture) than Kentucky bluegrass when surface inputs become scarce (Aronson et al., 1987b; Carrow, 1991; Madison and Hagan, 1962). But because none of these studies have directly compared

Kentucky bluegrass with tall fescue under decreasing irrigation levels or decreasing soil water potentials it is still a supposition as to whether tall fescue's primary drought avoiding mechanism is to mine a greater volume of soil for available water than Kentucky bluegrass when surface water inputs become scarce. Root mass and gravimetric soil moisture data were taken for KBG, TF, TF/KBG, and 609 and Prairie buffalograss, when uniformly well-watered and when irrigated at decreasing levels of estimated KBG-ET, in an attempt to test, for the first time, this common-sense mechanistic supposition.

A. 1993 and 1994 Rooting and Gravimetric Soil Moisture Results

Tables 5.1 to 5.3 report the root densities and root distribution prior to and following each year's irrigation cycle, for three sample depths: 0-30 cm, 30-60 cm, and 60-90 cm. Tables 5.4 to 5.6 report the main effect of turfgrass type on gravimetric soil moisture content immediately before and immediately after each year's irrigation cycle. Tables 5.7 to 5.12 report the interactive effect of turfgrass type by irrigation level on gravimetric soil moisture content for both years and all three depths. Figures 5.7 to 5.12 report the same data in graphical form. (Note: the tables reporting the interactive effect of turfgrass type and irrigation level indicate significant differences between turfgrass types at each irrigation level, while the figures corresponding to each table indicate significant differences between irrigation levels for each turfgrass type.) Although the rooting and soil moisture results for TF/KBG are reported in the tables and figures, this data will not be stressed because of the limitations of the sampling method used; the soil probe may have randomly sampled an area of the TF/KBG plot that was primarily tall fescue, primarily Kentucky bluegrass, or primarily TF/KBG. The TF/KBG data should be interpreted with these possibilities in mind. Even so, the often intermediate nature, relative to KBG and TF, of the TF/KBG rooting and soil moisture data is revealing.

The turfgrass type by irrigation level root mass values are not reported because this interaction was not significant in either year. A decline in root growth is generally observed as soil moisture is reduced in any given soil layer (Huck and Hillel, 1983). Although we expected to observe decreased rooting as irrigation level decreased, such an interaction was not measured in this study. It also was not observed for either tall fescue or Kentucky bluegrass in two previous studies (Younger et al., 1981; Agnew & Carrrow, 1985); no data is available concerning buffalograss. This result does not seem surprising when one considers the following line of reasoning.

First, during the spring and the fall of both years the study was uniformly well-watered, an irrigation practice which should have fostered uniform rooting. Second, it is well-established that greatest cool-season rooting occurs from the late fall, through the winter (if the soil temperature remains above 0 C), reaches a maximum in the spring, and then declines during the summer (Stuckey, 1941; Beard, 1973; Koski, 1983; Koski et al., 1988; DiPaola and Beard, 1992). During the summer, when the deficit irrigation treatments were applied, one would think some differentiation might occur between rooting for each species depending on irrigation level; the most roots dying at the lowest irrigation levels. While this may have been the case, there was no way of knowing because our root washing method precluded any differentiation between dead and alive roots. Thus, just as with the two previous studies cited, no significant turfgrass type by irrigation level interaction affect on rooting was measured.

In order to facilitate interpretation of the soil moisture data, a sorptivity analysis for the Nunn clay loam soil on which this study was conducted was performed by the Colorado State University Soil Testing Laboratory. Analysis of the top 30 cm of this soil revealed a permanent wilting point (WP) of 17.3% and a field capacity (FC) of 33.4% on a volume basis (Appendix E). Given a bulk density of 1.41 g/cc, this soil's WP on a weight or gravimetric basis is 12.3% and its FC is 23.7%. This analysis translates into 4.8 cm of available water per 30 cm of soil. The typical FC, WP, bulk density, and available water per 30 cm for a clay loam soil in Colorado as reported by the Soil Conservation Service is 27.3%, 15.1%, 1.40 g/cc, and 5.1 cm, respectively (USDA, 1991).

At the beginning of both the 1993 (7-1) and 1994 (6-10) irrigation cycles there was uniform soil moisture (Table 5.4) and fairly uniform cool-season root mass (Table 5.1) from 0 to 30 cm. Table 5.1 indicates that TF finished the 1993 season (on 9-10) with significantly more root mass in the 0-30 cm root zone than KBG even though they both began the 1993 irrigation cycle with statistically equivalent root mass. In 1994, TF and KBG began and finished the season with statistically equivalent root mass. These differential results, by year, indicate that it would not be accurate to state that TF produces more roots in the top 30 cm root zone. The initial 1993 root mass difference between these two turfs might be attributable to faster establishment root growth due to TF's higher relative growth rate and bunch-type growth habit. Much of KBG's initial underground vegetative growth may have been partitioned to rhizomes instead of roots, which, being primarily in the thatch, were not included in our determinations of root mass. Krans and Beard (1980) reported that 'Merion' Kentucky bluegrass allocated 5% of assimilated carbon-14 to rhizomes following six weeks of growth, with <10% of assimilated carbon being allocated to roots. From their data, Krans and Beard (1980) suggested that rhizomes constitute a strong sink for photosynthate and have priority over roots in the partitioning of photoassimilated carbon during establishment (Hull, 1992). In mature Kentucky bluegrass turf, however, Hull (1987) reported that rhizomes never contained more than 0.5% of the carbon-14 recovered.

Soil moisture was also uniform for the 30 to 60 cm (Table 5.5) and 60 to 90 cm (Table 5.6) depths on 7-1-93, but not for 6-10-94. Once the turfs had matured, we see that TF and TF/KBG had significantly less soil moisture at these deeper depths, indicating nearly equal root mass for the three cool-season turfs at these depths during the establishment year (7-1-93), and significantly more total roots distributed at these deeper depths for TF (Tables

5.2 and 5.3), relative to KBG, by the second year (6-10-94). Although TF and KBG in 1993 and 1994 had the same amount of root mass in the top 30 cm, KBG tended to distribute a greater proportion of its roots shallower in the soil relative to TF. In this case, 81% of KBG root mass vs. 68% for TF in 1993 and 90% of KBG root mass vs. 82% for TF in 1994 (Table 5.1). This result is congruent with many of the studies reviewed earlier and supports the supposition that mature stands of KBG and TF, when uniformly well-watered, tend to extract moisture differently from the soil profile based on their PET-rates and rooting distribution. Thus, it seems reasonable to conclude that TF, when uniformly well-watered, used more water deeper in the soil because of its deeper root distribution and higher PET-rate relative to KBG.

Over both years, the two warm-season buffalograss cultivars had significantly less root mass than the three cool-season turfs (Tables 5.1, 5.2, and 5.3), coupled with significantly greater soil moisture contents at the end of each irrigation cycle (9-10-93 and 9-10-94). Looking at the data for all three depths, two explanations for these results are apparent. The most obvious is the fact that the warm-season buffalograsses have a much shorter growing season; their active soil moisture uptake period was only three months compared to six months for the cool-season species. Second, the data in these three tables indicates that buffalograss partitions a greater proportion of its roots into the deeper root zones (30-90 cm) relative to the cool-season turfs. Such rooting distribution, in conjunction with its more efficient C-4 physiology and leaf-blade characteristics which function to give it a low ET-rate, make buffalograss very drought resistant.

Table 5.1: Root Mass and Distribution*: 0-30 cm
Main Effect of Turfgrass Type

Turfgrass Type	7-1-93	9-10-93	6-10-94	9-10-94
KBG	0.290 ab (77)	0.222 b (81)	0.535 ab (85)	0.687 ab (90)
TF/KBG	0.349 a (78)	0.218 b (73)	0.416 b (79)	0.616 abc(86)
TF	0.344 a (78)	0.312 a (68)	0.583 a (73)	0.697 a (82)
'609' B	0.116 bc (79)	0.109 c (55)		0.393 c (74)
'Prairie' B	0.210 bc (80)	0.117 c (55)		0.458 bc (80)

HSD = 0.186, 0.046, 0.144, 0.236; p = 0.05

*** Reported as g/500 cubic cm; Numbers in ( ) indicate percent of total root mass.**

Table 5.2: Root Mass and Distribution*: 30-60 cm
Main Effect of Turfgrass Type

Turfgrass Type	7-1-93	9-10-93	6-10-94	9-10-94
KBG	0.064 ab (17)	0.027 c (10)	0.075 b (12)	0.048 b (6)
TF/KBG	0.059 ab (13)	0.055 b (18)	0.068 b (13)	0.059 ab (8)
TF	0.071 a (16)	0.090 a (20)	0.135 a (17)	0.092 a (11)
'609' B	0.028 b (19)	0.061 b (31)		0.087 a (16)
'Prairie' B	0.040 ab (15)	0.060 b (28)		0.073 ab (13)

HSD = 0.046, 0.027, 0.049, 0.038; p = 0.05

*** Reported as g/500 cubic cm; Numbers in ( ) indicate percent of total root mass.**

Table 5.3: Root Mass and Distribution*: 60-90 cm
Main Effect of Turfgrass Type

Turfgrass Type	7-1-93	9-10-93	6-10-94	9-10-94
KBG	0.024 ab (6)	0.024 b (9)	0.022 b (3)	0.033 a (4)
TF/KBG	0.038 a (9)	0.026 b (9)	0.042 b (8)	0.043 a (6)
TF	0.026 ab (6)	0.056 a (12)	0.078 a (10)	0.058 a (7)
'609' B	0.003 b (2)	0.029 b (14)		0.052 a (10)
'Prairie' B	0.013 ab (5)	0.035 ab (17)		0.042 a (7)

HSD = 0.025, 0.027, 0.028, 0.027; p = 0.05

*** Reported as g/500 cubic cm; Numbers in ( ) indicate percent of total root mass.**

Table 5.4: Gravimetric Soil Moisture Content*: 0-30 cm
Main Effect of Turfgrass Type

Turfgrass Type	7-1-93	9-10-93	6-10-94	9-10-94
KBG	0.200 a	0.225 ab	0.195 a	0.160 b
TF/KBG	0.186 a	0.237 ab	0.204 a	0.175 b
TF	0.198 a	0.201 b	0.198 a	0.184 b
'609' B	0.202 a	0.256 a		0.227 a
'Prairie' B	0.195 a	0.261 a		0.229 a

HSD = 0.046, 0.041, 0.014, 0.023; p = 0.05
*** reported as g H2O/g dry soil**

Table 5.5: Gravimetric Soil Moisture Content*: 30-60 cm
Main Effect of Turfgrass Type

Turfgrass Type	7-1-93	9-10-93	6-10-94	9-10-94
KBG	0.196 a	0.167 b	0.180 a	0.140 b
TF/KBG	0.180 a	0.164 b	0.161 b	0.131 b
TF	0.175 a	0.147 b	0.160 b	0.141 b
'609' B	0.199 a	0.211 a		0.180 b
'Prairie' B	0.177 a	0.202 a		0.173 a

HSD = 0.039, 0.028, 0.014, 0.023; p = 0.05
*** reported as g H2O/g dry soil**

Table 5.6: Gravimetric Soil Moisture Content*: 60-90 cm
Main Effect of Turfgrass Type

Turfgrass Type	7-1-93	9-10-93	6-10-94	9-10-94
KBG	0.175 a	0.155 a	0.161 a	0.123 bc
TF/KBG	0.163 a	0.125 b	0.131 b	0.100 d
TF	0.148 a	0.114 b	0.124 b	0.105 cd
'609' B	0.175 a	0.178 a		0.144 ab
'Prairie' B	0.159 a	0.170 a		0.147 a

HSD = 0.037, 0.024, 0.012, 0.023; p = 0.05
*** reported as g H2O/g dry soil**

Recall the conclusion above that TF and KBG, when uniformly well-watered (7-1-93 and 6-10-94), extract moisture differently from the soil profile based on their differential PET-rates and rooting distribution. Our data indicates that TF uses more water deeper in the soil because of its deeper root distribution and higher PET-rate relative to KBG when water is not limiting. The next logical step is to see if this trend continues when these two turfs are irrigated at less than optimum levels; thereby supporting our hypothesis that TF avoids drought longer than KBG by extracting more water from deeper in the soil when surface inputs become limiting. For TF, the result would be more green tissue because of greater transpiration at any given deficit irrigation level relative to KBG. Since the data in Tables 5.7 to 5.12 report this interaction, these results will be discussed rather than the soil moisture data in Tables 5.4 to 5.6, for 9-10-93 and 9-10-94, which were averaged over irrigation.

Both KBG and TF had significantly less soil moisture than the buffalograsses at the 80%-level and 0-30 cm depth in 1993 (Table 5.7). At this irrigation level and depth, the cool-season turfs had soil moisture contents which were right at FC (~ 0.24), while 609 and Prairie soil moisture contents were above FC and had actually accumulated (or increased), compared to their initial values of 0.202 and 0.195 (Table 5.4), at all three reported irrigation levels over the course of the irrigation cycle. At the 60% and 20%-levels, TF extracted significantly more water than KBG. Given that these two turfs had statistically equivalent root mass at this depth (Table 5.1), this result is a good indication of TF's higher ET-rate relative to KBG at this irrigation level (80%), possibly caused by higher TF leaf area. The two buffalograss cultivars at this depth (0-30 cm) had significantly more soil moisture than KBG and TF.

At the 80%-level and 30-60 cm depth in 1993 (Table 5.8), the buffalograsses again had more soil moisture than the cool-season turfs. As with the 0-30 cm depth, at the 60% and 20%-levels, TF extracted more water than KBG, although not in an amount which was statistically significant. This result is most likely a reflection of TF's partitioning of a significantly greater proportion of its roots to this depth relative to KBG (Table 5.2).

Both buffalograss cultivars, at the 30-60 cm depth, had more soil moisture than the cool-season turfs at all three irrigation levels. At the 20%-level, the buffalograsses still had the highest soil moisture contents when compared to the other turfs, but as happened with the cool-seasons, had less soil moisture than initially (7-1-93, Table 5.5). Although much of this reduction should be attributed to transpirational use, a minor portion must have also been due to drainage. By comparing the TF results with the buffalograss results in Figure 5.8, one can visually estimate how much of the difference between the initial soil moisture content (indicated by the line marked "uniform irrigation") and the final content can be attributed to transpirational use versus drainage. Since all of the turfs received the same amount of irrigation at each irrigation level, any major differences should be mostly attributable to actual root uptake. With the buffalograsses we see that there was an accumulation of soil moisture when irrigated every three days at the 80% and 60%-levels. While the TF was using about as much water as was applied at the 80%-level, the buffalograsses were doing the same at the 20%-level. These results might be a strong indicator of the level of irrigation needed to maintain acceptable quality. Finally, Figure 7.8 shows that TF, when irrigated every three days at the 60% and 20%-levels, was depleting the soil of moisture much more than all of the other turfs at the 30-60 cm depth, again indicating its higher ET-rate and greater ability to extract water from deep in the soil.

The soil under the TF at the 60-90 cm depth contained less moisture than KBG at the 80%-level in 1993 (Table 5.9). At the 60% and 20%-levels, TF extracted more water than KBG (significantly more at the 20%-level), most likely a reflection of its significantly greater distribution of roots at this depth (Table 5.3). Again, at this depth, both buffalograss cultivars had more soil moisture than the cool-season turfs at all three irrigation levels. At the 20%-level, the buffalograsses still had higher soil moisture, but as with the cool-seasons, had less soil moisture than initially, indicating some transpirational use.

These results are most likely an indication that buffalograss had lower ET-rates. Couple this supposition with the fact of its shorter growing season, and greater probable water use efficiency (Noble, 1992; Jones, 1993) and it becomes fairly clear why buffalograss had much more soil moisture at all depths in comparison to the cool-season turfs. These results also indicate that inputs (i.e., irrigation) exceeded outputs (i.e., water lost through drainage or buffalograss transpirational use) at all irrigation levels and depths, except perhaps the 20%-level, where final (9-10-93; Tables 5.7-5.9, and Figures 5.7-5.9) soil moisture contents were less than they were initially (7-1-93) at the two deeper depths (Tables 5.5 and 5.6).

The 1994 results were very similar to those of 1993, with some interesting differences. Table 5.10 indicates that KBG had less soil moisture than TF at all three irrigation levels from 0-30 cm in 1994, while at the deeper depths, TF had about the same or less soil moisture than KBG (Tables 5.11 and 5.12). These results are most likely a reflection of the different rooting distribution, once mature, of the two turfs. Kentucky bluegrass, although having a root mass statistically equivalent to TF, used more water in the top 0-30 cm of soil because it had less of its roots deeper in the soil. Although not measured in this study, KBG most likely had more of a thatch layer owing to its rhizomatous nature; a factor which may have contributed to the reduction in soil moisture in this top layer of soil when compared to TF. The fact that the TF/KBG contained some rhizomes and that it used less water than KBG, but more than TF at this depth, provides additional evidence for the above statement.

In addition, notice that in 1994 all of the cool-season turfs had less root mass in the 30-90 cm root zone after the irrigation cycle than before the cycle. This phenomenon does not seem surprising given that it occured in the stressful 1994 summer season, where soil moisture contents in the 30-90 cm soil profile had dropped to below or near-below the measured WP (~0.12). In the surface 30 cm, where soil moisture contents did not drop below the WP, cool-season turfgrass root mass increased during the irrigation cycle (6-10 to 9-10-94). This information suggests that there may have been some significant root death and decomposition in the very dry 30-90 cm soil profile between the first sampling date (6-10) and the second (9-10), coupled with fairly regular root growth in the 0-30 cm soil profile, where water was still available at all irrigation levels (Table 5.10).

A look at Figures 5.10, 5.11, and 5.12 indicates that, just as in 1993, the two buffalograss cultivars were being overwatered (i.e., irrigation inputs were exceeding transpiration and drainage outputs) at the top two irrigation levels sampled, 95% and 75% ET, whereas this was not the case at the 35%-level. At the 35% irrigation level, 609 and Prairie soil moisture contents in the top 30 cm were still safely above the WP (~0.12) at 0.186 and 0.193, respectively (Table 5.10), while in the deeper layers they had fallen below the WP (Tables 5.11 and 5.12). Given that both buffalograsses distributed a fairly large proportion of their roots in the deeper layers (13-16% from 30-60 cm (Table 5.2) and 7-10% from 60-90 cm (Table 5.3)), it is not unreasonable to suppose that at the 35%-level each cultivar was extracting significant amounts of soil moisture from these deeper soil zones. At the two higher irrigation levels, the soil moisture contents for 609 and Prairie at the 0-30 cm depth were right around the measured field capacity of 0.24 (Table 5.10); a poor soil aeration situation which, if prolonged, could have resulted in a reduction in quality. This consideration, coupled with the goal of water conservation, indicates that the 35% irrigation level was appropriate to maintain buffalograss of acceptable quality in 1994.

