COMPARATIVE EVAPOTRANSPIRATION RATES OF THIRTEEN TURFGRASSES GROWN UNDER BOTH NON-LIMITING SOIL MOISTURE AND PROGRESSIVE WATER STRESS CONDITIONS

KIM

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A Thesis

by

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ABSTRACT

Comparative Evapotranspiration Rates of Thirteen
Turfgrasses Grown Under Both Non-limiting
Soil Moisture and Progressive Water Stress Conditions
(May 1983)

Ki Sun Kim, B.S., Seoul National University, Korea
Chairman of Advisory Committee: Dr. James B. Beard

The evapotranspiration (ET) rates of twelve C-4 warm season turfgrasses and one C-3 cool season turfgrass were evaluated in mini-lysimeters utilizing the water balance method. The turf plots were constructed to insure a natural environment surrounding each mini-lysimeter. ET rates of each species were measured under both non-limiting soil moisture and progressive water stress conditions. During the uniform cultural practices study, the grasses were mowed at a 3.8 cm cutting height and fertilized with 0.25 kg N are^{-1} growing month^{-1} , while for the optimum cultural practices study the cutting height and nitrogen fertilization rate selected were based on the specific optimums for each species.

Significant differences in ET rates were observed at both the interspecies and intraspecies levels. Emerald zoysiagrass, buffalograss, Tifgreen bermudagrass, and centipedegrass had low ET rates; while tall fescue, St.Augustinegrass, bahiagrass, and Adalayd sand knotgrass were characterized as having high ET rates. Common bermudagrass, Tifway bermudagrass, Meyer zoysiagrass, and blue grama possessed intermediate ET rates. The ranking among grasses in terms of their ET rates did not show large relative changes between the uniform and optimum cultural practices and between the different soil moisture regimes, except for bahiagrass which had a low ET rate under progressive water stress conditions in contrast to a high ET rate under the non-limiting soil moisture conditions.

All grass species exhibited higher ET rates when maintained at their optimum nitrogen fertility and cutting height which was attributed to a rapid vertical leaf extension rates. Those grass species possessing a slow vertical leaf extension rate, high shoot density, low leaf area, and prostrate growing habit tended to have low ET rates.

DEDICATION

To my parents without whose support
I could never have made what I am.

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

INTRODUCTION

A properly functioning turfgrass community requires water for survival and growth. Typically the turfgrass plant has a water content in the range of 75 to 85% by weight (1). A 10% reduction in water content from 75 to 65% within a short time frame may be lethal to the grass plant.

As much as 50% of the water used in large urban areas during the summer season is for irrigation of lawns and shrubs. In 1978, 2.3 billion m^3 of water was used by municipalities and rural communities of Texas (46). This amount is expected to double by the year 2000.

Water was readily available at a low cost, in the past, therefore little attention was paid to water conservation strategies. Water cost have increased substantially and now water availability also is becoming a major factor in growing turfgrass, especially in warm semi-arid climatic regions of the southern United States (8).

Water use rate (WUR) is defined as the total amount of water required for plant growth plus the quantity lost by transpiration and evaporation from soil and plant surfaces, respectively (1). The general range reported for the WUR's of most turfgrasses is 2 to 6 mm/day (0.1 to 0.3 inch/day), with over 10 mm/day (0.45

The style and format for this thesis are those followed by the *Agronomy Journal*.

inch/day) occurring occasionally (1).

Evapotranspiration (ET) is the combined process by which water is transferred from the earth's surface to the atmosphere. It includes evaporation of liquid or solid water from soil and plant surfaces plus transpiration of liquid water through plant tissues expressed as the latent heat transfer per unit area or its equivalent depth of water per unit area (6).

During the past two decades, a few studies have involved the characterization of ET rates of turfgrasses. The mechanism that controls how much water turfgrasses use is very complicated, because it is influenced by many factors. It varies according to the species or cultivar involved and can be strongly influenced by both environmental and cultural factors.

Some experiments have been conducted to determine the ET rate responses under specific turfgrass cultural practices, including different cutting heights, nitrogen fertility levels, and irrigation frequencies. Certain chemicals, such as antitranspirants (44) and growth inhibitors (21) also have been shown to reduce ET from turfs.

A major goal of turfgrass culture is the maintenance of quality turf at low cost, and the least possible resource inputs, including water. The most basic, long term approach to reduce ET rates of turfgrasses is to use turfgrass species and cultivars with the lowest possible ET rates. The ET rate characterization of the commonly used turfgrass species is required to utilize this approach.

The objectives of this study were:

1. to compare the ET rates of thirteen major turfgrasses commonly grown in warm climatic regions,
2. to characterize the ET rates of thirteen turfgrasses under non-limiting soil moisture and progressive water stress conditions,
3. to characterize the ET rates of turfgrasses under uniform and optimum cultural regimes, and
4. to demonstrate the relationship of certain environmental factors to the ET rates of turfgrasses.

LITERATURE REVIEW

Water use rate (WUR) is defined as the total amount of water required for turfgrass growth plus the quantity lost by transpiration and evaporation from plant surfaces and soil (1). The practitioners typically express WUR as inches per week (inch/week), while researchers express it as millimeters per day (mm/day). Another comparable term occasionally used is consumptive water use. However, WUR is preferred as it is more descriptive and permits easy information transfer between the scientist and practitioners in the field. Another term frequently used in crop and horticultural literature that is confused with WUR is water use efficiency, which is refers to the dry matter produced per unit water use (3), and thus is distinctly different from WUR.

The term evapotranspiration (ET) rate combines the evaporative processes which occur from the soil and transpiration from the plants growing thereon. ET rate is commonly expressed quantitatively as milligrams per square meter per second (mg m^{-2} sec^{-1}) or as millimeters per day (mm/day). The term ET rate is preferred to WUR in scientific literature, because ET rate is the process actually being quantitatively measured in most studies (14,16,22,29,31,47, 48). WUR is only slightly greater than ET rate in absolute terms, because the plants use a negligible amount of water in metabolic activities. The differentials has no practical effect on relative comparisons of water use among turfgrass species or cultivars.