Given the observation that 609 and Prairie buffalograss quality was not adversely affected when irrigated every three days at 35% of estimated KBG-ET in 1994 and 20% in 1993, and given that there was sufficient available soil moisture remaining in the 0-30 cm root zone at these irrigation levels, buffalograss represents a turfgrass species which may be used on Colorado lawns to realize considerable water conservation when compared to the cool-season alternatives. Not only can it maintain acceptable quality when irrigated by less than half of the cool-season species, its growing season is also half as long. Of course, even if buffalograss is the turfgrass of choice for water conservation, other factors such as its poor utility as a recreational turf (i.e., a turf that can recover from severe wear) and its poor aesthetics, because of its early dormancy, light green color, and poor stand density, may rule out its use for many Colorado homeowners.

Table 5.7: Gravimetric Soil Moisture Content*: 0-30 cm
Turfgrass Type x Irrigation Level: 1993

Turfgrass Type	80% ET	60% ET	20% ET
KBG	0.238 b	0.237 b	0.200 bc
TF/KBG	0.250 b	0.241 b	0.221 ab
TF	0.238 b	0.194 c	0.172 c
'609' B	0.277 a	0.262 ab	0.239 a
'Prairie' B	0.275 a	0.268 a	0.240 a

LSD = 0.029; p = 0.05
*** reported as g H2O/g dry soil**

Table 5.8: Gravimetric Soil Moisture Content*: 30-60 cm
Turfgrass Type x Irrigation Level: 1993

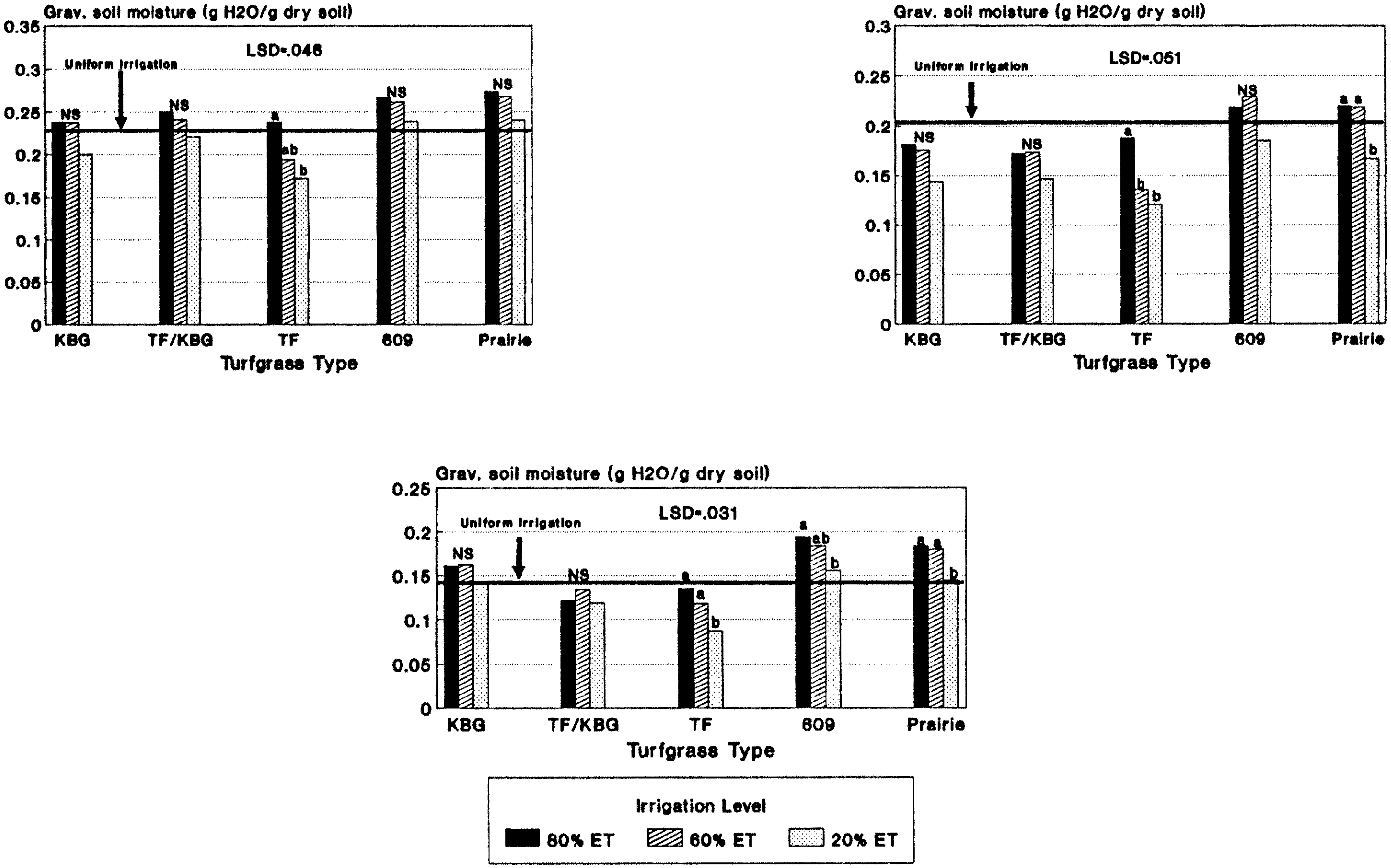
Turfgrass Type	80% ET	60% ET	20% ET
KBG	0.181 ab	0.176 bc	0.144 ab
TF/KBG	0.172 b	0.173 bc	0.147 ab
TF	0.188 ab	0.133 c	0.121 b
'609' B	0.219 ab	0.229 a	0.185 a
'Prairie' B	0.220 a	0.219 ab	0.167 ab

LSD = 0.047; p = 0.05
*** reported as g H2O/g dry soil**

Table 5.9: Gravimetric Soil Moisture Content*: 60-90 cm
Turfgrass Type x Irrigation Level: 1993

Turfgrass Type	80% ET	60% ET	20% ET
KBG	0.161 abc	0.163 ab	0.142 a
TF/KBG	0.122 c	0.134 ab	0.119 ab
TF	0.136 bc	0.118 b	0.087 b
'609' B	0.194 a	0.184 a	0.156 a
'Prairie' B	0.184 ab	0.180 a	0.145 a

LSD = 0.052; p = 0.05
*** reported as g H2O/g dry soil**



Figures 5.7, 5.8, and 5.9: Turfgrass Type by Irrigation Level Interaction on Gravimetric Soil Moisture from 0-30 cm (top left), 30-60 cm (top right), and 60-90 cm (bottom) in 1993. P = 0.05.

Table 5.10: Gravimetric Soil Moisture Content*: 0-30 cm
Turfgrass Type x Irrigation Level: 1994

Turfgrass Type	95% ET	75% ET	35% ET
KBG	0.186 c	0.166 b	0.127 c
TF/KBG	0.202 bc	0.181 b	0.141 bc
TF	0.217 b	0.182 b	0.152 b
'609' B	0.248 a	0.246 a	0.186 a
'Prairie' B	0.247 a	0.248 a	0.193 a

LSD = 0.016; p = 0.05
* reported as g H2O/g dry soil

Table 5.11: Gravimetric Soil Moisture Content*: 30-60 cm
Turfgrass Type x Irrigation Level: 1994

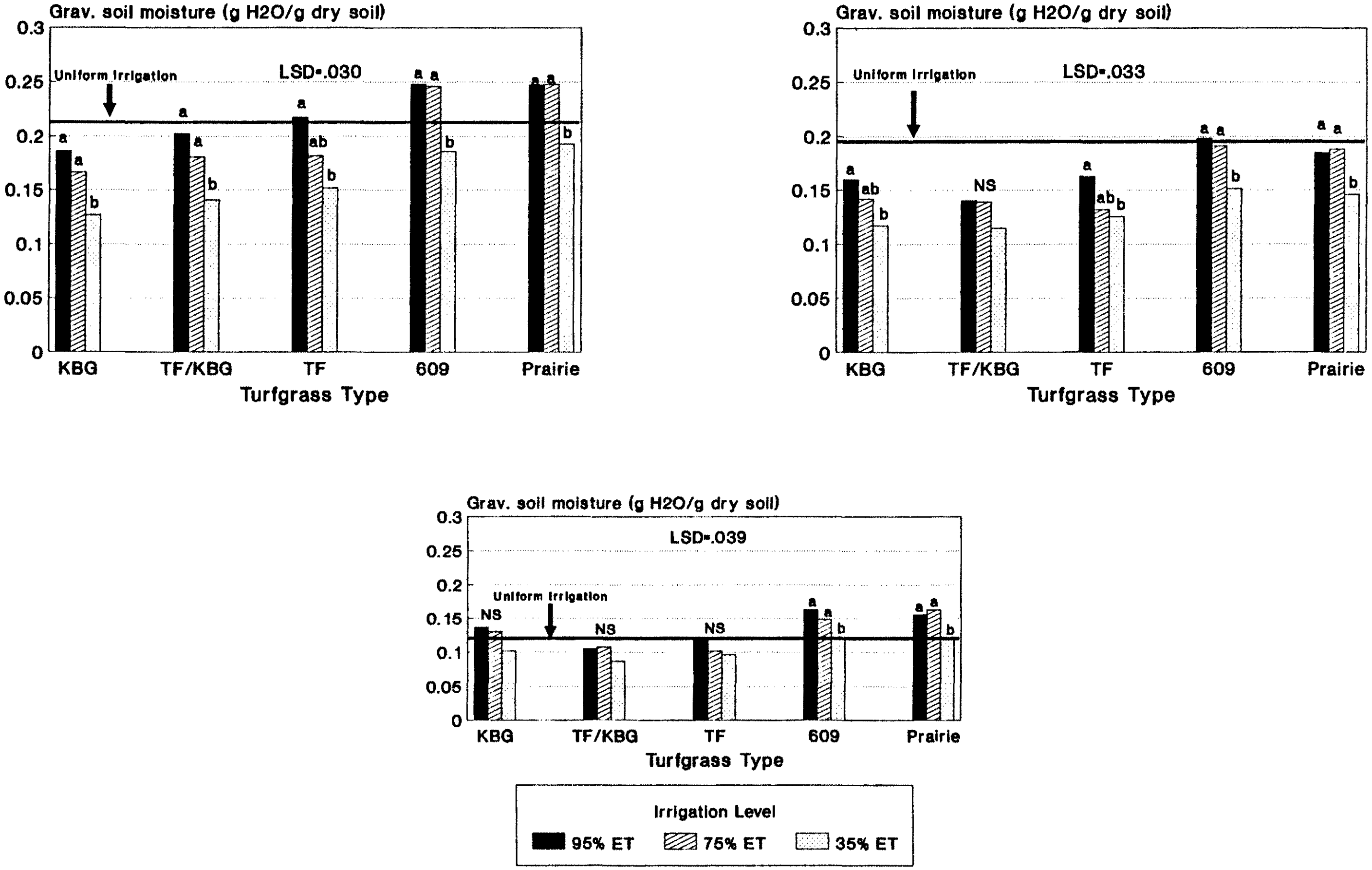
Turfgrass Type	95% ET	75% ET	35% ET
KBG	0.160 bc	0.142 b	0.117 c
TF/KBG	0.140 c	0.139 b	0.115 c
TF	0.163 bc	0.132 b	0.126 bc
'609' B	0.198 a	0.191 a	0.151 a
'Prairie' B	0.185 ab	0.188 a	0.146 ab

LSD = 0.023; p = 0.05
* reported as g H2O/g dry soil

Table 5.12: Gravimetric Soil Moisture Content*: 60-90 cm
Turfgrass Type x Irrigation Level: 1994

Turfgrass Type	95% ET	75% ET	35% ET
KBG	0.137 ab	0.130 bc	0.102 ab
TF/KBG	0.105 c	0.107 cd	0.086 b
TF	0.118 bc	0.102 d	0.096 ab
'609' B	0.163 a	0.148 ab	0.122 a
'Prairie' B	0.156 ab	0.163 a	0.122 a

LSD = 0.026; p = 0.05
* reported as g H2O/g dry soil



Figures 5.10, 5.11, and 5.12: Turfgrass Type by Irrigation Level Interaction on Gravimetric Soil Moisture from 0-30 cm (top left), 30-60 cm (top right), and 60-90 cm (bottom) in 1994. P = 0.05.

Table 5.13: Estimated Available Soil Water at Three Irrigation Levels as Calculated by Equation 5.1

Year	Available Soil Water: IRR1* (mm)	Available Soil Water: IRR3 (mm)	Available Soil Water: IRR5 (mm)
1993	150.8	95.7	-11.7
1994	134.0	34.7	-94.6

* IRR1 stands for the highest irrigation level in both years, 80% ET in 1993 and 95% ET in 1994. IRR3 = 60% ET & 75% ET; IRR5 = 20% ET and 35% ET.

Table 5.13 contains estimates of the amount of available water in the 0-60 cm root zone following each year's irrigation cycle as calculated by the following soil-water balance equation:

$$W_r = AC + I + R - ETkbg \qquad [5.1]$$

where W_r is the estimated amount of available water in the estimated effective root zone (0-60 cm); AC is the available water of the Nunn clay loam soil at the beginning of the irrigation cycle as determined by its desorption analysis (see Appendix A) and adjusted by the amount that the soil moisture in 0-60 cm root zone was below FC; I is the amount of irrigation applied; R is the amount of rainfall and ETkbg is the Kimberly-Penman estimated KBG-evapotranspiration as reported in Tables B.1 and B.2. An example calculation for the 80% irrigation level in 1993 (IRR1):

W_r = 79.4 mm + 222.5 mm + 130.6 mm - 281.7 mm = 150.8 mm of remaining available soil water in the 0-60 cm root zone; this corresponds to an approximate soil moisture reserve of 37 days (assuming an average ET of 4.1 mm/day). Note, of course, that the estimates in Table 5.13 are based on KBG-estimated-ET, making them fairly applicable to cool-season water availability in the top 60 cm root zone, but not to warm-season buffalograss water availability. A rough estimate of available soil water beneath the buffalograsses, based on the soil moisture data in this study, would be to increase the numbers in Table 5.13 by approximately 30-50%.

B. Summary

A major objective of this study, and of this chapter, was to provide evidence for the supposition that a primary drought avoidance mechanism, (maybe *the* primary drought avoidance mechanism), of TF, relative to KBG, is to distribute more of its roots deeper in the soil, thereby extracting more moisture from deeper in the soil, and staying green longer by maintaining some minima of an ET-rate relative to KBG when surface water inputs become limiting. In effect, we wanted to provide evidence for the irrigation-level recommendations that will be presented at the end of the next chapter on visual quality and leaf firing.

The data in this chapter indicated that TF, in addition to having more total root mass following each year's irrigation cycle, had a greater proportion of its roots distributed deeper in the soil. Greater total root mass and deeper root distribution functioned to allow TF to extract greater amounts of soil moisture from deep in the soil, allowing it to avoid drought (i.e., stay greener longer) than KBG when surface irrigation inputs became limiting. Finally, both 609 and Prairie buffalograss were able to maintain acceptable quality at the lowest irrigation levels (20-35%) in this study because of their very low ET-rates, deep root distributions, and greater probable water use efficiency relative to the cool-season turfs.

CHAPTER 6: QUALITY AND LEAF FIRING RATINGS

I. Visual Quality Ratings

Turfgrass quality was visually rated every three to four days during each year's study period. In visually rating the quality of turfgrass, the color, texture, density, and uniformity, or overall appeal of each plot was taken into consideration. Quality was rated on a scale of one to nine, where nine is an ideal turf area or lawn, six corresponds to a lawn of minimum acceptable quality, and one indicates a turf that is completely dormant or dead. Skogley and Sawyer (1992) have pointed out that Northeastern Turfgrass Research Committee members, meeting once or twice annually since 1962, have demonstrated and agreed that subjective quality ratings are valid when taken by experienced researchers.

In comparing a number of different turfgrass types, there is a need on the part of the researcher to have a top quality rating for each type firmly set in his or her mind (Skogley and Sawyer, 1992). The following were the top quality levels possible for each turfgrass type in this study: KBG = 8.5; TF/KBG = 8.5; TF = 8.0; 609 = 7.0; Prairie = 7.0. These "top score levels" should be kept in mind when comparing and interpreting the quality ratings presented below. In particular, it should be noted that TF's "top score" was lower in the researcher's mind because of its coarser texture and lower density (a result of its bunch-type growth habit) in comparison to KBG. The TF, therefore, in order to be rated at statistically greater quality levels than KBG already had a 0.5 point handicap to overcome. In the same manner, the buffalograsses, due to their lighter green color, poor density, and poor uniformity relative to KBG began with a 1.5 point handicap.

A. 1993 Results

Quality ratings for each turfgrass type in 1993 are represented in Figures 6.1 to 6.5, with tabular data for each sampling date shown in Tables 6.1 to 6.4.

Significant effects of irrigation on turfgrass quality did not appear until four weeks after irrigation treatments began. Delayed response at the lower irrigation levels was probably related to the low temperatures and above-normal precipitation which occurred in the summer of 1993. By 27 July (Table 6.1), only KBG and TF/KBG displayed lower quality in response to irrigation (at the 20%-level). It was not until approximately five weeks into the irrigation cycle (8-9; Table 6.2), that TF quality had significantly decreased, relative to the four higher irrigation levels, at the 20% irrigation level. This delayed loss of quality at the 20%-level in comparison to KBG was the first indication of TF's greater ability to avoid drought, as the data in the last chapter indicated, by maintaining a greater water supply (Tables 5.7-5.9) through deeper rooting (Tables 5.2 and 5.3).

At seven weeks into the irrigation cycle (8-23; Table 6.3), KBG quality had declined significantly at the 45% and 20% irrigation levels; TF/KBG and TF quality ratings were significantly lower only at the 20%-level. More importantly, KBG and TF (at the 20%-level) first displayed quality ratings lower than 6.0. The quality of TF at the 20%-level (on 8-23) was slightly less than 6.0, while KBG was rated at a significantly lower 4.94.