Genetic Diversity In ET Rates

There have been a few ET studies conducted on grasses during the past 20 years. Most of these studies were concerned with forage crops and therefore the experiments were conducted in terms of the amount of water used per unit of dry matter produced (4,7, 29). In the case of turfgrasses, the functional survival of the grass plant is the important criterion rather than yield. Only a limited number of references are available concerning ET rate studies on turfgrasses (2,4,14,15,16,22,23,27,28,29,31,32,35,41,47,51). The general range reported for ET rates of most turfgrass is 2 to 6 mm (0.1 to 0.3 inch) per day (1,14,16,18,19,45,48). Even fewer studies involved interspecies comparisons (4,15,27,28,51).

Kneebone and Pepper (26,27) reported that tall fescue (*Festuca arundinacea* Schreb.) and St.Augustinegrass (*Stenotaphrum secundatum* (Walt) Kuntze) had high ET rates, whereas bermudagrass (*Cynodon dactylon* L. Pers.) and zoysiagrass (*Zoysia japonica* Steud) had relatively lower ET rates. Youngner et al. (51) assessed the ET rates of tall fescue, Kentucky bluegrass (*Poa pratensis* L.), bermudagrass, and St.Augustinegrass, and concluded that cool season grasses required more water than warm season grasses.

A more extensive comparative ET rate study was conducted by Biran et al. (4). They used two bermudagrasses, two St.Augustinegrasses, two zoysiagrasses, kikuyugrass (*Pennisetum clandestinum* Hochst.), sand knotgrass (*Paspalum vaginatum* Sw.), centipedegrass (*Eremochloa ophiuroides* (Munro.) Hack.), tall fescue, and perennial ryegrass (*Lolium perenne* L.). They concluded that C-3 photosynthetic pathway grasses, which are cool season grasses, used 45% more water than C-4 photosynthetic pathway grasses, which are warm season grasses. This conclusion is questionable as only two C-3 grasses versus nine C-4 grasses were compared. Among C-4 grasses, they concluded that the sparse, tall growing grasses had high ET rates and the dense, low growing grasses had low ET rates.

ET rate differences also have been reported within species. Biran et al. (4) found significant ET rate differences between 'Suwannee' bermudagrass and 'Santa Ana' bermudagrass, between a common species of St.Augustinegrass and a dwarf cultivar of St.Augustinegrass, and between *Zoysia matrella* and Emerald zoysiagrass (*Zoysia japonica* Steud x *Z. tenuifolia* Willd. ex Trin.).

Beard and coworkers (2) and Shearman (41) also reported intraspecies differentials in ET rates among 17 Kentucky bluegrass and 20 Kentucky bluegrass cultivars, repectively. Comparative rankings of those cultivars in terms of ET rates were also established.

Cultural Practices Influencing ET Rates

It has been shown that as cutting height is increased, the amount of water lost from grasses also is greater (4,15,22,23,32,40). Shearman and Beard (40,42) showed that increasing the cutting height of 'Penncross' creeping bentgrass (*Agrostis palustris* Huds.) from 0.7 to 2.5 cm resulted in a 53% greater ET rate and from 2.5 to 12.5 cm resulted in a doubling of the ET rate. They proposed that the leaf area exposed to desiccating conditions is greater at the higher cutting height, and in addition, a higher of cut encourage more extensive, deeper rooting.

Johns and Beard (22) found that increased ET rates are associated with an increased leaf area index, resulting from an increased total leaf area from which water could transpire.

Biran et al. (4) noted that the change in cutting height from 3 to 6 cm resulted in a permanent increase in water consumption and growth of cool season grasses; while increasing the cutting height of warm season grasses only resulted in a temporary increase in water use with no significant differences observed after 6 weeks. They attributed this change to a shift in the leaf area index over the long term. Raising the cutting height probably caused only a temporary increase in the leaf area index of the C-4 grasses, while in the case of C-3 grasses the leaf area index remained stable.

Most studies concerning the effects of nitrogen fertilization on the ET rate of plants were associated with dry matter measurements. Therefore only a few references can be cited for turfgrasses. It has been shown that nitrogen fertilization increases the total water use of turfgrasses (1,7,27,29,35). However, Shearman and Beard (40,42) reported that high nitrogen fertility decreased the percent moisture lost from 'Penncross' creeping bentgrass. He explained that it was due to decreased stomatal density caused by the increased nitrogen fertility.

Environmental Factors Influencing ET Rates

Water use by turfgrass is a dynamic system involving interactions among the soil, the turfgrass plant, and the surrounding atmosphere (31).

Chang (10) stated that the rate of potential ET depended upon evaporative power of the air as determined by temperature, wind, humidity, and radiation with radiation being the dominant factor. Only recently have research workers begun to realize that the relationship between ET rate and soil moisture tension depends upon a number of factors, such as soil texture, moisture tension characteristics, hydraulic conductivity of the soil, rooting depth, shoot density, and atmospheric conditions. The most important factor probably is the evaporative power of the atmosphere.

Slatyer (43) classified the factors which influence ET in 3 inter-dependent groups. The first of these is the availability of energy at evaporating surface, to supply the latent heat demand. Possible sources are radiation from the sun, sky, and clouds and sensible heat transfer from the adjacent air and soil. The other two factors are those which determine the vapor pressure gradient (or difference) between the water at the evaporating surface and the bulk air and those which contribute to resistances in the water vapor pathway. Lemon et al. (31) and Doss et al. (14) demonstrated that soil moisture is also an important factor.

There have been many studies concerning the effects of above environmental factors on ET from plants. Tew et al. (45) demonstrated the effect of air and soil temperature on transpiration from sunflower (*Helianthus annus*). They found that under a variety of transpiring conditions, lessened water uptake from the soil might limit the transpiration rate at low soil temperatures. Cameron (9) also reported that soil temperature influenced water consumption in orange trees (Citrus aurantium).

Many researchers have noted the relationship of pan evaporation and net radiation to ET rate of plants. Incoming radiant energy from the sun is partly reflected from the earth's surface and the rest of them is absorbed. The surface, in turn, looses radiant energy as far infra-red (heat) radiation to the atmonphere. The difference between incoming and outgoing radiation is termed net radiation, and represents the total amount of energy available (31).