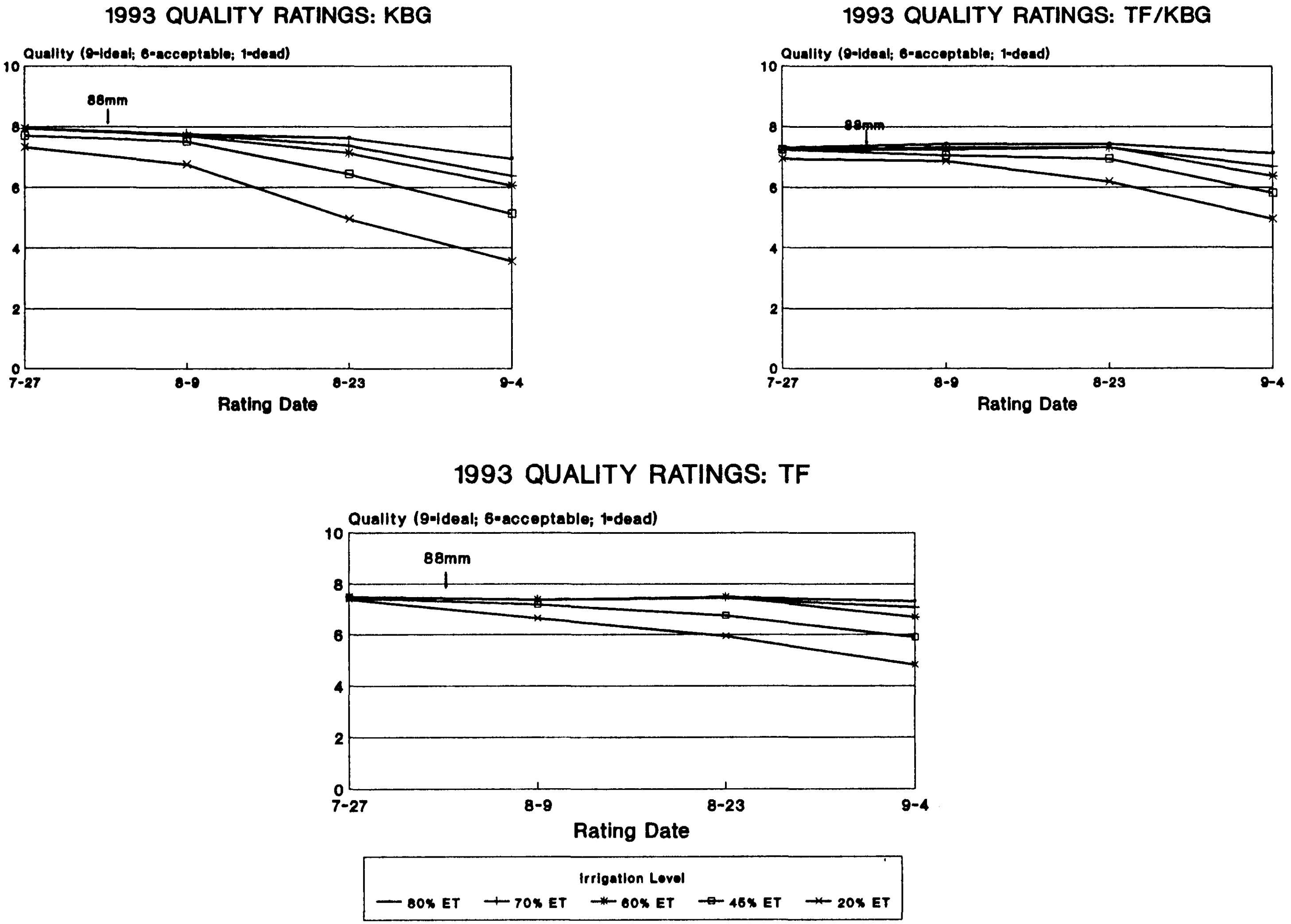
At nine weeks into the irrigation cycle (9-4; Table 6.4), all three cool-season turfs were showing lower quality at the 60%, 45%, and 20%-levels; the quality ratings of all three turfs were less than acceptable at the 45% and lower irrigation levels. KBG ended the ten-week 1993 irrigation cycle with the lowest quality among the cool-season turfs at all irrigation levels and TF finished with the highest quality. While end of the cycle TF/KBG and TF quality was not rated significantly different at the 60%, 70%, and 80% irrigation levels, KBG quality at the 60%-level was significantly lower than at the 70% and 80% irrigation levels. These differences in quality for TF and KBG at the 60%-level are most likely attributable to their differences in water extraction at this irrigation level. At all three sample depths, final TF soil moisture was lower than KBG soil moisture: 4.3% lower from 0-30 cm, 4.3% lower from 30-60 cm, and 4.5% lower from 60-90 cm (Tables 5.7-5.9). Thus, because quality did not significantly improve for TF when watered above the 60%-irrigation level in 1993, it is reasonable to conclude that minimally acceptable TF quality could be maintained (given a similarly low evaporative demand summer) by irrigating it at the 60%-level, while KBG would require a level of 70% or higher.

Visual quality of the 609 and Prairie buffalograsses was not significantly affected by any of the irrigation levels during the 1993 summer season. The quality of Prairie constantly remained at 6.0 to 6.5 for the whole season at all irrigation levels. The reduction in 609 quality at all irrigation levels over the course of the season is a reflection of poor stand density and lack of aggressive growth following a spot treatment of atrazine in mid-July to rid the 609 and Prairie plots of invasive cool-season grasses. While 609 experienced noticeable phytotoxicity and slowness of recovery, Prairie experienced only slight phytotoxicity and was fairly quick to fill in the bare spots left by the dead cool-season grassy weeds.

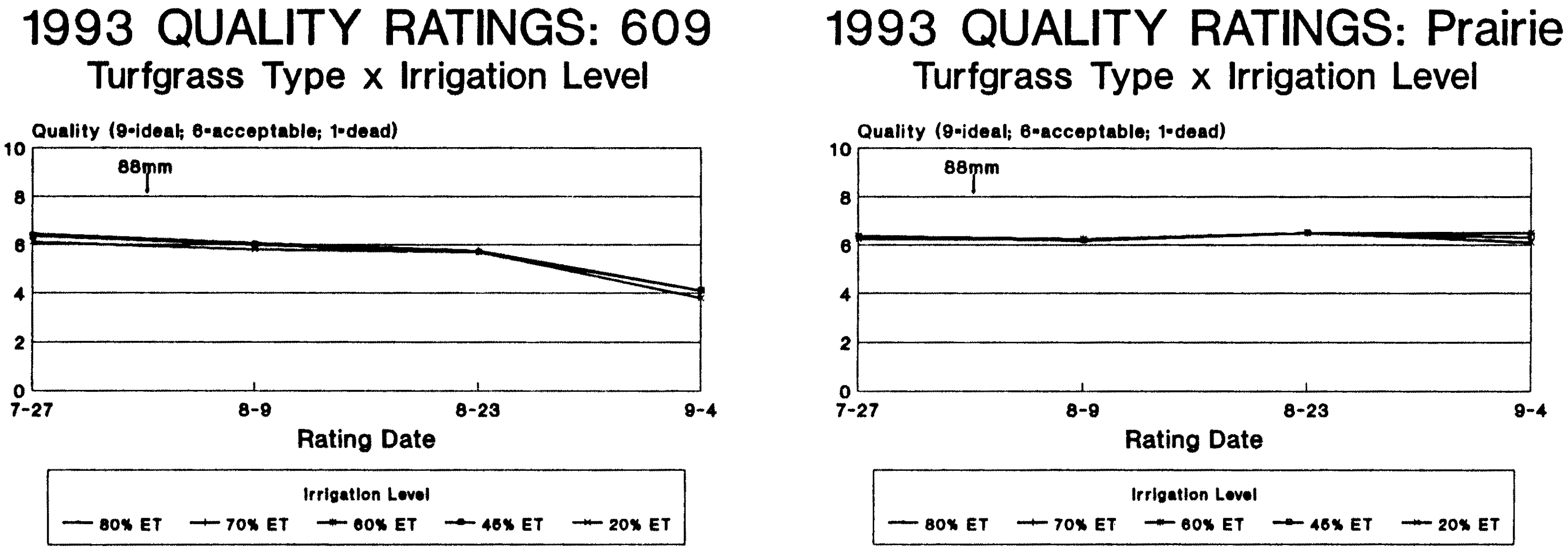
Visual quality results from 1993 indicate that 609 and Prairie buffalograss can be irrigated at 20% of KBG-estimated ET and maintain acceptable quality in Colorado. This recommendation is supported by the soil moisture data which showed that both buffalograsses had near FC soil moisture from 0-30 cm (Table 5.7) and significantly higher soil moisture than the cool-season turfgrasses at the deeper depths (Tables 5.8 and 5.9) even though all five turfs began the irrigation cycle (at all depths) with statistically equivalent soil moisture (Tables 5.4-5.6).

The 1993 quality responses of the five turfgrass types to the irrigation treatments can be summarized by assigning each type with irrigation coefficients corresponding to the range of irrigation-levels at which it maintained acceptable quality throughout the season. For KBG, TF/KBG, and TF this range = 0.80 * (0.60 to 0.80) = 0.50 to 0.65. For '609' and 'Prairie' buffalograss this range = 0.80 * (0.20 to 0.45) = 0.16 to 0.36.

Note that these ranges basically represent a three-fold spectrum of turfgrass quality: the lowest values represent irrigation levels which would result in turfgrass quality which we characterize as being "minimally acceptable"; medium range values represent "acceptable" quality; and high range values represent "excellent" quality. In the text that follows, these terms, when used, will refer specifically to the above defined quality levels.



Figures 6.1 (KBG), 6.2 (TF/KBG), and 6.3 (TF): Quality Ratings for each Turf Type and each Irrigation Level by Sample Dates in 1993



Figures 6.4 (609) and 6.5 (Prairie): Quality Ratings for each Turf Type and each Irrigation Level by Sample Dates in 1993

Table 6.1: Quality Ratings for 7-27-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	7.94 a A	7.31 a B	7.50 a B	6.44 a C	6.38 a C
70% ET	7.94 a A	7.25 a B	7.50 a B	6.44 a C	6.38 a C
60% ET	7.94 a A	7.25 a B	7.50 a B	6.38 a C	6.38 a C
45% ET	7.69 a A	7.25 a B	7.44 a AB	6.38 a C	6.31 a C
20% ET	7.31 b A	6.94 b B	7.38 a A	6.13 a C	6.25 a C

LSD = 0.36 (down), 0.36 (ACROSS); p = 0.05

Table 6.2: Quality Ratings for 8-9-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	7.75 a A	7.44 a A	7.38 a A	6.06 a B	6.19 a B
70% ET	7.75 a A	7.31 a A	7.38 a A	6.00 a B	6.25 a B
60% ET	7.69 a A	7.25 ab A	7.38 a A	6.00 a B	6.25 a B
45% ET	7.50 a A	7.06 bc A	7.19 a A	6.00 a B	6.19 a B
20% ET	6.75 b AB	6.88 c A	6.63 b AB	5.81 a C	6.25 a BC

LSD = 0.34 (down), 0.58 (ACROSS); p = 0.05

Table 6.3: Quality Ratings for 8-23-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	7.63 a A	7.44 a A	7.50 a A	5.75 a C	6.50 a B
70% ET	7.38 a A	7.31 a A	7.44 a A	5.75 a C	6.50 a B
60% ET	7.13 a A	7.31 a A	7.50 a A	5.69 a C	6.50 a B
45% ET	6.44 b B	6.94 a A	6.75 a AB	5.69 a C	6.50 a B
20% ET	4.94 c D	6.19 b AB	5.94 b BC	5.69 a C	6.50 a A

LSD = 0.52 (down), 0.38 (ACROSS); p = 0.05

Table 6.4: Quality Ratings for 9-4-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	6.94 a AB	7.13 a A	7.31 a A	4.13 a C	6.50 a B
70% ET	6.38 ab B	6.69 a AB	7.06 a A	4.13 a C	6.50 a B
60% ET	6.06 b B	6.38 ab AB	6.69 ab A	4.13 a C	6.50 a AB
45% ET	5.13 c C	5.81 b B	5.88 bc AB	4.13 a D	6.31 a A
20% ET	3.56 d C	4.94 c B	4.81 c B	3.81 a C	6.13 a A

LSD = 0.83 (down), 0.46 (ACROSS); p = 0.05

B. 1994 Results

The 1994 quality ratings for the three cool-season turfgrass types are shown in Figures 6.6 to 6.8 and Tables 6.5 to 6.11. Quality data for the two buffalograss species were not taken because of poor cover caused by an herbicide application (see Section IV of Chapter 3).

In contrast to the much cooler and wetter 1993 season, significant decreases in quality were observed for all three cool-season turfgrasses at the lowest irrigation level following one week of irrigation treatments (Table 6.5).

By the end of June (Table 6.6), KBG and TF quality dropped below an acceptable level at the 35%-level and some significant separations of quality depending on irrigation level for all three turfs were apparent. The quality of both KBG and TF had significantly declined at the 60% level when compared to the 85% and 95%-levels and their quality was significantly worse at the 35%-level versus the 60%-level.

By 7-11 (Table 6.7), KBG quality had dropped below 5.0 at the 35%-level and was 6.0 at the 60%-level; TF quality at the 35%-level was still above 5.0 and was slightly above 6.0 at the 60%-level.

By five and a half weeks into the irrigation cycle, on 7-21 (Table 6.8), all three cool-season turfs reached their lowest quality for the entire cycle. Quality of KBG at the 35%-level had declined to 3.13, while TF quality was significantly higher at 4.38. Figure 6.6 shows that KBG quality never rose above 4.0 at the 35%-level from 7-21 until the end of the cycle, while Figure

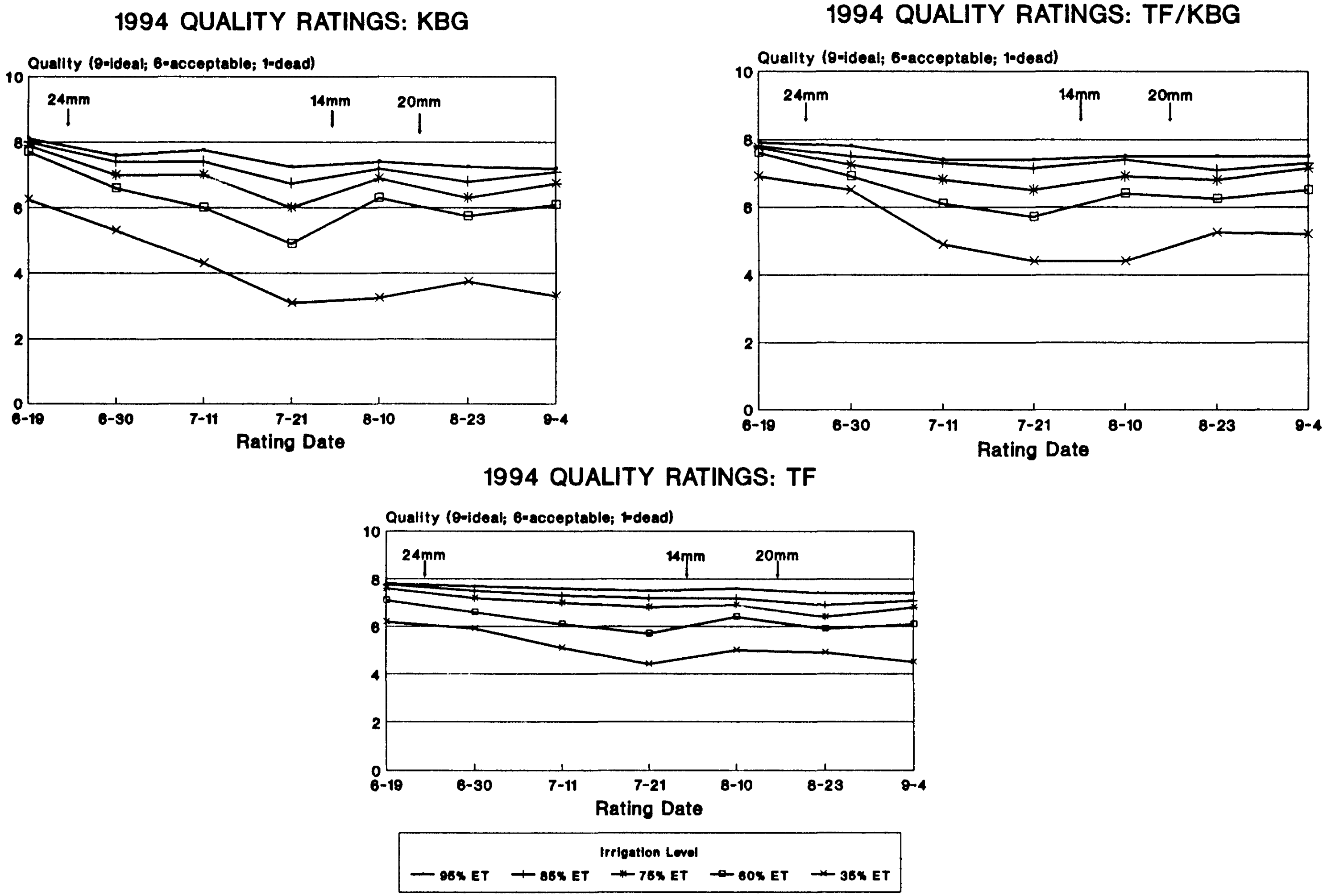
6.8 shows that TF quality at the 35%-level never dropped below 4.0. Table 6.8 also indicates that TF quality ratings were better than those of KBG at the 60%-level and significantly better at the 75%-level. This trend continues throughout the remainder of the irrigation cycle.

At the end of the 1994 irrigation cycle, TF and TF/KBG had maintained significantly better quality (although not minimally acceptable quality) than KBG at the 35%-level, while there were no significant differences in quality at any of the other irrigation levels (Table 6.11). These results, although not as clear-cut as the 1993 results, still indicate a greater ability to avoid drought for TF relative to KBG.

Beginning on 9-4-94, all plots were uniformly well-watered every three days at over 100% of reference KBG-ET in order to allow all water-stressed plots to recover. Also on this date, all plots were fertilized with 49 kg/ha of nitrogen. Table 6.12 shows turfgrass quality ratings following approximately three weeks of recovery. The data in this table indicate that all three cool-season turfs recovered well from three months of deficit irrigation. By this date, only those plots which had received 35% of the recommended irrigation had not yet fully recovered. Table 6.12 also shows that TF and TF/KBG at the 35%-level had recovered to significantly higher quality levels relative to KBG. These results help to emphasize the point that because TF had avoided drought better than KBG, it was able to regain quality faster once water was no longer limiting. What it does not adequately represent is the relative drought tolerance of these two species. A good test of this would have occurred if the simulated drought had been so severe that both species had gone completely dormant. Perhaps such a test would have resulted in faster KBG recovery, thereby indicating KBG's greater drought tolerance.

During the 1994 irrigation cycle, the two buffalograss species were irrigated in the same manner as the three cool-season turfs. By the end of July, both species had recovered from dithiopyr phytotoxicity and reached full cover. Their recovery was full regardless of the irrigation level at which they were being irrigated. Although there were no quality data taken for the buffalograsses in 1994, there were no observed differences in buffalograss quality across irrigation levels, just as with the 1993 season. The buffalograss soil moisture data indicate that both turfs were being overwatered at the 75% and 95%-levels because soil moisture had increased or accumulated over the course of the summer at all three depths (Figures 5.10-5.12). The same was not true for buffalograss soil moisture at the 35%-level, where only slight decreases were measured over the course of the irrigation cycle. These results indicate that the 35% irrigation level was more closely matching 609 and Prairie buffalograss ET. And this was the case even though a large portion of 1994 buffalograss ET was due to evaporation.

The 1994 quality response of the five turfgrass types to the irrigation treatments can be summarized by assigning each with irrigation coefficients corresponding to the range of irrigation-levels at which it maintained minimally acceptable quality to excellent quality throughout the season. For KBG, TF/KBG, and TF this Kc range = 0.80 * (0.75 to 0.95) = 0.60 to 0.75. For '609' and 'Prairie' buffalograss this Kc range = 0.80 * (0.35) = 0.28.