Doss et al. (14) found a significant correlation between ET rate and both pan evaporation and net radiation in alfalfa (Medicago sativa L.), bermudagrass, and sorghum (Sorghum bicolor L. Moench). As pan evaporation or net radiation increased, ET rates were increaed. Either open pan evaporation or net radiation was recommended as a tool to estimate the water use of grasses under conditions where moisture is not limiting (14,47,51).

Pruitt (35) reported that the ET rate from perennial ryegrass averaged about 0.7 to 0.8 of evaporation from a 1.2 m diameter United States Weather Bureau (USWB) pan which has its water surface about 35 cm above ground level. He also demonstrated the close relationship between ET rate and net radiation throughout the year. He showed a good relationship between net radiation, relative humidity, air temperature, and ET rate. Kneebone (26) noted that the water use of grasses ranged from 60 to 85% of evaporation. Ekern (16) also showed the close relationship between ET rate and relative humidity along with soil temperature, net radiation, wind velocity, and temperature gradient between air and leaf surface.

Studies have shown that under a limited water supply, the water use rate was principally a function of the amount of water in the soil (4,14,31,47). Hagan (19) reported that after irrigation 'Merion' Kentucky bluegrass showed a decline of water loss from 4.8 mm/day (0.19 inch/day) during the second week, 4.3 (0.17) during the third week, 2.3 (0.09) during the fourth week, and 1.8 (0.07) during the fifth week. During the progressive water stress, the decline in WUR of C-3 species was greater than that of C-4 species (4).

It is noteworthy that the decline in ET rate did not occur until the soil water potential reached a specific point. Biran et al. (4) demonstrated that both St.Augustinegrass and bermudagrass maintained the same ET rates until the soil water potential reached 15 bars, and then dropped rapidly; while ET rates of zoysiagrass and tall fescue started to decrease after the soil water potential reached 0.5 bar and 20 bars, respectively. Ekern (16) also reported that as the soil moisture stress increased, bermudagrass maintained high WUR until the soil moisture stress exceeded 1 bar, but was unable to sustain these rates as the soil moisture stress increased toward 15 bars.

Wind also has an influence on the ET rate of plants. Data obtained during the first half of of this century often seemed quite contradictory. Some indicated that wind increased transpiration (as it always increases evaporaion from a free surface); others; reported that wind decreased transpiration. When radiation loads are relatively low and leaf resistance is also low, tranpiration will certainly be increased by wind. If leaf temperature is below air temperature, increasing wind velocity always tends to increase transpiration. Yet it is now clear that transpiration may indeed be decreased by wind when the radiation heat is high, particularly if leaf resistance is also high. Under such conditions, the leaf temperature may be far above the air temperature, accounting for a high transpiration rate. The wind cools the leaf and this cooling effect is more important in reducing transpiration than is the wind in increasing evaporation (37). Sayre (35) and Ekern (16) showed the positive relationship between ET rate and wind velocity in tobacco (*Nicotiana* sp.), mullein (*Verbascum thapsus*), and bermudagrass.

MATERIALS AND METHODS

Twelve C-4 warm season turfgrass species and one C-3 cool season turfgrass species were used throughout this study (Table 1). The study consisted of three experiments.

Uniform Cultural System Study. This experiment was carried out to determine the ET rates and vertical leaf extension rates of 12 turfgrass species under the same cultural practice regimes. This experiment was conducted on a ET Experimental Area (Fig. 1) which was a specially constructed, contiguous plot area and maintained under non-limiting soil moisture conditions. All 12 grass species were maintained at the same cutting height (3.8 cm) and nitrogen fertility level (0.25 kg N are^{-1} growing month^{-1}).

Optimum Cultural System Study. This experiment was carried out to determine the ET rates and vertical leaf extension rates of 10 turfgrass species under optimum cultural practice regimes for each species. This experiment was conducted on the Turfgrass Cultivar Characterization Plots at the Texas A&M University Turfgrass Research Field Laboratory under non-limiting soil moisture conditions. Each grass species was maintained at a specific cutting height and nitrogen fertility level that is optimum for each species.

Water Stress Study. This experiment was carried out to determine the ET rates and vertical leaf extension rates of 12 turfgrass species under progressive water stress conditions and the same cultural regimes in comparison to those of non-limiting soil moisture

Table 1. Turfgrass species utilized during the ET rate studies

Turfgrass Species	Use[1]	Establishment
'Common' Bermudagrass (*Cynodon dactylon* (L.) Pers.)	U,O,W	Sod
'Tifway' Bermudagrass (*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Davy)	U,O,W	Sod
'Tifgreen' Bermudagrass (*Cynodon dactylon* (L.) Pers. x *C. Transvaalensis* Davy)	U,O,W	Sod
'Meyer' Zoysiagrass (*Zoysia japonica* Steud)	U,O,W	Sod
'Emerald' Zoysiagrass (*Z. japonica* Steud x *Z. tenuifolia* Willd. ex Trin.)	U,O,W	Sod
Zoysia tenuifolia Willd. ex Trin.	O	Sod
'Common' Centipedegrass (*Eremochloa ophiuroides* (Munro.) Hack)	U,O,W	Sod
'Common' Buffalograss (*Buchloe dactyloides* (Nutt.) Engelm)	U,O,W	Sod
'Common' Blue Grama (*Bouteloua gracilis* (H.B.K.) Lag. ex Steud)	U,W	Seed
[2]'Kentucky 31' Tall fescue (*Festuca arundinacea* Schreb.)	U,W	Seed
'Adalayd' Sand Knotgrass (*Paspalum vaginatum* Sw.)	U,O,W	Sod
'Argentine' Bahiagrass (*Paspalum notatum* Flugge.)	U,W	Seed
'Texas Common' St.Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntz)	U,O,W	Sod

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[1] U: Uniform Cultural System Study

O: Optimum Cultural System Study

W: Water Stress Study

[2] Cool season turfgrass species

Fig. 1. Front view of the ET Experimental Area.

content and the same cultural regimes. This experiment was conducted on a specially constructed, contiguous plot area and maintained under progressive water stress conditions. The cultural practices utilized on the 12 turfgrass species were the same as for the Uniform Cultural System Study.

Water Balance Method

The water balance equation is normally written as follows:

$$P - O - U - ET + W = 0$$

In which:

ET: Evapotranspiration from the plant and soil surfaces

W: The change in soil water storage during a specified monitoring period

P: The amount of precipitation

O: The amount of runoff

U: The amount of water draining beyond the root zone

In this equation, ET is derived by difference, with all other elements either measured or estimated. In this study, W, O, and U were eliminated from the equation because the mini-lysimeters were isolated from the surrounding soil, there were no runoff, and the mini-lysimeters have been weighed after gravitational water drainage.

Mini-lysimetry Technique. The two primary balance methods utilized involve (a) lysimetry and (b) monitoring changes in soil water storage under the plant community. The lysimetry approach was selected for the experiments reported herein. Lysimetry has been the most consistantly accurate technique for the measurement of ET rates (20,44). The uniformity, high plant density, and shallow root systems which are typical of perennial grasses maintained under turf conditions also enhance the effectiveness of lysimetry techniques. Mini-lysimeters have been successfully used in turfgrass water balance method for monitoring ET (21,44). The plastic mini-lysimeter used for these experiments was 21.6 cm in diameter and 20 cm in depth, with a black color. Each lysimeter was filled with "Absorb-N-Dry" (Balcones Mineral Corp., Flatonia, Texas), a fritted clay described by van Bavel et al. (49). It was chosen as the growing medium because of its low bulk density, its ability to drain rapidly, and its ability to retain a large quantity of plant availble water.

The turfs were established in the mini-lysimeters in August, 1981, and grown in the greenhouse (32°C for warm season grasses and 21°C for the cool season grass). Mowing was at a 3.8 cm cutting height for all grasses to be used in the Uniform Cultural System Study, and 2.5 or 5.0 cm for the grasses to be used in the Optimum Cultural System Study. Irrigation was applied daily by means of automatic sprinkler system in sufficient amounts to prevent wilt. Fertilization was applied at the same rate as planned for the field studies.

Measurement Procedures. The ET rate of each grass species was measured by the water balance method using a mini-lysimetry technique. At 8 o'clock in the morning, the lysimeter of each species was removed from the metal sleeve and weighed (W_{1a}) on a Mettler P10N Balance (Fig. 2), which had a weighing capacity of 10 kg, and an accuracy of (+ or -) 0.5 g. Leaf height was measured by metric ruler at the same time, from the top of pot edge to leaf tip. Five representative, healthy leaves were selected per pot. The amount of water lost during each 24 hour period was replaced after these measurements were taken. The lysimeters were hand watered with

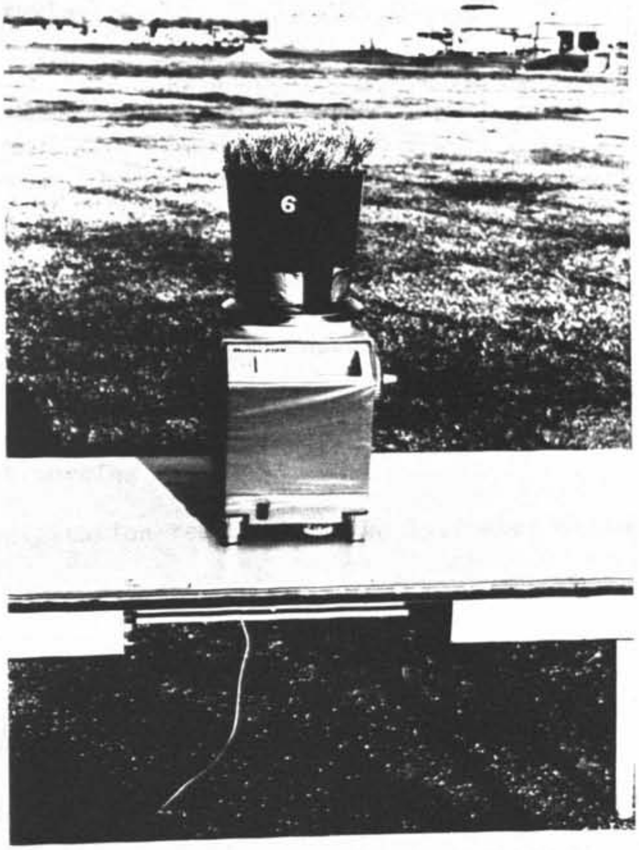

Fig. 2. Mini-lysimeter positioned on a balance for weighing.

1000 ml. After the soil moisture content reached field capacity, the lysimeters were weighed again (W_{1b}). Usually it took an hour and a half for the soil moisture to reach field capacity. After these measurements were completed, the lysimeters were returned to the metal sleeves in each plot. Next morning, the same measurements were taken again (W_{2a} and W_{2b}). The ET rate was calculated by the following formula:

$$ET = W_{1b} - W_{2a} + Pr$$

In which:

ET: evapotranspiration rate of turfgrass

W_{1b}: the second weight of lysimeter measured after the soil water content reached field capacity

W_{2a}: the first weight of lysimeter measured before watering the next morning

Pr: precipitation received by the lysimeter during the previous 24 hour period

The unit of ET was then converted to mm/day from gram/day.

ET Experimental Area

This plot area was designed for both the Uniform Cultural System Study and the Water Stress Study. It was established in August, 1981. All grass species were established by soilless sodding; except blue grama, bahiagrass, and tall fescue, which were established by seeding. The seeding rates were 1.5 kg are^{-1} for blue grama, 4 kg are^{-1} for bahiagrass, and 4.5 kg are^{-1} for tall fescue. The plot layout was a randomized block design with three replications.

Each plot of 1.5 m X 1.5 m was surrounded by metal sheets to a 10 cm depth to impair the encroachment of adjacent grass species. Between each replication row and surrounding the whole plot were alleys of Emerald zoysiagrass established by sodding. The root zone was a well drained sand of 1.5 m in depth with a subsurface drainage system of 10 cm corrugated plastic tubing at a 3 m spacing.