Figures 6.6 (KBG), 6.7 (TF/KBG), and 6.8 (TF): Quality Ratings for each Turf Type and each Irrigation Level by Sample Dates in 1994

Table 6.5: Quality Ratings for 6-19-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	8.06 a	7.88 a	7.81 a
85% ET	8.00 a	7.81 a	7.75 a
75% ET	7.94 a	7.75 a	7.62 a
60% ET	7.69 a	7.63 ab	7.06 a
35% ET	6.25 b	6.88 b	6.19 b

LSD = 0.85 (down), 0.79 (ACROSS, all NS); p = 0.05

Table 6.6: Quality Ratings for 6-30-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	7.63 a	7.81 a	7.69 a
85% ET	7.38 a	7.50 ab	7.50 a
75% ET	7.00 ab	7.19 b	7.19 ab
60% ET	6.63 b	6.94 bc	6.56 b
35% ET	5.31 c B	6.50 c A	5.88 c AB

LSD = 0.67 (down), 0.90 (ACROSS); p = 0.05

Table 6.7: Quality Ratings for 7-11-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	7.75 a	7.44 a	7.63 a
85% ET	7.38 a	7.31 a	7.31 a
75% ET	7.00 a	6.81 ab	7.00 a
60% ET	6.00 b	6.06 b	6.06 b
35% ET	4.31 c	4.88 c	5.13 c

LSD = 0.81 (down), 1.05 (ACROSS, all NS); p = 0.05

Table 6.8: Quality Ratings for 7-21-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	7.25 a A	7.44 a A	7.50 a A
85% ET	6.75 ab A	7.13 a A	7.19 a A
75% ET	6.00 bc B	6.50 ab AB	6.81 a A
60% ET	4.94 c A	5.69 b A	5.69 b A
35% ET	3.13 d B	4.38 c A	4.38 c A

LSD = 1.11 (down), 0.80 (ACROSS); p = 0.05

Table 6.9: Quality Ratings for 8-10-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	7.38 a	7.50 a	7.63 a
85% ET	7.19 a	7.38 a	7.19 ab
75% ET	6.94 a	6.94 a	6.94 ab
60% ET	6.31 a	6.44 a	6.44 b
35% ET	3.25 b B	4.44 b A	5.00 c A

LSD = 1.10 (down), 0.62 (ACROSS); p = 0.05

Table 6.10: Quality Ratings for 8-23-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	7.25 a	7.50 a	7.44 a
85% ET	6.81 ab	7.13 a	6.88 ab
75% ET	6.31 bc	6.81 ab	6.44 bc
60% ET	5.75 c	6.25 b	5.88 c
35% ET	3.75 d B	5.25 c A	4.88 d A

LSD = 0.75 (down), 0.63 (ACROSS); p = 0.05

Table 6.11: Quality Ratings for 9-4-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	7.19 a	7.50 a	7.38 a
85% ET	7.06 a	7.31 a	7.13 a
75% ET	6.75 ab	7.13 ab	6.81 ab
60% ET	6.06 b	6.50 b	6.13 b
35% ET	3.31 c C	5.19 c A	4.50 c B

LSD = 0.76, (down), 0.64 (ACROSS); p = 0.05

Table 6.12: Quality Ratings for 9-27-94
Turfgrass Type x Irrigation Level*

Irrigation Level	KBG	TF/KBG	TF
95% ET	8.00 a A	7.81 a AB	7.50 a B
85% ET	8.00 a A	7.75 a AB	7.50 a B
75% ET	7.94 a A	7.63 a AB	7.38 a B
60% ET	7.44 a A	7.44 a A	6.94 a B
35% ET	5.75 b B	6.50 b A	6.19 b A

LSD = 0.71 (down), 0.41 (ACROSS); p = 0.05; *Recovery of turfgrass following three weeks of uniform irrigation at over 100% of reference KBG-ET.

C. Summary

In summary, the five turfgrass types maintained acceptable quality over the course of the two seasons at the following range of proportions of alfalfa reference ET (the corresponding turfgrass ET levels are in parentheses):

KBG: 0.48 to 0.75 (0.60 to 0.95)

TF: 0.48 to 0.75 (0.60 to 0.95)

TF/KBG: 0.48 to 0.75 (0.60 to 0.95)

609 and Prairie buffalograss: 0.16 to 0.28 (0.20 to 0.35)

Although the above range was the same for all three cool-season turfs in 1993 and 1994, it should be noted that KBG quality was quite a bit lower than the other two turfs when watered at the lower end of this range. It would therefore be advisable to irrigate KBG with the more conservative alfalfa reference irrigation coefficient of 0.70 while a conservative alfalfa reference irrigation coefficient for TF would be 0.60. A conservative alfalfa reference irrigation coefficient to maintain 609 or Prairie buffalograss of acceptable quality in Colorado would be 0.30. We believe that these values represent the level of irrigation required to maintain acceptable turf quality.

Of course, these recommendations are only valid if some additional assumptions hold. First, a minimum level of turfgrass culture must be practiced as followed in this study and as outlined by CSU Cooperative Extension (Koski and Skinner, 1992). Second, good soil physical conditions (i.e., a deep, uncompacted, and non-saline soil) must exist to allow for adequate turfgrass rooting.

The available soil water estimates contained in Table 5.13 serve well to reinforce these visual quality results and subsequent irrigation recommendations. Table 5.13 indicates that the cool-season turfs were able to maintain minimum acceptable quality when irrigated at a 60% or above level because there was available soil water remaining at the end of each year's irrigation cycle. The turfs did not maintain minimum acceptable quality at the lowest irrigation level each year (IRR5) because they were trying to grow under conditions where soil moisture was, on average, unavailable.

These soil water availability estimates also serve well to illustrate the "safeness" of our recommendations. Recall that we recommended a KBG-irrigation coefficient of 0.70, a TF-irrigation coefficient of 0.60, and a buffalograss-irrigation coefficient of 0.30 for use with Kimberly-Penman weather station alfalfa reference ET estimates. If we adjust these proportions to the irrigation levels used in this study, we see that they correspond to irrigation levels of approximately 90% of estimated Kentucky bluegrass reference ET for KBG, 80% of estimated Kentucky bluegrass reference ET for TF, and 40% of estimated Kentucky bluegrass reference ET for buffalograss. Their "safeness", as concerns maintaining turfgrass of acceptable quality, is apparent given that there was available soil moisture remaining at the end of each year's irrigation cycle at the 60% ET-level in 1993 and at the 75% ET-level in 1994.

Additional evidence for these recommendations are provided by the leaf firing and canopy temperature data presented below. Also note that these recommendations agree fairly well with the reported results of five studies reviewed earlier, three of which were also conducted at Colorado State University (Feldhake et al., 1984; Minner, 1984; Fry and Butler, 1989; Carrow, 1991; Meyer and Gibeault, 1987). In all of these studies, the proportion of turfgrass PET needed to maintain acceptable quality was determined rather than the proportion of alfalfa PET needed to maintain acceptable quality; therefore, to make meaningful comparisons with this study, their results must be multiplied by 0.80 to adjust to an alfalfa reference crop. It should also be noted that until this study there has been no research concerning the proportion of the reference crop PET-estimates needed for the scheduling of buffalograss irrigation.

Recall that Feldhake et al. (1984) found that Kentucky bluegrass and tall fescue grown in 23.0 cm deep lysimeters maintained minimally acceptable quality when irrigated at 73% of Kentucky bluegrass-PET; the proportion of alfalfa PET needed to maintain acceptable quality then was 0.58 (i.e., 0.73 * 0.80 = 0.58).

Minner (1984) also reported minimally acceptable quality of 23.0 cm deep lysimeter grown Kentucky bluegrass when irrigated at 0.75 of Kentucky bluegrass PET or 0.60 of alfalfa PET.

Fry and Butler (1989) reported that tall fescue maintained minimally acceptable quality when irrigated every two days at 50% of tall fescue-PET (40% of alfalfa PET) or when irrigated every seven days at 75% of tall fescue-PET (60% of alfalfa PET).

Working in the relatively humid climate of Georgia, Carrow (1991) reported that acceptable quality was maintained when tall fescue was irrigated at 80% of tall fescue PET (64% of alfalfa PET).

Finally, Meyer and Gibeault (1987), working in California, reported that Kentucky bluegrass and tall fescue maintained acceptable season-long quality when irrigated at 79% of Kentucky bluegrass PET (alfalfa PET of 63%).

A summary of the proportion of alfalfa PET needed to maintain a turf of minimal acceptable quality from these studies indicates a range of 0.40 to 0.65, with tall fescue representing the low end of the range. The range for acceptable TF and KBG turf found in this study, as summarized above, was 0.48 to 0.75, with a recommended working value (i.e., safe range for the maintenance of acceptable turf) of 0.60 for TF and 0.70 for KBG. Thus, our recommendations agree quite closely with, and are even a bit more conservative than those of past research, while still representing considerable water-savings potential relative to the currently used proportion of alfalfa reference PET of 0.80.

Given that other researchers have found that acceptable turf can be maintained by irrigating every three days in the range of 0.60 to 0.70 of alfalfa reference PET, the question becomes why has the 0.80 level been used or accepted. A very plausible answer comes to mind. Plainly, that this higher level has been adopted and recommended out of safety concerns. That is, water managers have chosen to use and recommend this higher value to ensure that the lawn irrigation amounts they are recommending are great enough to overcome poor homeowner irrigation and cultural management practices.

II. Leaf Firing Ratings

Turfgrass leaf firing was visually rated at the same time as quality. In visually rating the leaf firing of a turfgrass plot, the researcher recorded an estimate of the percent of leaves fired or browned in order to estimate the amount of turfgrass tissue injury that was occurring, with no differentiation as to whether the stress was a result of drought and/or high temperature. Under the deficit irrigation conditions of this study, leaf firing was regarded as a good overall measure of the relative drought resistance of each turf type (Carrow, 1991).

Leaf firing was rated using a scale of one to nine, where nine indicated no visible leaf firing and one indicated that all leaves were fired. This scale is similar to that used in previous turfgrass research, with a minor difference: their rating scale was the other way around with nine being all leaves fired and one being no leaves fired (Burton et al., 1957; Kim, 1987).

A. 1993 Results

Leaf firing ratings comparing the five turfgrass types at each sampling date in 1993 are presented in Tables 6.13 to 6.16. It should be noted that all leaf firing data were taken on the same days as the quality data.

Not unlike what we observed with the 1993 quality ratings, it was not until approximately four weeks into the irrigation cycle (7-27) that any significant effects of irrigation on turfgrass leaf firing were observed (Table 6.13). At that time, KBG, TF/KBG, 609, and Prairie displayed significant levels of leaf firing only at the 20%-level. It was not until approximately five weeks into the irrigation cycle (8-9, Table 6.14) that TF displayed significant levels of leaf firing at the 20%-level, most likely indicating a greater ability to extract deep soil moisture.

At seven weeks into the irrigation cycle (Table 4.15), KBG was displaying significantly different levels of leaf firing at the 60%, 45%, and 20%-levels, while for TF/KBG and TF, leaf firing was still only significantly greater, compared to the other irrigation levels, at the 20%-level. There were no significant leaf firing differences across irrigation levels for both buffalograsses, a trend which held through the duration of the 1993 irrigation treatments (Table 4.16). It is also on this date (8-23), that KBG (at the 20%-level) had significantly more leaves fired than the other turfs, with these differences remaining until the last sample date of 9-4 (Table 4.16). The fact that KBG leaf firing at the 20%-level was significantly greater than that of the other turfs through the 1993 irrigation cycle is a direct cause of its diminished quality ratings relative to the other turfs. These results indicate KBG's diminished ability to avoid drought at such low irrigation levels relative to the other four turfs; a result that is most likely due to its lack of deep rooting.

Table 6.13: Leaf Firing Ratings for 7-27-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	9.00 a	9.00 a	9.00 a	9.00 a	8.94 a
70% ET	8.94 a	9.00 a	9.00 a	9.00 a	8.94 a
60% ET	8.94 a	8.94 ab	9.00 a	9.00 a	8.94 a
45% ET	8.56 b	8.63 bc	8.88 a	8.94 a	8.94 a
20% ET	8.19 c	8.56 c	8.69 a	8.19 b	8.50 b

LSD = 0.34 (down), 0.64 (ACROSS, all NS); p = 0.05

Table 6.14: Leaf Firing Ratings for 8-9-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	8.81 a	8.75 a	8.88 a	8.50 a	8.56 ab
70% ET	8.75 a	8.69 ab	8.88 a	8.44 a	8.69 a
60% ET	8.75 a	8.63 ab	8.88 a	8.38 ab	8.69 a
45% ET	8.56 a	8.44 b	8.63 a	8.38 ab	8.69 a
20% ET	7.88 b	8.13 c	8.13 b	8.13 b	8.38 b

LSD = 0.30 (down), 0.51 (ACROSS, all NS) ; p = 0.05

Table 6.15: Leaf Firing Ratings for 8-23-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	8.81 a A	8.69 a AB	9.00 a A	8.25 a B	9.00 a A
70% ET	8.44 a BC	8.63 a A	8.88 a AB	8.25 a C	9.00 a A
60% ET	8.31 a B	8.63 a AB	8.88 a A	8.19 a B	9.00 a A
45% ET	7.56 b C	8.06 a B	8.13 b B	8.19 a B	9.00 a A
20% ET	5.44 c D	6.94 b C	6.69 c C	8.13 a B	8.94 a A

LSD = 0.73 (down), 0.48 (ACROSS); p = 0.05

Table 6.16: Leaf Firing Ratings for 9-4-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	8.00 a A	8.31 a A	8.50 a A	6.88 a B	8.50 a A
70% ET	7.44 ab BC	7.81 ab AB	8.06 ab AB	6.88 a C	8.50 a A
60% ET	7.06 b BC	7.50 bc BC	7.69 b B	6.88 a C	8.50 a A
45% ET	6.19 c B	6.94 c B	6.88 c B	6.88 a B	8.31 a A
20% ET	4.31 d C	5.94 d B	5.69 d B	6.44 a B	8.13 a A

LSD = 0.79 (down), 0.80 (ACROSS); p = 0.05

B. 1994 Results

Leaf firing ratings for each of the three cool-season turfgrass types for each sample date are shown in Tables 6.17 to 6.24. Leaf firing data for the two buffalograss species were not taken because of poor turfgrass cover caused by an herbicide application.

With June of 1994 being the hottest on record, it was not surprising that, just one week after the irrigation cycle began (6-19), significant levels of leaf firing were already being observed for all three cool-season turfgrasses at the lowest irrigation level (Table 6.17). Additionally, KBG had significantly more leaves fired than TF or TF/KBG at this 35%-level, indicating early on TF's greater ability to avoid drought.

By the end of June (Table 6.18), some significant separations based on the amount of leaves fired across irrigation levels for all three turfs were apparent. That is, there were significantly more leaves fired at the 75% irrigation level than at the 95%-level and there were significantly more leaves fired at the 35%-level than at the 75%-level for all three turfs. At this date, TF continued to have significantly less leaves fired than KBG at the lowest irrigation level.

By 7-11 (Table 6.19), four weeks into the irrigation cycle, the three highest irrigation levels resulted in significantly less leaf firing, for all three turfs, than did the 60%-level. These differences were even more pronounced at the 35%-level, with over half of the KBG leaves fired at this date; again having significantly more leaves fired than TF.

Five and a half weeks into the irrigation cycle (Table 6.20), KBG and TF leaf firing at the 35%-level reached their highest levels for the entire irrigation cycle; quality ratings for these turfs were the lowest on this date also. Tall fescue leaf firing was significantly less than that of KBG at the 35%, 60%, and 75%-levels. This continued to be the case at the 35%-level for the rest of the irrigation cycle, while it did not for any of the other irrigation levels (Tables 6.21 to 6.23).

Three weeks after the 1994 irrigation cycle had ended and the plots were being uniformly well-watered, none of the turfgrass plots were displaying any leaf firing or stress, indicating good drought recovery (Table 6.24).

Table 6.17: Leaf Firing Ratings for 6-19-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	8.94 a A	8.94 a A	9.00 a A
85% ET	8.81 a A	8.81 a A	8.94 a A
75% ET	8.75 a A	8.75 a A	8.81 a A
60% ET	8.63 a A	8.63 a A	8.25 a B
35% ET	7.19 b C	8.00 b A	7.56 b B

LSD = 0.57 (down), 0.33 (ACROSS); p = 0.05

Table 6.18: Leaf Firing Ratings for 6-30-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	8.19 a A	8.56 a A	8.75 a A
85% ET	7.88 ab B	8.25 ab AB	8.50 ab A
75% ET	7.56 bc A	7.93 bc A	8.00 bc A
60% ET	7.25 c A	7.56 cd A	7.56 c A
35% ET	6.06 d B	7.13 d A	6.94 d A

LSD = 0.52 (down), 0.61 (ACROSS); p = 0.05

Table 6.19: Leaf Firing Ratings for 7-11-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	8.63 a	8.44 a	8.50 a
85% ET	8.25 a	8.25 a	8.31 a
75% ET	7.56 a	7.56 a	7.94 a
60% ET	6.31 b	6.13 b	6.38 b
35% ET	4.13 c B	4.88 c A	5.06 c A

LSD = 1.17 (down), 0.92 (ACROSS); p = 0.05

Table 6.20: Leaf Firing Ratings for 7-21-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	8.13 a A	8.38 a A	8.75 a A
85% ET	7.25 ab A	7.88 ab A	8.25 a A
75% ET	6.25 b B	6.88 b AB	7.63 a A
60% ET	4.88 c B	5.56 c AB	6.31 b A
35% ET	3.38 d B	4.19 d AB	4.81 c A

LSD = 1.19 (down), 1.10 (ACROSS); p = 0.05

Table 6.21: Leaf Firing Ratings for 8-10-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	8.31 a	8.50 a	8.75 a
85% ET	7.81 a	8.25 a	8.13 a
75% ET	7.50 ab	7.75 a	7.75 ab
60% ET	6.38 b	6.38 b	6.69 b
35% ET	3.44 c B	3.44 c B	5.06 c A

LSD = 1.35 (down), 0.87 (ACROSS); p = 0.05

Table 6.22: Leaf Firing Ratings for 8-23-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	7.88 a	8.31 a	8.50 a
85% ET	7.19 ab	7.94 ab	7.69 ab
75% ET	6.50 bc	7.31 bc	6.94 bc
60% ET	5.69 c	6.44 c	6.13 c
35% ET	3.75 d B	5.13 d A	5.06 d A

LSD = 0.89 (down), 0.82 (ACROSS); p = 0.05

Table 6.23: Leaf Firing Ratings for 9-4-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	8.13 a	8.75 a	8.75 a
85% ET	7.63 a	8.31 a	8.00 ab
75% ET	7.31 a	7.94 a	7.44 b
60% ET	6.13 b	7.00 b	6.44 c
35% ET	3.38 c B	5.19 c A	4.69 d A

LSD = 0.90 (down), 0.88 (ACROSS); p = 0.05

Table 6.24: Leaf Firing Ratings for 9-27-94*
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	9.00	9.00	9.00
85% ET	9.00	9.00	9.00
75% ET	9.00	9.00	9.00
60% ET	9.00	9.00	9.00
35% ET	9.00	9.00	9.00

LSD 0.00; p = 0.05; *Recovery of turfgrass following three weeks of uniform irrigation at 100% ET.