The metal sleeves for the mini-lysimeters were constructed of 24-gauge sheet metal with dimensions of 22 cm in diameter by 20 cm deep as open-end cylinders. One metal sleeve was placed in the center of each 1.5 m X 1.5 m plot. Plastic mini-lysimeters containing each grass species were positioned in these metal sleeves (Fig. 3 and Fig. 4). Pea gravel, 0.5 to 1.0 cm in diameter, was placed at the bottom of each metal sleeve to facilitate the drainage of gravitational water.

Irrigation was applied by means of a rotary pop-up sprinkler system for 30 minutes every day, when all lysimeters were removed for measurements. Fertilization was applied every 2 weeks at a rate of 0.25 kg N are^{-1} growing month^{-1} (0.5 lb N 1000 ft^{-2}). Ammonium sulfate was the nitrogen carrier used. Phosphate (P_2O_5) and potash (K_2O) were also applied at a rate of 0.25 kg P or K are^{-1} growing month^{-1}, respectively. The plot area was mowed at 3.8 cm cutting height once every week during the transition period between each experiment. Clippings were removed. Since there were no visual symptoms of disease or insect injury, no pesticides were applied during the experimental period. All weeds were removed manually as they appeared.

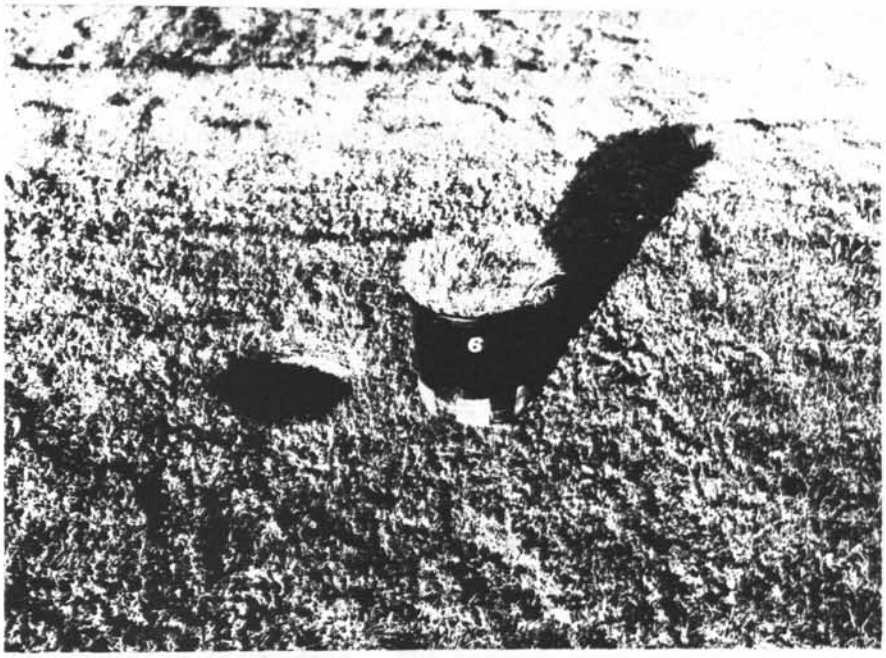

Fig. 3. View of a representative mini-lysimeter and metal sleeve.

Fig. 4. View of a representative mini-lysimeter positioned in the metal sleeve in a turf.

The ET Experimental Area was used for the Water Stress Study after the Uniform Cultural System Study was finished. During the Water Stress Study, irrigation was applied only at the beginning of each experiment. The grasses were mowed and fertilized at the same rate and by the same methods as the Uniform Cultural System Study previously described.

Cultivar Characterization Plot Area

This plot area was established for long-term cultivar characterization studies. It was located 100 m away from the ET Experimental Area. Root zones for all grass species were a well-drained modified loamy sand. The bermudagrass and St.Augustinegrass plots were established in August of 1978 with plot size of 1.5 m X 4.5 m and 1.8 m X 2.7 m, respectively. The zoysiagrass, buffalograss, and centipedegrass plots were established in August of 1979 with plot sizes of 1.5 m X 4.5 m, 1.5 m X 2.7 m, and 1.5 m X 2.7 m, respectively. The Adalayd sand knotgrass plots were established in July of 1980 with a plot size of 1.5 m X 4.5 m. All grass species and cultivars were replicated three times in a randomized block design. Irrigation was applied by a ratary pop-up sprinkler system. Nitrogen was applied at a rate of 0.25 kg N are^{-1} growing month^{-1} for St.Augustinegrass, bermudagrass, zoysiagrass, centipedegrass, and buffalograss until 1981. From 1981 each plot was divided into three sub-plots to apply three nitrogen rates of 0.13, 0.25, and 0.5 kg N are^{-1}growing month^{-1}. Phosphorus and potassium were applied only when they were needed based on an annual soil test.

Pesticides were applied on a curative basis only when they were needed to control of serious threatening problem pest.

For the Optimum Cultural System Study, metal sleeves were placed in each species plot on the proper nitrogen fertility sub-plot. There were three replications. The grasses were fertilized every two weeks. The cutting height and nitrogen fertility levels employed for each species were as shown in Table 2.

Leaf Water Potential Measurement

During the Water Stress Study, leaf water potentials of each turfgrass species were measured to assess changes in water content of the grasses during progressive water stress. A J-14 Press (Campbell Scientific, Inc., Logan, Utah) was used for these measurements (Fig. 5). A hydraulic press has advantages over the Scholander Pressure Chamber, such as low cost, ease of fabrication, rapidity of measurement, and ease of handling in the field (5,25,36, 39,50). Significant correlations were demonstrated between the hydraulic press and Scholander Pressure Chamber measurements, which corroborated the effectiveness of the hydraulic press.

The technique involved selecting healthy leaves of each species. Each leaf was severed by means of shears in the middle of the blade. That upper leaf tissue was mounted on the hydraulic press and the readings were made when the leaf color changed (darker) and larger amount of water exuded from the cut end of the leaf blade. Three replicated measurements were made per pot.

Table 2. Cutting height and nitrogen fertililization rate utilized for each turfgrass species during the Optimum Cultural System when grown under non-limiting soil moisture conditions.

Turfgrass Species	Cutting Height (cm)	Nitrogen Fertilization Rate (g are^{-1} growing $month^{-1}$)
Common Bermudagrass	2.5	500
Tifway Bermudagrass	2.5	500
Tifgreen Bermudagrass	2.5	500
Adalayd Sand Knotgrass	2.5	500
Texas Common St.Augustinegrass	5.0	250
Meyer Zoysiagrass	5.0	125
Emerald Zoysiagrass	5.0	125
Zoysia tenuifolia	5.0	125
Common Buffalograss	5.0	125
Common Centipedegrass	5.0	125

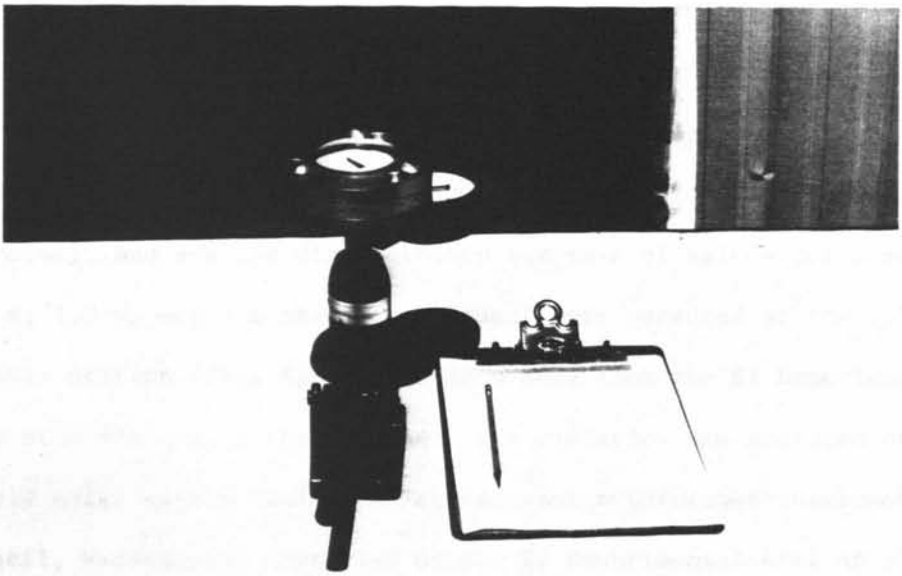

Fig. 5. J-14 Hydraulic Press for measuring the leaf water potential.

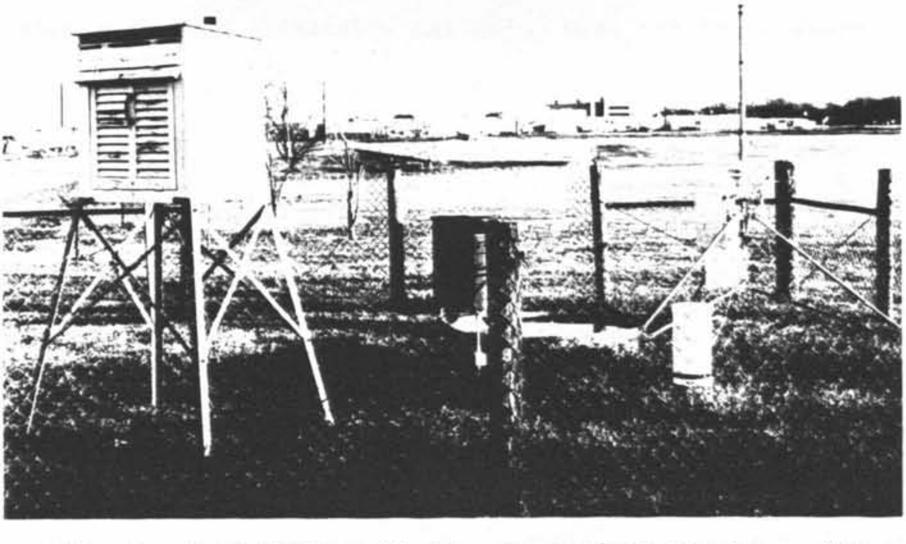

Fig. 6. Turf Weather Station located at the Texas A&M University Turfgrass Research Field Laboratory.

Climatological Data

Average daily maximum and minimum air temperatures (measured 1.5 m above the ground), average maximum and minimum soil temperatures (measured 0.3 m below the surface), pan evaporation (1.2 m in diameter), and average wind velocity (average of values measured 0.5 m, 1.5 m, and 3 m above the ground) were measured at the Turf Weather Station (Fig. 6) located 20 m away from the ET Experimental Area at 8 O'clock in the morning. Net radiation was measured on an hourly basis with a Miniature Net Radiometer (Micromet Instrements, Bothell, Washington) installed on the ET Experimental Area at a 1 m height above the turfgrass surface (Fig. 7). A CR5 Digital Recorder (Campbell Scientific, Inc., Logan, Utah) was used with the Miniature Net Radiometer to record the data (Fig. 7).

All measurements for the Uniform Cultural System Study and the Optimum Cultural System Study, including ET rates, vertical leaf extension rate, and climatological data, were collected every weekday for 3 weeks. All measurements for the Water Stress Study, including ET rates, vertical leaf extension rates, leaf water potential, and climatological data, were collected until tall fescue showed wilting symptoms, which indicated that the soil moisture content had reached the approximate wilting point.