C. Summary

In summarizing the above results three points stand out. First, no significant differences in leaf firing were observed with the cool-season turfs over the course of both seasons when they were irrigated at the 70% to 95% irrigation levels. These results support our irrigation recommendations made previously in the quality section. Secondly, KBG consistently had more leaf firing than TF at the lower irrigation levels. This indicates that KBG experiences stress sooner and to a greater extent than TF when the amount of water applied every three days decreases. That is, TF is better able to avoid drought than KBG. Third, all of the results presented indicate that buffalograss avoids drought much better than KBG or TF.

CHAPTER 7: INFRARED CANOPY TEMPERATURES AS A MEASURE OF TURFGRASS WATER STRESS

I. Canopy Temperature Results

Canopy temperatures were taken every third day during each summer's irrigation cycle between 11:30 and 14:00 hours if clear-sky conditions permitted. Following the Idso et al. (1981) empirical method, and using the turfgrass plots receiving the highest amount of irrigation to represent non-water stressed turfgrass plots (Horst et al., 1989), turfgrass-type upper and lower baselines were developed for the 1994 season (see Appendix D). These turfgrass type-specific baselines were then used to calculate crop water stress indices (CWSI) for each day sampled. It was not possible to develop non-water stressed baselines for 1993 given that the highest resulting irrigation level was 80% ET-a level which did not represent a non-water-limiting situation. Therefore, 1993 canopy temperature results are presented as the canopy temperature minus the air temperature with the vapor pressure deficit reported at the bottom of each table.

Irrigation scheduling based on CWSI's has a number of practical advantages. First, because they provide nearly direct, site-specific monitoring of turfgrass transpirative-cooling status, the turf manager is able to schedule irrigations which more closely match the plant's needs. In this way, the turf manager is able to predict that his or her turfgrass is undergoing significant water stress much earlier than would be apparent visually. Irrigating in such a manner should promote greater overall turfgrass health. Watering that is more "in tune" with the plant's needs will result in a turf that is more wear tolerant and less prone to weed invasion and pest damage. It would also promote and conserve deep rooting, making the plant more water and nutrient efficient.

A. 1993 Results

Infrared canopy temperature/air temperature differentials (Tc-Ta) for all five turfgrass types are shown in Tables 7.1 to 7.4. It should be noted that nearly all of the canopy temperature data presented were taken on the same days as the quality and leaf firing data.

Due to the aforementioned relatively cool and wet conditions seen in 1993, significant Tc-Ta treatment differences were not observed until approximately four weeks after the irrigation treatments began (7-27, Table 5.1). As late as 7-27, KBG and TF were the only turfgrass types for which the Tc-Ta readings were significantly higher at any of the irrigation levels. For KBG, the Tc-Ta mean at the 20%-level was significantly greater than at all other irrigation levels. For TF, the Tc-Ta mean at the 20%-level was only significantly greater than at the 95%-level. A similar pattern was observed for KBG visual quality (Table 6.1).

Approximately five weeks into the irrigation cycle (8-9, Table 7.2), increased plant stress was indicated by the greater number of significant differences in the Tc-Ta readings, especially for KBG. The Tc-Ta mean for KBG at the 20%-level was significantly greater than that of the 45%-level, while the KBG Tc-Ta mean at the 45%-level, was significantly greater than those at the 70% and 80%-levels. Thus, by this date (8-9), the KBG was beginning to experience some significant stress at the lowest irrigation levels, most likely due to a lack of adequate soil moisture. Though revealed by canopy temperature data, it is interesting to note that visual quality did not significantly decline and leaf firing did not significantly appear until two weeks later (Tables 6.2, 6.3, 6.14, 6.15). This occurrence emphasizes the utility of using canopy temperatures or CWSI's in order to detect plant water-stress early and to apply irrigation in a more timely manner.

The Tc-Ta readings on the TF and TF/KBG plots on 8-9 only indicate a significant difference between the 20%-level and the 80%-level. These results indicate that the plots with TF in them were avoiding water stress more readily than the KBG plots. This may have occurred due to greater TF soil moisture mining efficiency or because the KBG was "shutting down" in anticipation of drought (i.e., closing its stomates and greatly reducing its photosynthesis in response to low soil water potentials). The results of the Aronson et al. (1987b) study, reviewed earlier, support the latter explanation. In that study, they reported that Kentucky bluegrass was much more sensitive to decreases in soil water potential relative to two fine fescue species. While Kentucky bluegrass growth ceased at a soil water potential of -0.13 MPa, fine fescue growth did not cease until -0.40 MPa. Regardless of the precise explanation for why the Tc-Ta readings for TF were significantly lower than those of KBG, they still indicate greater TF drought avoiding abilities.

On 8-23 (Table 7.3), similar patterns of stress were observed for all turf types. However, the magnitude of the Tc-Ta readings had increased, indicating a cumulative effect of water stress even at the highest irrigation level. Notice also that, even though there were no important differences in the Tc-Ta means for the two buffalograsses on any of the sample dates to this point, their Tc-Ta means were noticeably higher at all irrigation levels than the cool-season turfs.

Do these higher values indicate that the buffalograsses were experiencing more stress than the cool-season turfs? A look at the leaf firing data (Table 6.15) for this date indicate that this was not the case at all. In fact, almost no visual leaf firing was observed for most of the study. Higher Tc-Ta differentials for the buffalograsses were expected due to differences in warm- and cool-season physiology. As Feldhake and Boyer (1985) showed, buffalograsses have higher internal resistances (i.e., greater stomatal sensitivity to small changes in vapor pressure deficit) to water vapor loss when compared to cool-season grasses such as tall fescue. In other words, the warm-season buffalograsses have significantly lower transpiration ratios (mol H_2O transpired/mol CO_2 fixed) than cool-season grasses (Noble, 1991; Jones, 1992). This results in lower PET-rates and warmer canopy temperatures at any given air temperature and vapor pressure deficit for the buffalograsses.

At nine weeks into the irrigation cycle (9-3, Table 7.2), KBG Tc-Ta means got significantly higher as irrigation level decreased, whereas TF and TF/KBG Tc-Ta means were not as widely separated as irrigation level decreased.

In comparing means across turf types at each irrigation level (as indicated with upper case letters), one can see that TF had significantly lower Tc-Ta readings than KBG on all sample dates and at all irrigation levels. This is not only good evidence for TF's reported higher ET-rate (especially at the higher irrigation levels), but it is also good evidence for TF's ability to maintain this higher ET-rate by more efficiently mining soil moisture when water becomes limiting at shallower soil depths. While the major canopy temperature differences between TF and KBG at the two highest irrigation levels are most likely a reflection of TF's higher relative ET-rate, KBG's much higher canopy temperatures at the two lowest irrigation levels throughout the season, and especially by 8-23 (Table 7.3), were most likely a result of significant KBG dormancy. Additional evidence that KBG was not avoiding drought as well as TF by 8-23 is the fact that TF quality was appreciably higher and leaf firing was appreciably lower than KBG quality and leaf firing (Tables 6.3 and 6.15).

It is also apparent that KBG and the two buffalograss cultivars had similar Tc-Ta readings at the three highest irrigation levels over the 1993 season. This may indicate a similar ET-rate for these two species (Table 2.1). The significantly higher Tc-Ta means for KBG versus the buffalograsses at the lower irrigation levels (especially after 8-9, Tables 7.3 and 7.4), possibly indicates buffalograss' greater ability to avoid drought by reducing the radiative load on its leaves (via its waxy, finely textured, and sparsely hairy leaves), by mining soil moisture more efficiently, and by maintaining growth (while much of the KBG may have been going dormant), which in large part may be attributed to its greater heat tolerance and more sensitive stomatal control.

Table 7.1: Canopy Temp.- Air Temp.: 7-27-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	5.54 b AB	4.78 a B	3.14 b C	6.26 a A	6.00 a AB
70% ET	6.28 b A	5.18 a A	3.61 ab B	5.90 a A	5.94 a A
60% ET	6.31 b A	4.92 a B	3.85 ab B	6.29 a A	5.99 a A
45% ET	6.92 b A	5.49 a BC	4.33 ab C	6.32 a AB	6.28 a AB
20% ET	9.29 a A	6.40 a BC	5.66 a C	7.61 a B	6.91 a BC

LSD = 2.19 (down); 1.31 (ACROSS); p = 0.05 VPD = 1.23 kPa

Table 7.2: Canopy Temp.- Air Temp.: 8-9-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	4.49 c B	3.95 b B	2.63 b C	6.51 b A	6.48 a A
70% ET	5.07 c B	4.79 ab B	3.68 ab C	6.58 b A	6.38 a A
60% ET	5.91 bc AB	5.03 ab B	3.46 b C	6.66 ab A	6.47 a A
45% ET	7.24 b A	5.84 ab B	4.18 ab C	6.98 ab A	6.79 a AB
20% ET	9.93 a A	6.77 a C	5.65 a D	8.78 a B	7.65 a C

LSD = 2.15 (down); 1.09 (ACROSS); p = 0.05 VPD = 1.12 kPa

Table 7.3: Canopy Temp.- Air Temp.: 8-23-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	8.78 c B	6.43 b C	5.54 b C	10.66 a A	9.12 a A
70% ET	9.52 bc AB	7.20 ab C	5.89 b C	10.65 a A	8.88 a B
60% ET	9.49 bc B	7.64 ab C	5.72 b D	10.98 a A	8.82 a BC
45% ET	11.49 b A	7.80 ab BC	7.28 b C	11.48 a A	8.77 a B
20% ET	16.33 a A	9.33 a C	9.71 a C	12.53 a B	10.15 a C

LSD = 2.41 (down); 1.33 (ACROSS); p = 0.05 VPD = 0.89 kPa

Table 7.4: Canopy Temp.- Air Temp.: 9-3-93
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF	'609' B	'Prairie' B
80% ET	7.73 d AB	5.08 c C	4.28 c C	9.31 b A	7.32 bc B
70% ET	9.38 cd A	4.49 c C	4.92 c BC	9.78 ab A	6.67 c B
60% ET	9.81 c A	6.73 bc BC	5.38 c C	9.83 ab A	7.77 abc B
45% ET	13.17 b A	7.75 ab C	7.88 b C	10.17 ab B	8.48 ab BC
20% ET	15.23 a A	9.12 a C	10.62 a BC	11.51 a B	9.42 a C

LSD = 1.79 (down); 1.33 (ACROSS); p = 0.05 VPD = 1.16 kPa

B. 1994 Results

Crop water stress indices (CWSI) for the three cool-season turfgrass types are shown in Figures 7.1 to 7.3. The canopy temperature data for 1994 are presented as CWSI's because this type of data presentation is a better quantification of turfgrass water stress. This is the case owing to the fact that these CWSI's take into account both Tc-Ta and vapor pressure deficit (VPD). The addition of the VPD variable into the index provides a more accurate indication of each day's atmospheric moisture demand. The non-water-stressed baselines used to calculate the CWSI's are contained in Appendix C. Tables 7.5 to 7.12 show the same data as contained in Figures 4.6 to 4.8 broken down by sample date. CWSI data for the two buffalograss cultivars could not be not collected because of poor turfgrass cover caused by herbicide application.

There were no significant CWSI differences measured on 6-23, two weeks after the irrigation cycle had begun (Table 7.5). By three weeks into the cycle (6-30, Table 7.6), there were some large differences between the 35%, 75%, and 95% irrigation levels for all three turfs, but especially for KBG, whose quality at the 35%-level was already appreciably below an acceptable level of six. Given that it was the hottest June on record, it is not surprising that such high levels of stress were accumulated in just three weeks. The TF and TF/KBG had significantly lower CWSI's than KBG at all five irrigation levels, once again providing a clear indication of TF's greater ability to extract water from the soil given high atmospheric demand and implying a greater ability to avoid drought than KBG.

Table 7.7 shows that on 7-12 the CWSI differences between irrigation levels for each turf type had, to a certain extent, converged, with only the 35%-level KBG plots having significantly higher CWSI's than at any other irrigation level or turf type. These results are most likely a result of a large irrigation treatment on 7-6 (Table B.2).

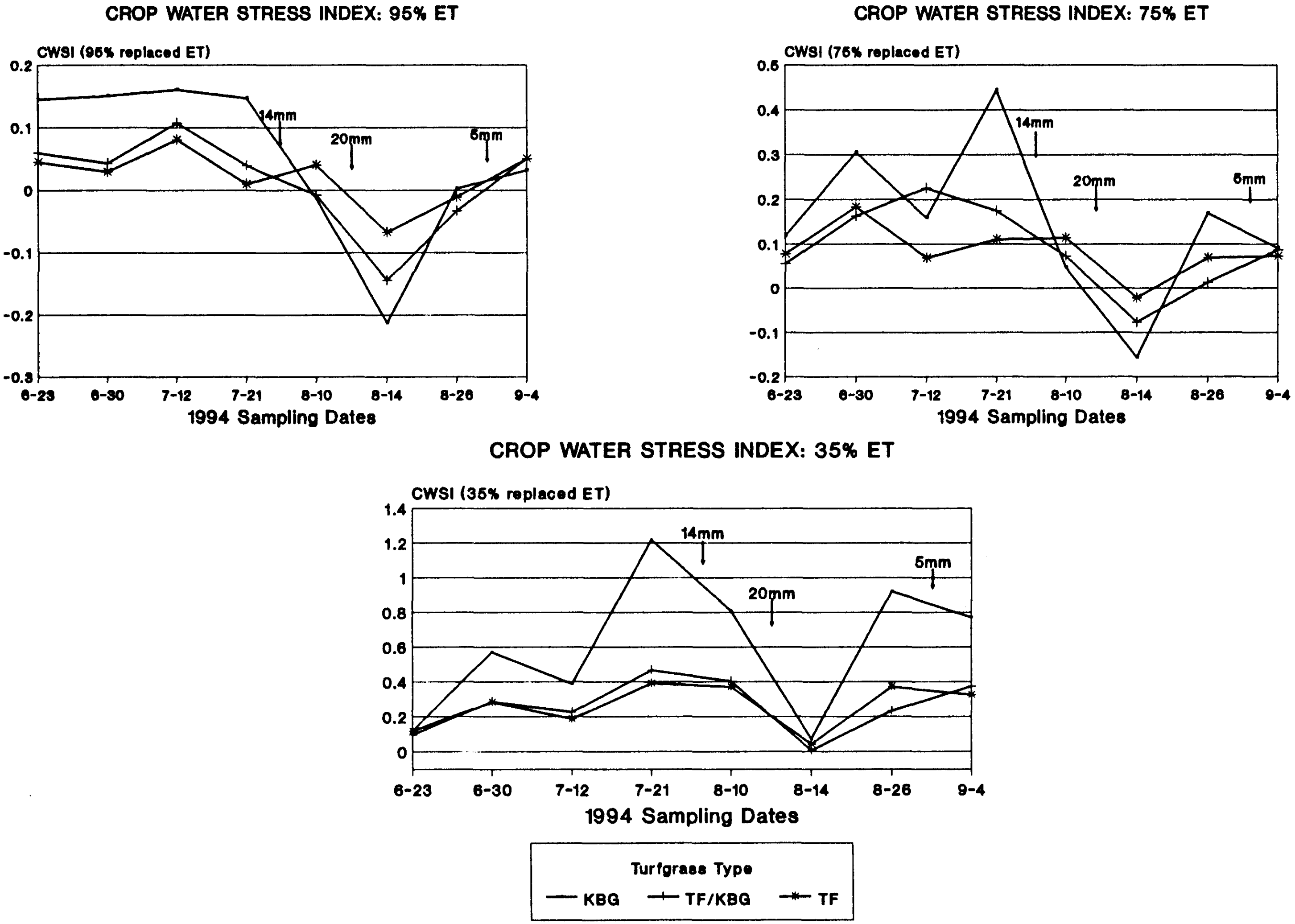
On 7-21 (Table 7.8) some of the highest CWSI's of the 1994 season were measured for each turfgrass type at the two lowest irrigation levels. As discussed previously, visual quality ratings were lowest and leaf firing ratings the highest, on this date. Significant differences among turf types were also observed. The CWSI for KBG at the 35%-level exceeded 1.0 indicating that most of the grass in these plots had become completely brown or dormant. This was not the case for the TF and TF/KBG plots. In comparing the turfgrass types at each irrigation level, it is seen that the CWSI's for TF and TF/KBG were significantly less than for KBG at all of the irrigation levels except the 95%-level. These results strongly suggest that the TF and TF/KBG turfs were consistently cooler, probably because of tall fescue's ability to maintain higher ET-rates than KBG. The ability to maintain higher ET-rates likely results from TF's capacity to form deep roots and utilize water contained in deeper soil profiles.

Turf that had become injured at low irrigation levels recovered quickly when cooler temperatures and significant rainfall occured (Tables 7.9 and 7.10;

Figures 7.1-7.3). Especially apparent was KBG's tremendous ability to recover from drought, given sufficient moisture and cooler temperatures.

The duration of KBG recovery was short-lived, however, as the CWSI for KBG at the 35%-level had again risen to a very high level (0.920) on 8-26 (Table 7.11). The CWSI's were significantly lower for the TF and TF/KBG turfs at the 35% and 60%-levels relative to KBG, suggesting more regular growth patterns that were not as susceptible to fluctuations of the surface environment.

The 1994 irrigation cycle ended on 9-4 (Table 7.12) with significant differences in CWSI's between the 35%, 60%, and 75%-levels for KBG. With the TF and TF/KBG, the only significant differences measured were between the 35%-level and all other levels. In addition, TF again had a significantly lower CWSI than KBG at the 35% irrigation level. So even though the TF at 35% was stressed relative to the more well-irrigated TF, it was not nearly as stressed as the KBG at the same irrigation level.