Statistical Analyses

The Duncan's multiple range test was utilized to assess differences among the ET rates of each turfgrass species, and to determine differences in ET rates between the Uniform Cultural System Study and the Optimum Cultural System Study. Single

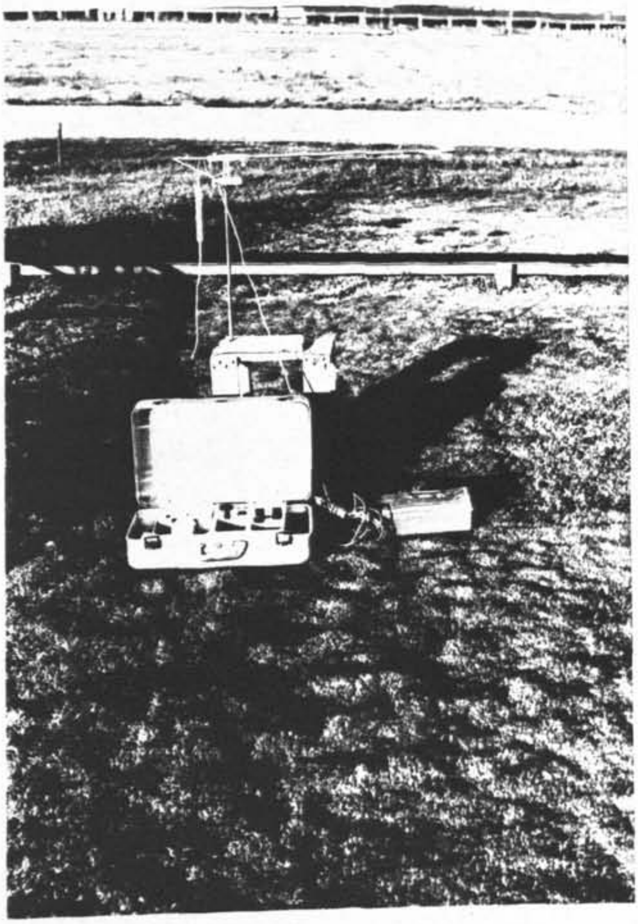

Fig. 7. Miniature Net Radiometer with CR5 Digital Recorder installed on the Turfgrass ET Experimental Area site.

correlations were calculated to demonstrate the relationship between the ET rates of each species and the environmental factors, leaf water potential, and accumulative leaf height.

RESULTS AND DISCUSSION

ET Rates Under Non-limiting Soil Moisture

The comparative ET rates and vertical leaf extension rates of twelve turfgrass species under non-limiting soil moisture conditions and uniform cultural practices are shown in Tables 3 and 4, respectively. The comparative ET rates and vertical leaf extension rates of ten turfgrass species under non-limiting soil moisture condition and optimum cultural practices are listed in Tables 5 and 6, respectively.

Significant differences were observed in ET rates at both the interspecies and intraspecies levels under both uniform and optimum cultural practices. The differences may be associated with the respective growth habits, shoot densities, and vertical leaf extension rates. Johns et al. (24) reported that in St.Augustinegrass grown under non-limiting soil water conditions, the external resistance, which was the sum of canopy resistance (Rc) and turbulent exchange resistance (Ra), were two to four times greater than the leaf resistance (Rs). This means that the ET rate is controlled to a large extent by factors which are external to the plant rather than internal anatomical and physiological factors. These external factors would include the number and position of leaves and stems within the turfgrass canopy. A turf with high leaf and stem densities plus substantial horizontal leaf orientation would cause greater impairment of the normal upward movement of

Table 3. Comparative ET rates of twelve turfgrasses grown under non-limiting soil moisture conditions and uniform cultural practices (0.25 kg N are^{-1} growing month^{-1} and 3.8 cm cutting height).

Turfgrass Species	Evapotranspiration Rate (mm/day)	(inch/week)	(%)[1]	[2]
Emerald Zoysiagrass	4.84	1.33	0	
Common Buffalograss	5.26	1.45	9	
Tifgreen Bermudagrass	5.43	1.50	12	
Common Centipedegrass	5.50	1.51	14	
Common Blue Grama	5.69	1.57	18	
Common Bermudagrass	5.77	1.59	19	
Meyer Zoysiagrass	5.82	1.61	20	
Tifway Bermudagrass	5.88	1.62	21	
Adalayd Sand Knotgrass	6.15	1.70	27	
Argentine Bahiagrass	6.25	1.72	29	
Texas Common St.Augustinegrass	6.32	1.74	31	
Kentucky 31 Tall fescue	7.13	1.97	47	

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[1] $\frac{\text{ET rate of the species - ET rate of Emerald Zoysiagrass}}{\text{ET rate of Emerald Zoysiagrass}}$

[2] Means linked with the same line are not significantly different at P=0.05 level in Duncan's multiple range test.

Table 4. Vertical leaf extension rates of twelve turfgrasses grown under non-limiting soil moisture conditions and uniform cultural practices (0.25 kg N are^{-1} growing month^{-1} and 3.8 cm cutting height).

Turfgrass Species	Vertical Leaf EXtension Rate (mm/day)	[1]				
Common Blue Grama	4.44	│				
Adalayd Sand Knotgrass	3.85	│	│			
Argentine Bahiagrass	3.48	│	│	│		
Common Bermudagrass	3.17	│	│	│	│	
Common Buffalograss	2.80	│	│	│	│	│
Meyer Zoysiagrass	2.74	│	│	│	│	│
Kentucky 31 Tall fescue	2.71	│	│	│	│	│
Texas Common St.Augustinegrass	2.15		│	│	│	│
Tifway Bermudagrass	1.77			│	│	│
Emerald Zoysiagrass	1.56				│	│
Tifgreen Bermudagrass	1.50				│	│
Common Centipedegrass	1.27					│

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[1] Means linked with the same line are not significantly different at P=0.05 level in Duncan's multiple range test.

Table 5. Comparative ET rates of ten turfgrasses grown under non-limiting soil moisture conditions and optimum cultural practices for each species.

Turfgrass Species	Evapotranspiration Rate								
	(mm/day)	(inch/week)	(%)[1]	[2]					
Common Centipedegrass	6.58	1.81	0	|					
Tifway Bermudagrass	6.69	1.84	2	|					
Emerald Zoysiagrass	6.82	1.88	4	|	|				
Meyer Zoysiagrass	7.17	1.97	10	|	|	|			
Common Buffalograss	7.34	2.02	12	|	|	|	|		
Tifgreen Bermudagrass	7.58	2.09	16		|	|	|		
Adalayd Sand Knotgrass	7.87	2.17	21			|	|		
Common Bermudagrass	8.18	2.25	25				|	|	
Zoysia tenuifolia	8.81	2.43	35					|	|
Texas Common St.Augustinegrass	9.07	2.50	39						|

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[1] $\frac{\text{ET rate of the species - ET rate of Common Centipedegrass}}{\text{ET rate of Common Centipedegrass}}$

[2] Means linked with the same line are not significantly different at P=0.05 level in Duncan's multiple range test.