Figures 7.1 (95%ET), 7.2 (75%ET), 7.3 (35%ET): Crop Water Stress Indices for 1994

Table 7.5: Crop Water Stress Index: 6-23-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	0.145 a A	0.060 a A	0.045 a A
85% ET	0.150 a A	0.105 a A	0.052 a A
75% ET	0.118 a A	0.056 a A	0.077 a A
60% ET	0.072 a A	0.057 a A	0.089 a A
35% ET	0.118 a A	0.096 a A	0.117 a A

LSD = 0.135 (down); 0.179 (ACROSS) p = 0.05

Table 7.6: Crop Water Stress Index: 6-30-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	0.151 c A	0.043 b B	0.030 c B
85% ET	0.248 bc A	0.112 b B	0.099 bc B
75% ET	0.305 b A	0.162 ab B	0.183 ab B
60% ET	0.458 a A	0.261 a B	0.281 a B
35% ET	0.569 a A	0.284 a B	0.282 a B

LSD = 0.146 (down) 0.088 (ACROSS); p = 0.05

Table 7.7: Crop Water Stress Index: 7-12-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	0.161 b A	0.108 a A	0.081 a A
85% ET	0.197 b A	0.153 a AB	0.079 a B
75% ET	0.159 b A	0.123 a A	0.069 a A
60% ET	0.112 b A	0.106 a A	0.086 a A
35% ET	0.386 a A	0.225 a B	0.186 a B

LSD = 0.119 (down); 0.100 (ACROSS); p = 0.05

Table 7.8: Crop Water Stress Index: 7-21-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	0.147 d A	0.040 c A	0.010 c A
85% ET	0.360 c A	0.135 c B	0.064 bc B
75% ET	0.444 c A	0.174 bc B	0.110 bc B
60% ET	0.825 b A	0.368 ab B	0.254 ab B
35% ET	1.217 a A	0.466 a B	0.390 a B

LSD = 0.199 (down); 0.199 (ACROSS); p = 0.05

Table 7.9: Crop Water Stress Index: 8-10-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	-0.013 c A	-0.007 c A	0.041 c A
85% ET	0.054 bc A	0.062 bc A	0.069 bc A
75% ET	0.047 bc A	0.073 bc A	0.113 bc A
60% ET	0.205 b A	0.187 b A	0.207 b A
35% ET	0.810 a A	0.403 a B	0.371 a B

LSD = 0.160 (down); 0.159 (ACROSS); p = 0.05

Table 7.10: Crop Water Stress Index: 8-14-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	-0.213 c B	-0.144 c B	-0.067 b A
85% ET	-0.149 bc B	-0.124 bc AB	-0.073 b A
75% ET	-0.157 bc B	-0.077 bc A	-0.021 ab A
60% ET	-0.130 b B	-0.065 b AB	-0.027 ab A
35% ET	0.073 a A	0.008 a A	0.042 a A

LSD = 0.072 (down); 0.075 (ACROSS); p = 0.05

Table 7.11: Crop Water Stress Index: 8-26-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	0.003 d A	-0.033 c A	-0.011 c A
85% ET	0.115 cd A	0.000 bc A	0.008 bc A
75% ET	0.169 c A	0.013 bc B	0.069 bc AB
60% ET	0.457 b A	0.091 b B	0.211 b B
35% ET	0.920 a A	0.232 a C	0.370 a B

LSD = 0.131 (down); 0.130 (ACROSS); p = 0.05

Table 7.12: Crop Water Stress Index: 9-4-94
Turfgrass Type x Irrigation Level

Irrigation Level	KBG	TF/KBG	TF
95% ET	0.032 c A	0.051 b A	0.051 b A
85% ET	0.081 c A	0.067 b A	0.053 b A
75% ET	0.090 c A	0.087 b A	0.073 b A
60% ET	0.243 b A	0.148 b A	0.156 b A
35% ET	0.771 a A	0.771 a A	0.326 a B

LSD = 0.137 (down); 0.130 (ACROSS) p = 0.05

C. Summary

The correlation coefficients between the CWSI's and quality ratings and the CWSI's and leaf firing ratings, for five dates in 1994, are shown in Tables 7.13 and 7.14. All of the correlations were significant at the 0.01 probability level on every date, providing strong quantitative support for the accuracy of the subjective ratings of quality and leaf firing taken in this study. Therefore, the CWSI means may be used to provide non-subjective verification of the previously developed (quality-based) irrigation or Kc recommendations.

This is accomplished for each turfgrass type by using the lowest irrigation level where CWSI readings were not significantly different from those of the highest irrigation level (on all sample dates), and multiplying this ET-level by the base Kc of 0.80. For KBG, this level was 85% in 1994. The resulting Kc of 0.68 corresponds well to the Kc of 0.70 suggested previously. For TF and TF/KBG this level was 75% in 1994. The resulting Kc of 0.60 corresponds to the Kc which was recommended previously, as well. For the two buffalograss cultivars, this level was 45% in 1993 and 35% in 1994 (although no canopy temperature data were taken). If one uses the average of 0.4, the resulting Kc is 0.32, quite close to the previously suggested Kc of 0.30.

Table 7.13: Crop Water Stress Index & Quality Ratings 1994 Correlation Coefficients (R)			
Sample Date	**KBG**	**TF/KBG**	**TF**
6-30	-0.7798	-0.6691	-0.7960
7-21	-0.8275	-0.7310	-0.8365
8-10	-0.9400	-0.8149	-0.9033
8-23	-0.8874	-0.8614	-0.8314
9-4	-0.8568	-0.8331	-0.8131

*** All correlations are significant at the 0.01 level**

Table 7.14: Crop Water Stress Index & Leaf Firing Ratings 1994 Correlation Coefficients (R)			
Sample Date	**KBG**	**TF/KBG**	**TF**
6-30	-0.7831	-0.8201	-0.8869
7-21	-0.7771	-0.7582	-0.8857
8-10	-0.9315	-0.8067	-0.9007
8-23	-0.9159	-0.8716	-0.8571
9-4	-0.8705	-0.8406	-0.8612

*** All correlations are significant at the 0.01 level**

CONCLUSIONS

1. There were no significant effects observed or measured in either year of this study for any parameter due to soil compaction and differential tillage treatment at sod establishment. This result was attributed to the large amount of shrinking and swelling (characteristic of soils which contain large amounts of montmorillonite), which may have occurred between sod establishment (9-22-92) and irrigation treatment initiation (7-1-93).

2. At the end of both years, the tall fescue blend had more total root mass (down to 90 cm) than Kentucky bluegrass. Consequently, the tall fescue extracted greater amounts of soil moisture from deep in the soil (30-90 cm), especially at the lower irrigation levels.

3. Kentucky bluegrass quality decreased faster and to a greater extent than the quality of the tall fescue blend as irrigation level decreased. The quality of both buffalograss cultivars was not significantly affected during either year by irrigation level.

4. The tall fescue blend consistently maintained significantly lower canopy temperatures in 1993 and significantly lower crop water stress indices in 1994, at the three lowest irrigation levels, relative to the Kentucky bluegrass. These results were likely a reflection of tall fescue's greater rooting and greater

ability to extract subsoil moisture. They were also highly correlated with visual quality and leaf firing ratings.

5. All of the turf types maintained acceptable quality when irrigated below the currently recommended level of 0.80 of Kimberly-Penman alfalfa reference ET, indicating significant potential for turfgrass water conservation. The two buffalograss cultivars displayed the greatest ability to avoid drought by maintaining acceptable quality at 20-40% of 0.80 adjusted alfalfa reference ET. To maintain acceptable lawn quality it is recommended to irrigate buffalograss with an irrigation coefficient of 0.30 when using Kimberly-Penman alfalfa reference ET estimates. The turf type tall fescue blend was medium in its ability to avoid drought in this study. It is recommended to irrigate tall fescue with an irrigation coefficient of 0.60. Lastly, the Kentucky bluegrass displayed the worst relative ability to avoid drought. It is recommended to irrigate Kentucky bluegrass with an irrigation coefficient of 0.70.

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APPENDIX A: SOIL ANALYSES

Horticulture Department
Room 219, Shepardson Building
Colorado State University

DATE RECEIVED: 01/13/92

RESEARCH SOIL ANALYSIS

Lab #	Sample ID #	% H_2O BAR 15	5	1	1/3	0.1
R5780	1 of 3	17.6	18.3	23.0	29.6	37.6
R5781	2 of 3	17.0	17.8	23.3	28.8	37.2
R5782	3 of 3	17.3	18.2	23.6	29.6	37.6

APPENDIX B: IRRIGATION DATA

Table B.1: 1993 LSIS Application Amounts							
DATE	ETo mm	ETkbg mm	IRR5 mm	IRR4 mm	IRR3 mm	IRR2 mm	IRR1 mm
7-4	23.37	18.70	3.56	7.62	8.64	9.78	13.84
7-7	23.62	18.90	5.97	15.11	13.08	20.07	21.46
7-10	19.05	15.24	0.00	0.00	0.00	0.00	0.00
7-13	16.51	13.21	3.94	7.87	13.08	17.65	21.08
7-16	-3.05	-2.44	0.00	0.00	0.00	0.00	0.00
7-19	15.49	12.39	0.00	0.00	0.00	0.00	0.00
7-22	18.54	14.83	2.92	4.83	6.35	6.86	7.62
7-25	23.11	18.49	5.08	12.95	16.64	17.78	20.96
7-28	20.32	16.26	5.84	12.57	17.78	19.69	21.08
7-31	17.53	14.02	4.19	6.10	8.38	8.76	9.53
8-3	23.11	18.49	0.00	0.00	0.00	0.00	0.00
8-6	5.59	4.47	0.00	0.00	0.00	0.00	0.00
8-9	15.49	12.39	1.40	2.54	4.19	4.95	5.33
8-12	15.75	12.60	3.05	4.45	7.62	9.02	10.41
8-15	14.22	11.38	3.18	7.24	9.65	10.41	11.43
8-18	17.02	13.62	0.00	0.00	0.00	0.00	0.00
8-21	15.24	12.19	2.54	7.62	10.29	11.30	12.95
8-24	16.51	13.21	4.57	5.84	9.02	9.53	11.68
8-27	18.29	14.63	2.92	9.27	12.57	13.84	15.24
8-30	13.21	10.57	4.32	9.65	14.35	16.89	18.67
9-2	13.46	10.77	0.00	0.00	0.00	0.00	0.00

Table B.1: 1993 LSIS Application Amounts

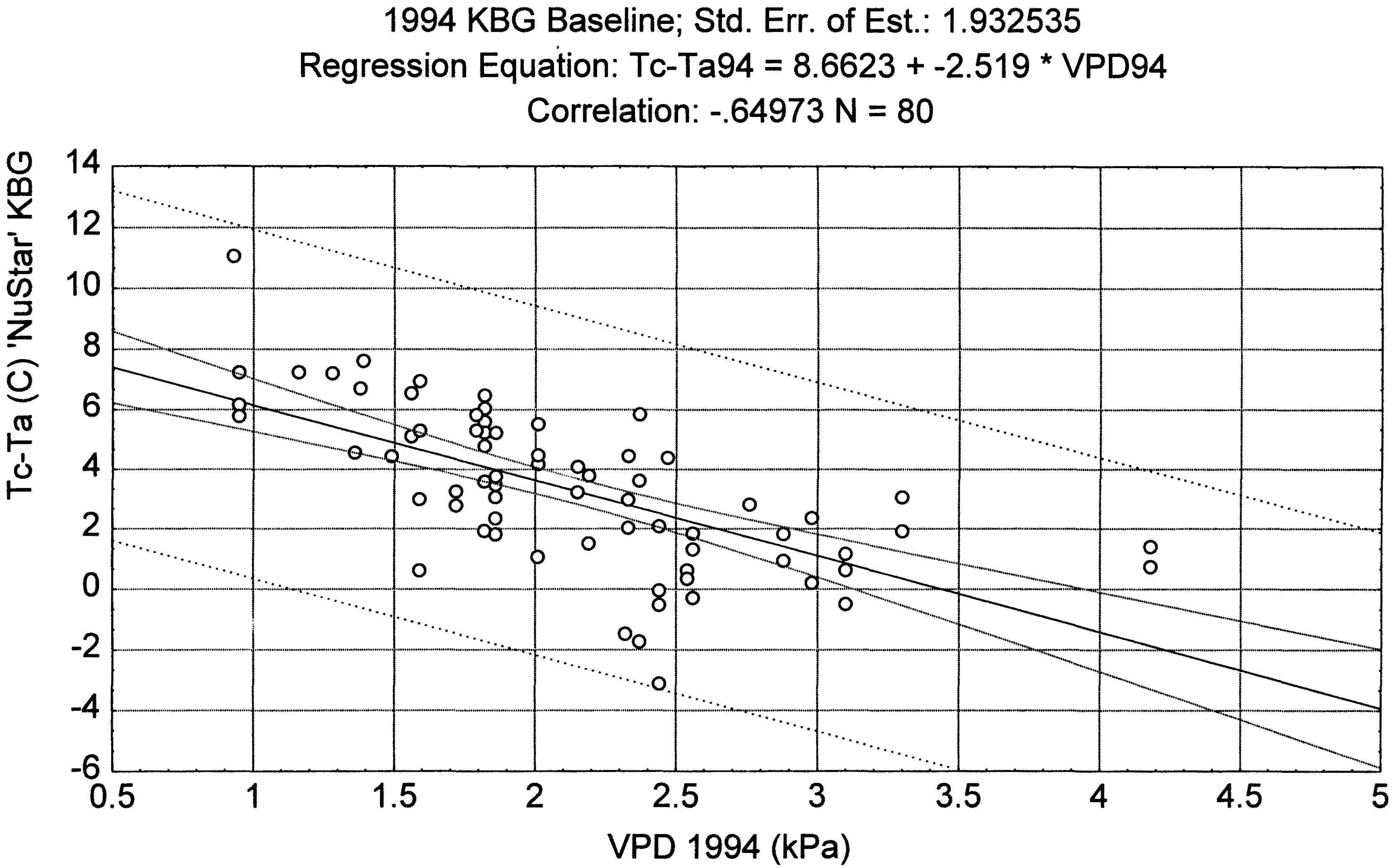
DATE	ETo mm	ETkbg mm	IRR5 mm	IRR4 mm	IRR3 mm	IRR2 mm	IRR1 mm
9-5	12.19	9.75	6.34	12.68	15.85	17.96	21.13
9-8	-2.54	-2.03	0.00	0.00	0.00	0.00	0.00
TOTAL	352.03	281.62	59.82	126.34	167.49	194.49	222.41
DAILY AV.	5.10	4.08	0.87	1.83	2.43	2.82	3.22
ET%	100	80	21.25	44.88	59.49	69.09	79.00

Table B.2: 1994 LSIS Application Amounts							
DATE	ETo mm	ETkbg mm	IRR5 mm	IRR4 mm	IRR3 mm	IRR2 mm	IRR1 mm
6-12	24.13	19.30	4.83	8.13	14.61	15.37	16.76
6-15	27.18	21.74	7.87	9.91	12.57	14.48	21.84
6-18	21.84	17.47	3.94	9.14	12.83	14.61	16.38
6-21	15.75	12.60	23.62	23.62	23.62	23.62	23.62
6-24	17.02	13.62	4.32	4.32	4.32	4.32	4.32
6-27	27.94	22.35	9.02	8.89	11.05	15.75	19.18
6-30	25.65	20.52	4.57	11.05	14.86	15.75	17.53
7-3	23.88	19.10	5.08	10.80	13.97	15.88	17.78
7-6	19.81	15.85	8.13	17.53	26.29	31.12	35.94
7-9	22.35	17.88	0.00	0.00	0.00	0.00	0.00
7-12	20.07	16.06	11.30	22.35	28.58	30.35	33.53
7-15	17.27	13.82	0.00	0.00	0.00	0.00	0.00
7-18	9.40	7.52	0.00	0.00	0.00	0.00	0.00
7-21	18.03	14.42	4.19	7.49	10.67	13.08	15.37
7-24	15.24	12.19	10.54	16.38	18.80	21.21	21.59
7-27	12.45	9.96	0.00	0.00	0.00	0.00	0.00
7-30	20.07	16.06	4.45	10.03	12.57	12.83	14.10
8-2	17.53	14.02	4.45	8.76	10.67	11.43	12.57
8-5	13.72	10.98	4.32	7.37	9.14	10.29	11.68
8-8	20.83	16.66	5.84	10.03	12.32	12.95	14.48
8-11	10.67	8.54	0.00	0.00	0.00	0.00	0.00
8-14	3.05	2.44	0.00	0.00	0.00	0.00	0.00
8-17	15.49	12.39	4.32	8.13	8.89	9.53	10.80
8-20	15.49	12.39	0.00	0.00	0.00	0.00	0.00
8-23	16.00	12.80	5.59	12.95	18.80	20.83	23.62
8-26	17.02	13.62	4.57	10.54	11.68	12.19	13.34
8-29	16.51	13.21	6.86	10.92	13.08	13.72	15.37
9-1	9.14	7.31	2.67	5.59	7.37	8.13	9.27

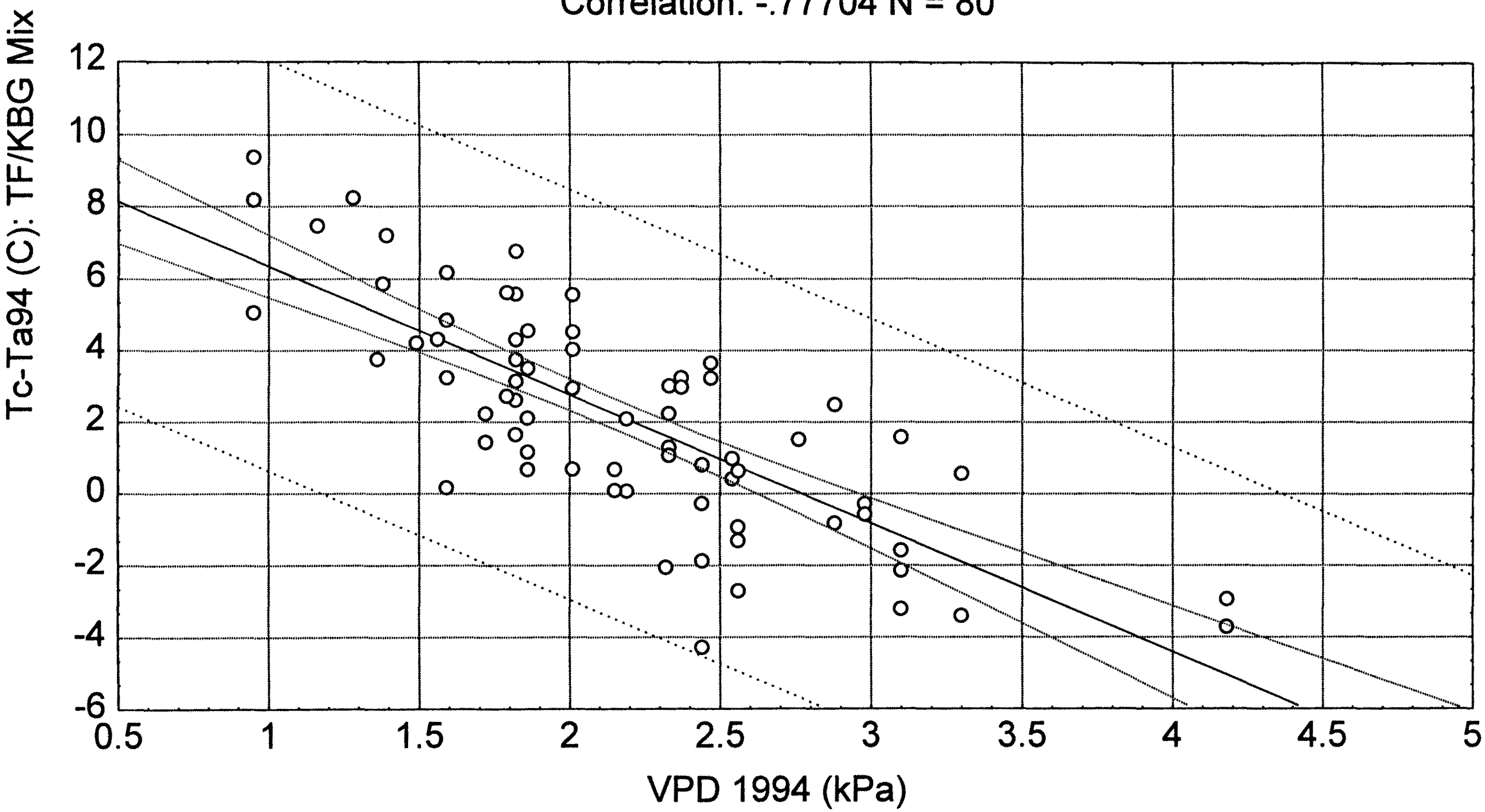
Table B.2: 1994 LSIS Application Amounts

DATE	ETo mm	ETkbg mm	IRR5 mm	IRR4 mm	IRR3 mm	IRR2 mm	IRR1 mm
TOTAL	493.5	394.8	140.48	233.93	296.69	327.44	369.07
DAILY AV.	5.88	4.70	1.67	2.78	3.53	3.90	4.39
ET%	100	80	35.60	59.22	75.18	82.91	93.48

APPENDIX C: CWSI NON-WATER-STRESSED BASELINES



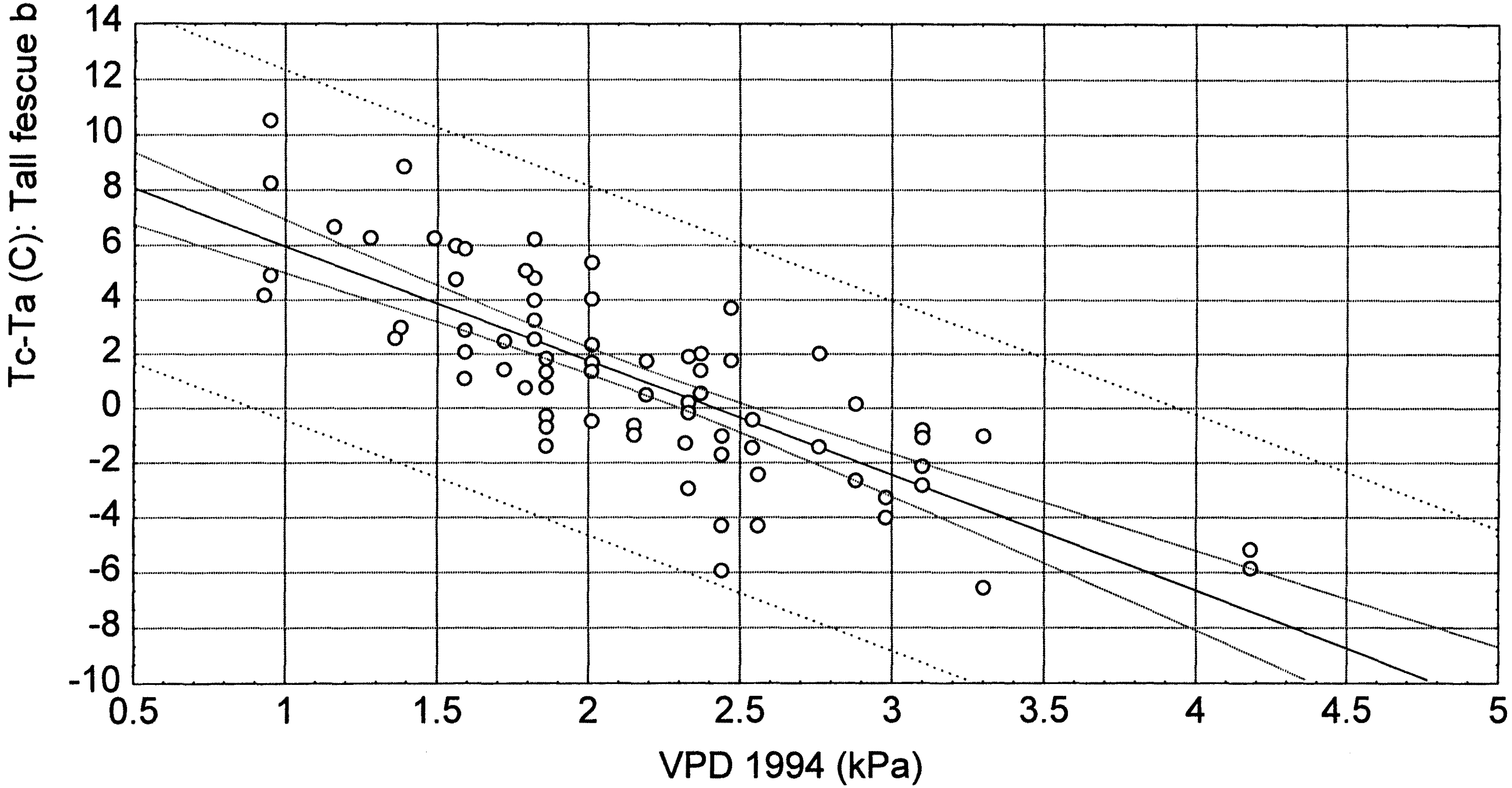
1994 KBG Baseline; Std. Err. of Est.: 1.932535
Regression Equation: Tc-Ta94 = 8.6623 + -2.519 * VPD94
Correlation: -.64973 N = 80



1994 TF/KBG Baseline; Std. Err. of Est.: 1.902973

Regression Equation: TC_TA94 = 9.9197 + -3.583 * VPD94

Correlation: -.77704 N = 80



1994 TF-Blend Baseline; Std. Err. of Est.: 2.132313
Regression Equation: Tc-Ta94 = 10.157 + -4.203 * VPD94
Correlation: -.79084 N = 80

APPENDIX D: WEATHER DATA

4-JAN-95

Northern Colorado Water Conservancy District
Irrigation Management Service

Weather station : Ft Collins, CO Cellular

Summary for : JUNE 1993

	Air temperature			Rel hum-idity	Ave vapor press	Ave dew-point	Prec-ipit-ation	Wind		Solar rad	ETReference	
	Max	Min	Ave					Max	Travel		Haise	Penmn
Day	F	F	F	%	m-bar	F	inch	mph	miles	Langly	inch	inch
1	82.1	50.7	67.5	48.2	9.440	43.1		17.8	160.3	588.3	0.28	0.29
2	66.8	45.1	57.3	75.9	12.060	49.5	0.40	16.4	165.6	345.0	0.13	0.16
3	63.6	41.0	50.5	78.9	9.780	44.0	0.48	18.0	161.5	370.0	0.13	0.17
4	57.2	40.7	48.5	76.2	8.880	41.5		9.6	107.4	313.6	0.10	0.13
5	72.1	45.3	58.2	78.5	12.790	51.1		9.4	79.0	562.8	0.23	0.18
6	68.4	49.8	59.6	80.5	13.990	53.6		20.4	132.2	380.1	0.15	0.13
7	63.3	45.6	54.3	50.6	6.960	35.3	0.29	23.9	204.0	516.5	0.19	0.25
8	65.4	48.8	57.7	46.9	7.610	37.5		22.5	267.5	505.6	0.20	0.28
9	68.3	44.1	56.8	64.7	9.730	43.9		13.4	71.2	607.5	0.23	0.21
10	75.4	42.3	61.2	55.2	9.150	42.3	0.01	10.5	85.1	769.0	0.31	0.27
11	82.4	48.6	64.1	56.0	10.530	45.9	0.01	21.0	112.5	594.3	0.28	0.26
12	87.6	45.5	66.2	49.3	9.510	43.3		17.3	142.5	615.2	0.29	0.32
13	75.3	47.4	62.0	32.5	5.780	30.6		16.0	145.3	767.0	0.33	0.35
14	83.4	44.1	66.0	52.1	10.690	46.3		13.0	119.2	750.0	0.34	0.32
15	87.5	55.4	68.8	58.0	12.540	50.6		11.6	86.9	425.3	0.22	0.23
16	80.5	51.0	66.0	57.8	11.900	49.2		21.6	165.3	613.2	0.29	0.29
17	56.1	49.9	53.9	90.7	12.830	51.2	0.69	13.4	136.2	100.6	0.04	0.07
18	59.9	48.5	53.3	80.6	11.140	47.4	0.02	17.5	97.7	343.3	0.12	0.14
19	76.7	47.9	61.6	70.7	12.480	50.5	0.02	10.2	85.1	737.0	0.32	0.25
20	84.6	48.7	66.5	56.7	11.060	47.2		10.2	79.0	760.0	0.36	0.29
21	82.0	49.2	67.1	58.7	12.350	50.2	0.01	20.5	125.0	627.5	0.29	0.27
22	93.1	48.3	68.2	55.1	11.550	48.4		16.7	114.3	657.4	0.34	0.33
23	77.7	51.9	63.9	48.5	9.870	44.2	0.01	28.8	190.6	584.4	0.27	0.31
24	77.8	44.8	60.8	32.7	5.630	30.0		19.8	176.6	775.0	0.33	0.39
25	77.8	39.4	60.1	52.0	8.370	39.9		10.8	100.7	765.0	0.31	0.32
26	87.7	45.4	67.9	49.7	10.280	45.3		10.0	92.7	774.0	0.37	0.33
27	90.6	50.5	69.5	47.5	10.510	45.9		22.2	110.4	566.5	0.29	0.30
28	91.3	50.2	71.2	46.7	11.020	47.1		10.3	104.8	696.8	0.36	0.33
29	93.4	53.6	75.2	40.2	10.310	45.4		18.8	123.3	747.0	0.41	0.38
30	77.9	54.2	66.4	58.2	12.490	50.5		12.2	93.7	614.2	0.29	0.27
Total							1.94		3835.6		7.80	7.82
Extr	93.4	39.4						28.8				
Avg	76.9	47.6	62.3	58.3	10.374	45.0			127.9	582.4	0.26	0.26

4-JAN-95

Northern Colorado Water Conservancy District
Irrigation Management Service

Weather station : Ft Collins, CO Cellular

Summary for : JULY 1993

	Air temperature			Rel humidity	Ave vapor press	Ave dew-point	Precipitation	Wind		Solar rad	ETReference	
	Max	Min	Ave					Max	Travel		Haise	Penmn
Day	F	F	F	%	m-bar	F	inch	mph	miles	Langly	inch	inch
1	87.0	56.1	70.1	60.8	13.930	53.4		13.9	89.4	590.3	0.31	0.27
2	88.5	50.0	70.7	59.1	14.330	54.2		17.1	138.7	735.0	0.37	0.34
3	84.8	51.5	65.3	46.5	9.310	42.7	0.03	38.2	222.1	390.0	0.19	0.34
4	72.3	44.8	60.8	41.8	7.460	37.0		20.1	163.2	533.8	0.21	0.29
5	76.5	46.5	61.7	45.4	8.030	38.9		17.7	143.0	640.1	0.27	0.31
6	83.2	43.7	65.3	43.2	8.450	40.2		14.0	146.4	629.7	0.28	0.33
7	83.4	42.1	64.5	55.6	11.130	47.4		14.3	128.3	715.0	0.31	0.31
8	82.9	54.3	67.1	63.1	13.750	53.1		19.6	108.4	471.3	0.23	0.23
9	79.5	54.1	65.8	66.0	13.960	53.5		14.4	123.8	418.9	0.20	0.21
10	90.7	47.3	69.6	56.9	12.260	50.0	0.04	21.0	161.9	590.8	0.30	0.34
11	70.8	52.8	59.4	84.2	14.520	54.6		9.7	99.0	190.9	0.08	0.12
12	86.0	50.1	66.0	66.2	13.470	52.5	0.02	23.6	109.8	497.8	0.24	0.25
13	75.7	53.7	63.0	75.5	14.590	54.7	0.60	15.8	134.0	428.6	0.20	0.20
14	75.0	55.2	62.1	87.7	16.700	58.4	0.10	11.4	134.0	225.1	0.10	0.12
15	87.0	58.3	69.0	74.6	17.570	59.9		12.6	82.0	680.0	0.36	0.26
16	87.4	52.1	68.5	72.2	16.460	58.0		11.4	85.0	510.8	0.26	0.23
17	68.5	58.4	62.3	82.3	15.770	56.8	0.03	11.9	135.7	259.6	0.12	0.13
18	87.7	58.0	71.1	60.1	14.160	53.9	0.03	17.7	100.4	730.0	0.39	0.31
19	79.7	57.2	67.8	68.6	15.650	56.6	0.05	15.9	139.4	656.2	0.32	0.27
20	78.1	58.8	66.1	72.5	15.830	56.9		17.0	123.2	350.8	0.17	0.18
21	85.1	49.7	66.9	63.8	13.590	52.8	0.04	31.5	115.7	638.4	0.31	0.29
22	82.4	50.3	67.2	60.4	12.980	51.5		14.7	128.6	684.8	0.32	0.30
23	75.7	50.8	64.6	64.4	13.240	52.1		13.8	131.8	444.7	0.20	0.21
24	77.6	54.3	65.0	59.7	11.990	49.4		13.4	105.6	446.8	0.21	0.22
25	83.5	44.9	66.1	57.2	11.790	48.9		10.0	92.2	697.3	0.32	0.28
26	86.7	51.5	68.6	58.0	13.180	51.9		20.2	165.5	714.0	0.36	0.33
27	80.1	45.8	65.4	50.1	9.980	44.5		10.2	101.6	721.0	0.32	0.30
28	86.4	46.7	67.9	53.5	11.710	48.7		9.3	96.7	715.0	0.34	0.30
29	91.4	53.9	74.2	54.0	14.250	54.1		10.6	112.4	696.2	0.37	0.31
30	91.5	57.7	72.6	55.9	14.680	54.9	0.06	17.5	99.6	502.8	0.28	0.25
31	94.8	55.3	76.9	43.3	12.110	49.6	0.01	13.5	115.9	647.0	0.36	0.33
Total							1.01		3833.3		8.30	8.16
Extr	94.8	42.1						38.2				
Avg	82.6	51.8	66.8	61.4	13.124	51.3			123.7	553.3	0.27	0.26

4-JAN-95

Northern Colorado Water Conservancy District
Irrigation Management Service

Weather station : Ft Collins, CO Cellular

Summary for : AUGUST 1993

	Air temperature			Rel humidity	Ave vapor press	Ave dew-point	Precipitation	Wind		Solar rad	ETReference	
	Max	Min	Ave					Max	Travel		Haise	Penmn
Day	F	F	F	%	m-bar	F	inch	mph	miles	Langly	inch	inch
1	78.3	58.7	69.2	57.6	13.730	53.0	0.02	12.8	131.9	620.4	0.31	0.28
2	75.8	49.7	63.1	64.0	12.370	50.2	0.16	19.6	164.4	593.8	0.26	0.27
3	67.9	52.1	59.6	71.8	12.350	50.2	0.01	10.4	83.5	400.3	0.17	0.17
4	76.3	46.2	59.3	77.2	13.100	51.8	0.03	17.4	99.8	408.5	0.17	0.18
5	78.2	47.1	59.2	78.9	13.190	51.9	0.26	12.6	105.1	370.2	0.16	0.17
6	78.1	47.1	61.8	69.9	12.610	50.7	0.01	9.3	88.2	571.1	0.25	0.21
7	85.3	46.5	65.6	60.9	12.100	49.6	0.01	15.5	93.5	531.6	0.25	0.23
8	89.2	51.2	69.0	59.3	13.080	51.7	0.06	24.7	115.8	530.2	0.27	0.25
9	90.1	49.8	72.2	52.6	13.030	51.6		12.0	99.5	604.0	0.31	0.27
10	85.6	57.6	67.7	66.8	15.060	55.6	0.08	17.5	137.6	321.9	0.17	0.20
11	85.5	51.8	66.8	71.7	15.350	56.1	0.01	9.5	92.4	569.4	0.28	0.24
12	74.7	52.8	65.1	71.0	14.910	55.3	0.01	13.9	122.9	511.5	0.23	0.21
13	79.4	54.5	67.0	73.6	16.380	57.9		11.6	88.6	416.6	0.20	0.17
14	83.0	54.7	67.2	59.3	12.710	50.9		14.3	105.5	348.0	0.17	0.19
15	82.2	50.8	64.4	69.2	14.060	53.7	0.10	29.6	117.1	585.9	0.28	0.24
16	88.1	46.9	67.5	60.1	12.420	50.3	0.02	15.1	129.9	665.1	0.32	0.30
17	87.1	50.0	69.3	55.8	12.460	50.4		10.8	105.3	562.0	0.28	0.25
18	81.3	59.9	69.4	62.7	15.080	55.6	0.05	18.2	164.2	526.4	0.27	0.25
19	80.7	53.0	65.0	75.1	15.600	56.5		20.7	117.8	460.9	0.22	0.20
20	80.6	57.5	67.3	73.8	16.530	58.1		18.4	120.5	483.8	0.24	0.20
21	81.5	53.5	65.4	71.7	14.910	55.3	0.01	21.7	103.6	408.9	0.20	0.19
22	80.9	51.2	65.3	60.2	11.790	48.9		10.2	87.3	517.3	0.24	0.22
23	80.6	46.1	64.2	59.3	11.530	48.3		10.9	102.3	633.8	0.28	0.25
24	89.5	45.4	70.1	47.1	10.330	45.4		14.0	121.5	644.6	0.31	0.30
25	85.6	53.8	68.9	54.9	12.630	50.8	0.02	20.4	187.5	541.9	0.27	0.29
26	74.9	50.2	63.1	67.5	13.110	51.8		14.6	126.2	280.9	0.12	0.15
27	66.6	49.4	58.6	75.6	12.660	50.8		11.1	110.8	258.8	0.10	0.12
28	81.6	48.4	63.1	63.6	11.610	48.5		11.7	104.3	506.1	0.23	0.21
29	83.0	48.4	64.9	55.4	10.880	46.8	0.05	23.6	167.2	406.9	0.19	0.24
30	61.4	41.6	51.3	66.9	8.490	40.3		20.5	139.6	248.9	0.08	0.14
31	73.5	39.3	56.5	65.7	9.950	44.4		11.9	89.5	553.9	0.21	0.19
Total							0.91		3623.3		7.04	6.78
Extr	90.1	39.3						29.6				
Avg	80.2	50.5	64.7	65.1	13.033	51.4			116.9	486.6	0.23	0.22

4-JAN-95

Northern Colorado Water Conservancy District
Irrigation Management Service

Weather station : Ft Collins, CO Cellular

Summary for : SEPTEMBER 1993

	Air temperature			Rel humidity	Ave vapor press	Ave dew point	Precipitation	Wind		Solar rad	ETReference	
	Max	Min	Ave					Max	Travel		Haise	Penmn
Day	F	F	F	%	m-bar	F	inch	mph	miles	Langly	inch	inch
1	81.8	43.7	63.7	52.0	9.640	43.6		17.6	121.5	426.9	0.19	0.20
2	65.4	41.0	55.3	66.2	9.710	43.8	0.05	22.1	161.8	286.8	0.10	0.14
3	80.5	35.2	57.5	58.2	8.520	40.4		9.9	99.6	606.4	0.24	0.23
4	81.0	43.1	63.5	47.6	9.120	42.2	0.07	27.0	127.9	528.2	0.23	0.23
5	62.2	51.4	55.1	82.0	12.160	49.8	0.02	15.4	121.5	262.9	0.10	0.10
6	70.9	52.2	59.4	80.1	13.680	52.9	0.07	12.3	107.2	432.5	0.19	0.14
7	70.5	47.8	56.0	85.7	13.020	51.6	0.36	24.3	85.1	278.7	0.11	0.11
8	75.4	41.2	58.3	70.2	10.970	47.0	0.02	10.5	89.1	570.8	0.23	0.19
9	74.3	44.2	61.2	54.5	9.560	43.4	0.05	23.2	147.8	484.9	0.20	0.21
10	76.2	43.6	58.7	65.4	10.610	46.1		10.8	97.3	546.4	0.23	0.19
11	86.4	44.1	66.9	41.9	8.000	38.8		15.1	118.3	566.1	0.26	0.25
12	88.1	44.5	63.9	47.8	8.440	40.2	0.02	32.4	245.9	419.2	0.20	0.33
13	44.7	31.3	37.6	79.1	6.020	31.6	0.87	25.4	204.8	159.8	0.03	0.11
14	63.6	27.2	44.0	68.3	6.420	33.2		12.5	92.0	554.6	0.15	0.17
15	75.8	32.0	53.4	60.3	7.600	37.5		11.1	107.2	551.2	0.20	0.19
16	66.1	44.5	55.4	55.7	8.160	39.3	0.04	17.8	153.9	451.0	0.17	0.15
17	64.0	48.2	52.9	78.0	10.560	46.0	0.12	21.2	126.1	344.6	0.13	0.12
18	52.9	41.8	48.2	89.2	10.260	45.2	0.91	13.2	105.6	91.9	0.03	0.05
19	67.5	36.3	51.5	68.0	8.260	39.6	0.04	20.7	126.7	466.2	0.16	0.16
20	72.6	36.7	54.1	61.6	8.020	38.9		12.0	116.4	532.9	0.19	0.18
21	83.1	37.8	60.2	55.4	8.570	40.6		16.9	119.6	529.4	0.22	0.20
22	53.8	45.7	49.9	79.1	9.670	43.7		13.8	112.2	111.9	0.04	0.06
23	55.2	45.8	50.9	77.1	9.780	44.0		11.3	133.3	131.7	0.04	0.07
24	66.6	38.9	52.0	72.4	9.390	42.9	0.01	24.8	154.2	461.4	0.16	0.16
25	73.5	35.3	54.2	52.5	6.620	34.0		27.7	163.3	420.8	0.15	0.19
26	67.6	38.5	52.3	58.0	7.300	36.5		17.1	160.0	495.5	0.17	0.18
27	81.5	35.1	55.6	55.8	7.380	36.7		8.6	95.1	498.0	0.20	0.18
28	65.9	38.5	51.7	60.7	7.660	37.7		10.2	97.1	465.0	0.16	0.15
29	73.1	35.3	53.1	63.0	8.100	39.1		9.9	93.8	476.6	0.17	0.16
30	84.0	35.8	61.0	41.0	5.890	31.1		21.5	179.8	463.8	0.19	0.26
Total							2.65		3864.1		4.84	5.06
Extr	88.1	27.2						32.4				
Avg	70.8	40.6	55.3	64.2	8.970	41.2			128.8	420.5	0.16	0.17

4-JAN-95

Northern Colorado Water Conservancy District
Irrigation Management Service

Weather station : Ft Collins, CO Cellular

Summary for : JUNE 1994

	Air temperature			Rel humidity	Ave vapor press	Ave dew-point	Precipitation	Wind		Solar rad	ETReference	
	Max	Min	Ave					Max	Travel		Haise	Penmn
Day	F	F	F	%	m-bar	F	inch	mph	miles	Langly	inch	inch
1	79.1	51.6	65.5	65.6	13.490	52.6	0.02	18.3	83.1	624.6	0.29	0.24
2	77.2	51.7	64.7	64.5	13.020	51.6	0.04	28.1	145.0	605.7	0.28	0.26
3	80.5	55.1	66.5	71.2	15.430	56.2		19.6	104.5	551.0	0.27	0.22
4	87.0	54.5	69.6	54.2	11.950	49.3		24.8	119.7	586.5	0.30	0.28
5	86.4	50.0	70.4	43.3	10.050	44.7		20.0	141.1	742.0	0.37	0.35
6	89.6	51.6	70.5	47.8	10.920	46.9	0.01	25.9	116.4	669.3	0.34	0.33
7	89.9	48.6	70.8	34.1	7.480	37.1	0.12	23.2	151.1	685.4	0.34	0.38
8	79.9	48.9	64.5	46.9	9.390	42.9	0.03	29.1	127.5	708.0	0.32	0.32
9	72.5	39.4	58.0	47.3	7.240	36.3		20.5	115.9	654.6	0.25	0.29
10	79.5	45.2	64.0	36.4	6.800	34.7		15.9	129.5	748.0	0.33	0.33
11	87.3	47.5	67.9	42.3	9.280	42.6		18.3	143.3	683.9	0.33	0.33
12	92.0	49.2	70.8	45.5	9.880	44.3	0.03	31.3	137.1	490.5	0.25	0.31
13	91.0	50.1	74.5	34.2	8.260	39.6		25.2	150.1	458.1	0.24	0.33
14	95.0	56.9	80.6	18.4	6.040	31.7		43.4	251.8	506.0	0.29	0.46
15	83.0	45.1	65.3	50.9	10.700	46.3		26.5	167.5	700.0	0.32	0.35
16	78.8	55.0	64.6	63.7	13.000	51.6	0.01	23.7	158.7	557.5	0.27	0.27
17	82.6	55.7	68.3	68.6	15.780	56.9		20.2	130.8	542.7	0.27	0.25
18	79.1	64.6	69.3	73.1	17.750	60.1		15.3	106.3	273.5	0.14	0.15
19	87.3	52.8	68.9	60.1	13.980	53.5		23.7	133.8	457.2	0.23	0.27
20	84.9	56.5	65.3	74.7	15.530	56.4	0.93	32.6	135.9	290.2	0.15	0.20
21	75.4	59.6	66.0	79.6	17.240	59.3	0.02	21.9	89.9	421.6	0.20	0.18
22	77.3	57.2	65.0	72.5	15.050	55.6	0.14	26.6	129.7	356.8	0.17	0.19
23	84.4	49.8	66.2	64.6	13.440	52.5	0.01	26.8	119.5	669.9	0.32	0.30
24	91.8	50.5	71.2	53.4	12.090	49.6		18.7	121.4	751.0	0.39	0.36
25	89.8	51.9	72.3	42.6	10.390	45.6		21.7	141.2	745.0	0.39	0.37
26	97.8	50.1	73.6	48.6	12.480	50.5		17.2	100.6	758.0	0.41	0.37
27	86.7	58.9	74.1	29.9	8.620	40.7		18.2	154.9	752.0	0.40	0.39
28	83.5	46.8	68.0	42.7	9.700	43.8		14.7	101.9	624.3	0.29	0.31
29	92.3	49.1	70.0	47.9	10.930	46.9	0.02	33.7	143.8	450.3	0.23	0.33
30	96.2	48.6	74.3	43.6	10.150	45.0		31.0	131.4	727.0	0.39	0.40
Total							1.38		3983.4		8.77	9.12
Extr	97.8	39.4						43.4				
Avg	85.3	51.8	68.7	52.3	11.535	47.5			132.8	593.0	0.29	0.30

4-JAN-95

Northern Colorado Water Conservancy District
Irrigation Management Service

Weather station : Ft Collins, CO Cellular

Summary for : JULY 1994

	Air temperature			Rel humidity	Ave vapor press	Ave dew-point	Precipitation	Wind		Solar	ETReference	
	Max	Min	Ave					Max	Travel	rad	Haise	Penmn
Day	F	F	F	%	m-bar	F	inch	mph	miles	Langly	inch	inch
1	91.1	54.5	75.5	42.1	12.000	49.4		28.9	120.7	603.6	0.32	0.32
2	84.8	54.4	67.0	67.5	14.880	55.2		21.8	104.2	377.7	0.19	0.22
3	82.2	51.8	65.5	66.0	13.650	52.9	0.12	33.5	141.7	532.8	0.26	0.27
4	87.7	55.8	70.4	57.5	13.580	52.7		20.7	81.5	733.0	0.39	0.31
5	85.0	52.2	70.2	49.5	11.880	49.1		15.0	131.5	682.6	0.34	0.32
6	89.1	54.2	70.4	51.9	12.250	50.0	0.01	36.5	169.1	503.0	0.26	0.32
7	69.8	45.6	58.6	46.9	7.790	38.1	0.01	26.1	207.2	446.7	0.18	0.29
8	78.8	41.6	61.4	60.0	10.410	45.6		16.8	108.8	703.0	0.29	0.29
9	87.1	48.6	68.8	53.4	11.920	49.2		14.8	102.4	729.0	0.36	0.31
10	91.5	48.7	70.9	51.3	11.470	48.2		32.7	104.7	571.0	0.29	0.29
11	80.9	53.9	70.4	50.0	12.370	50.2	0.06	28.2	146.8	458.3	0.22	0.25
12	89.6	51.5	68.9	55.9	12.040	49.5	0.02	23.0	104.4	602.7	0.31	0.30
13	76.7	49.3	64.6	62.9	12.710	50.9	0.01	22.8	147.0	674.4	0.30	0.28
14	76.0	55.2	63.1	74.1	14.330	54.2	0.08	17.5	96.9	478.8	0.22	0.21
15	73.7	51.1	62.6	74.1	14.010	53.6	0.04	27.3	121.6	315.4	0.14	0.16
16	80.3	50.2	63.6	75.6	15.000	55.5	0.20	34.8	123.9	479.2	0.22	0.21
17	82.9	49.7	64.6	73.9	15.010	55.5		17.5	88.0	619.7	0.29	0.24
18	90.1	52.9	70.5	59.9	14.010	53.6	0.03	33.2	86.0	491.0	0.26	0.24
19	81.3	55.7	69.6	53.8	12.930	51.4		25.4	164.0	623.6	0.31	0.30
20	72.3	55.4	63.2	68.8	13.490	52.6		21.3	97.5	464.9	0.21	0.20
21	81.1	47.9	65.6	59.0	11.840	49.0		13.7	89.5	717.0	0.33	0.29
22	89.0	48.4	70.3	53.0	12.290	50.0		15.3	115.6	709.0	0.35	0.32
23	86.1	52.8	68.6	63.8	14.630	54.8	0.23	21.9	104.9	444.9	0.22	0.22
24	88.1	53.2	67.9	74.7	16.910	58.8	0.02	21.4	97.5	450.1	0.23	0.22
25	86.2	55.7	69.2	70.5	16.630	58.3	0.14	29.1	109.8	527.0	0.27	0.24
26	75.9	56.6	64.0	76.8	15.460	56.3	0.01	27.8	73.9	529.5	0.25	0.20
27	82.7	51.7	67.2	68.9	14.950	55.4		15.2	90.8	675.4	0.33	0.26
28	86.6	50.6	67.5	65.0	14.120	53.8		25.1	91.7	552.0	0.27	0.25
29	84.5	54.8	69.9	60.5	14.110	53.8		21.3	126.6	643.6	0.33	0.28
30	88.5	50.4	70.4	57.7	13.570	52.7		15.9	93.8	614.6	0.31	0.27
31	85.7	53.6	68.1	65.1	14.840	55.2		21.6	119.2	277.3	0.14	0.19
Total							0.98		3561.2		8.39	8.07
Extr	91.5	41.6						36.5				
Avg	83.4	51.9	67.4	61.6	13.390	52.1			114.9	555.8	0.27	0.26

4-JAN-95

Northern Colorado Water Conservancy District
Irrigation Management Service

Weather station : Ft Collins, CO Cellular

Summary for : AUGUST   1994

	Air temperature			Rel humidity	Ave vapor press	Ave dew-point	Precipitation	Wind		Solar rad	ETReference	
	Max	Min	Ave					Max	Travel		Haise	Penmn
Day	F	F	F	%	m-bar	F	inch	mph	miles	Langly	inch	inch
1	85.9	55.1	66.8	71.7	15.300	56.0	0.01	30.7	118.0	461.9	0.24	0.24
2	81.0	53.5	67.0	70.5	15.420	56.2		17.5	108.3	501.4	0.24	0.22
3	85.1	55.0	68.0	67.3	14.940	55.4	0.16	32.9	120.0	542.4	0.28	0.25
4	82.3	52.7	67.5	68.5	15.200	55.8		14.4	97.4	554.3	0.27	0.23
5	87.1	54.8	69.0	64.0	14.860	55.2	0.01	19.4	134.4	464.7	0.24	0.25
6	94.9	55.4	74.4	50.7	13.260	52.1		17.8	118.1	551.6	0.31	0.29
7	92.4	52.8	73.3	47.4	12.470	50.4		18.2	133.4	453.5	0.24	0.29
8	85.1	54.9	69.4	64.4	15.340	56.1		14.6	100.6	516.1	0.26	0.24
9	84.5	60.0	71.9	61.8	15.800	56.9		12.3	87.1	370.8	0.20	0.19
10	90.0	59.1	74.6	53.4	14.860	55.2	0.31	21.5	149.3	601.4	0.33	0.30
11	81.0	60.9	69.7	73.9	18.110	60.7	0.11	18.2	115.3	482.2	0.25	0.21
12	85.2	55.2	70.4	67.6	16.530	58.1	0.02	22.5	121.9	406.9	0.21	0.21
13	82.9	57.8	66.2	78.3	16.780	58.6	0.35	36.2	103.9	345.0	0.18	0.18
14	80.0	51.7	65.8	73.2	15.280	56.0	0.01	13.9	80.5	637.4	0.30	0.24
15	82.9	51.4	67.4	65.0	13.890	53.4		11.5	79.4	622.7	0.30	0.24
16	90.5	51.2	69.3	61.4	13.870	53.3	0.09	44.9	97.6	489.6	0.25	0.23
17	86.4	53.2	69.5	59.6	13.840	53.3		13.7	83.1	618.2	0.31	0.25
18	87.9	54.4	68.9	61.3	13.600	52.8		15.3	100.5	320.3	0.17	0.19
19	75.6	52.6	63.1	68.1	13.080	51.7		15.5	97.8	328.4	0.15	0.17
20	79.7	49.0	63.5	70.2	13.510	52.6		12.2	82.8	548.8	0.25	0.21
21	83.8	50.3	66.5	63.2	13.400	52.4		15.3	102.9	441.7	0.21	0.21
22	90.8	49.5	68.8	60.7	13.540	52.7	0.03	24.0	112.4	510.7	0.26	0.24
23	86.0	51.2	68.7	55.8	12.310	50.1		18.0	119.0	597.3	0.30	0.26
24	92.7	49.4	69.4	55.9	12.760	51.1	0.03	18.8	96.6	462.2	0.24	0.23
25	89.9	52.1	71.2	53.2	12.760	51.1		14.2	78.9	414.1	0.21	0.21
26	90.5	49.3	70.4	54.1	12.730	51.0		17.0	109.6	592.9	0.30	0.27
27	91.9	50.9	72.3	48.8	12.020	49.4		38.5	137.7	433.0	0.23	0.26
28	72.5	55.1	62.8	75.0	14.440	54.4		16.5	79.7	241.0	0.11	0.12
29	82.3	48.0	63.9	70.0	13.790	53.2	0.10	29.4	93.7	412.8	0.19	0.19
30	76.7	46.5	64.3	56.0	11.110	47.3	0.02	19.3	111.1	506.4	0.22	0.21
31	65.2	54.5	58.0	81.9	13.420	52.4	0.03	23.7	201.7	183.1	0.08	0.11
Total							1.28		3372.7		7.33	6.94
Extr	94.9	46.5						44.9				
Avg	84.6	53.1	68.1	63.6	14.136	53.7			108.8	471.4	0.24	0.22

4-JAN-95

Northern Colorado Water Conservancy District
Irrigation Management Service

Weather station : Ft Collins, CO Cellular

Summary for : SEPTEMBER 1994

	Air temperature			Rel humidity	Ave vapor press	Ave dew-point	Precipitation	Wind		Solar rad	ETReference	
	Max	Min	Ave					Max	Travel		Haise	Penmn
Day	F	F	F	%	m-bar	F	inch	mph	miles	Langly	inch	inch
1	70.5	51.3	59.5	77.6	13.290	52.2		13.7	91.6	314.7	0.13	0.12
2	79.0	51.7	63.2	71.6	13.670	52.9	0.02	14.3	88.9	491.3	0.23	0.17
3	77.9	50.0	63.4	71.5	13.950	53.5	0.01	19.7	72.3	236.3	0.11	0.11
4	86.1	46.3	66.3	48.9	9.310	42.7	0.01	25.2	128.3	523.0	0.25	0.25
5	73.6	49.8	62.0	51.7	9.860	44.2	0.03	29.1	141.7	522.0	0.22	0.22
6	84.8	43.0	61.6	56.2	9.790	44.0		13.7	98.7	514.4	0.23	0.22
7	83.4	49.5	65.7	45.7	9.320	42.7		16.4	112.6	503.2	0.24	0.22
8	87.6	41.9	63.7	52.6	9.150	42.3		13.1	90.0	536.1	0.25	0.23
9	84.3	43.4	63.8	53.3	10.100	44.8		26.0	99.4	426.3	0.19	0.20
10	88.2	48.5	65.3	53.7	10.210	45.1		17.2	89.3	421.6	0.21	0.19
11	84.9	50.4	66.1	46.3	9.840	44.1		22.4	116.4	381.4	0.19	0.20
12	87.3	49.5	68.4	51.4	11.300	47.8		14.7	86.4	499.5	0.25	0.21
13	81.8	54.3	66.5	59.6	12.600	50.7	0.14	30.8	139.3	415.4	0.20	0.20
14	74.5	50.4	60.4	60.0	10.150	45.0	0.04	28.6	131.9	299.3	0.13	0.17
15	69.9	40.0	57.1	49.4	7.530	37.2		31.3	178.4	477.4	0.18	0.23
16	72.5	36.9	54.8	59.0	8.120	39.2		12.6	84.4	511.8	0.19	0.18
17	78.0	40.3	57.2	56.0	8.420	40.1		16.1	102.2	466.4	0.19	0.18
18	81.0	38.5	61.2	46.6	7.750	38.0		27.6	104.0	386.2	0.16	0.17
19	73.3	42.5	58.3	55.9	9.120	42.2		22.6	105.9	171.7	0.07	0.11
20	76.3	42.0	58.5	57.1	9.050	42.0		24.3	80.1	403.7	0.16	0.15
21	61.3	31.4	46.3	70.4	7.540	37.3	0.16	32.5	189.4	177.6	0.05	0.13
22	67.4	26.9	46.5	51.7	4.870	26.5	0.01	30.0	164.6	504.3	0.15	0.22
23	75.7	37.8	57.1	43.4	6.100	32.0		32.3	222.0	506.3	0.19	0.26
24	77.6	33.4	54.6	48.8	6.010	31.6		19.0	124.2	503.4	0.19	0.20
25	77.3	37.7	56.5	45.6	6.480	33.5		13.7	106.9	492.0	0.19	0.18
26	84.0	34.2	58.6	40.2	5.220	28.1		26.3	174.6	480.5	0.19	0.27
27	82.7	37.5	58.2	36.6	5.320	28.6		16.3	116.4	455.9	0.19	0.21
28	89.1	35.8	60.8	36.5	5.710	30.3		15.6	120.3	468.1	0.20	0.23
29	87.3	38.9	64.6	32.4	6.370	33.0		27.5	135.7	345.7	0.15	0.22
30	77.7	51.8	62.9	50.9	9.660	43.7		28.5	103.8	221.5	0.10	0.12
Total							0.42		3599.7		5.38	5.77
Extr	89.1	26.9						32.5				
Avg	79.2	42.9	60.3	52.7	8.860	40.5			120.0	421.9	0.18	0.19