Table 6. Vertical leaf extension rates of nine turfgrasses grown under non-limiting soil moisture conditions and optimum cultural practices for each species.

Turfgrass Species	Vertical Leaf Extension Rate (mm/day)	[1]				
Adalayd Sand Knotgrass	7.46	|				
Texas Common St.Augustinegrass	7.43	|				
Common Bermudagrass	7.10	|	|			
Tifway Bermudagrass	5.78		|	|		
Common Buffalograss	4.70			|	|	
Tifgreen Bermudagrass	4.64			|	|	
Emerald Zoysiagrass	4.49			|	|	
Meyer Zoysiagrass	3.92				|	
Common Centipedegrass	2.51					|

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[1] Means linked with the same line are not significantly different at P=0.05 level in Duncan's multiple range test.

water vapor and at the same time reduce turbulent eddy movements with a resultant increase in vapor density. Table 7 shows the shoot densities, number of leaves per unit area, and leaf width of 13 turfgrasses.

Tall fescue has the highest ET rates. This is consistent with the results of Kneebone and Pepper (27,28). The very high ET rate of tall fescue may be associated with its C-3 photosynthetic pathway (4), fairly erect leaf orientation, a medium rapid vertical leaf extension rate (Table 4), low shoot density, and high leaf area, which caused low canopy resistance (Table 7).

St.Augustinegrass exhibited the second highest ET rates, which was actually the highest value among the warm season grasses, under both uniform and optimum cultural practices. This high ET rate of St.Augustinegrass could be due to its low canopy resistance in terms of a low shoot density, high leaf area, and rapid vertical leaf extension rate (Tables 4 and 7).

Bahiagrass also showed a high ET rate under non-limiting soil moisture conditions, which was similar to the rate for St.Augustinegrass. This could be a result of a rapid vertical leaf extension rate, high leaf area, and low shoot density, which resulted in a low canopy resistance.

Adalayd sand knotgrass showed medium high ET rate under both uniform and optimum cultural practices. This high ET rate could be due to its very high vertical leaf extension rate and lower shoot density compared to bermudagrass.

Bermudagrass species showed medium to low ET rates. Significant

Table 7. Shoot densities, leaf number per unit area, and leaf width of thirteen turfgrasses grown under non-limiting soil moisture conditions and uniform cultural pracitces (0.25 kg N are^{-1} growing month^{-1} and 3.8 cm cutting height).[1]

Turfgrass Species	Shoot Density (No./25cm^{2})	Leaf No. (No./25cm^{-2})	Leaf Width (mm)
Common Bermudagrass	45.0^{d}[2]	62.7^{e}[2]	1.9^{ef}[2]
Tifway Bermudagrass	57.7^{c}	114.0^{c}	0.8^{hi}
Tifgreen Bermudagrass	65.3^{bc}	128.0^{c}	0.9^{hi}
Meyer Zoysiagrass	19.7^{e}	59.0^{e}	2.9^{cd}
Emerald Zoysiagrass	73.3^{b}	188.7^{b}	1.0^{ghi}
Zoysia tenuifolia	168.0^{a}	506.7^{a}	0.3^{i}
Common Centipedegrass	18.3^{ef}	54.3^{e}	3.4^{c}
Common Buffalograss	8.3^{f}	43.3^{e}	1.7^{fg}
Common Blue Grama	10.3^{ef}	44.3^{e}	1.2^{fgh}
Kentucky 31 Tall fescue	15.3^{ef}	49.7^{e}	3.6^{c}
Adalayd Sand Knotgrass	48.0^{d}	93.3^{d}	2.6^{de}
Argentine Bahiagrass	9.7^{ef}	40.3^{e}	5.0^{b}
Texas Common St.Augustinegrass	9.3^{ef}	41.3^{e}	8.0^{a}

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[1] One exception; _Zoysia tenuifolia_ which was grown under optimum cultural practices (0.13 kg N are^{-1} growing month^{-1} and 5.0 cm cutting height).

[2] Means with the same letter in a column are not significantly different at P=0.05 level in Duncan's multiple range test.

differences were observed within the *Cynodon* species. Tifgreen bermudagrass showed a low ET rate, while Common bermudagrass and Tifway bermudagrass showed medium ET rates under uniform cultural practices (Table 3). A slow vertical leaf extension rate, high shoot density, and low leaf area of Tifgreen bermudagrass may have contributed to the medium low ET rate.

Like bermudagrass, significant differences were also found within the zoysiagrass species. Emerald zoysiagrass, which is a hybrid between *Zoysia japonica* and *Z. tenuifolia* , showed a very low ET rate, while Meyer zoysiagrass had a medium ET rate. The low rate of Emerald zoysiagrass may be attributed to its very slow vertical leaf extension rate, high shoot density, and low leaf area. The high ET rate of *Zoysia tenuifolia* was unexpected. It is postulated that the deep thatch present in the *Zoysia tenuifolia* held a portion of the water in this zone following irrigation. Subsequently the water in that thatch evaporated to the atmosphere, which resulted in unexpectedly high ET rate.

Buffalograss and blue grama have a sparse shoot density and a tall, erect growing habit. Although Biran et al. (4) reported that the sparse,tall growing species such as kikuyugrass and Suwannee bermudagrass had high ET rates, buffalograss and blue grama showed low and medium low ET rates, respectively. The hairs on the leaf surface and low leaf area may have contributed to the low ET rate of buffalograss, while the low leaf area could contribute to the medium low ET rate of blue grama. Perhaps of more importance is the low shoot density which may have caused soil evaporation to become a more substantial component of ET than for the more dense turfgrasses included in this study.

Centipedegrass showed a low ET rate which is contradictory to Biran et al. (4), which could be attributed to its slow vertical leaf extension rate and prostrate growth habit, which contributes to a high canopy resistance.

It is concluded from this study that grass species which have a low vertical leaf extension rate, high shoot density, and low leaf area are more likely to have a low ET rate.

ET Rates Under Progressive Water Stress

The comparative ET rates and vertical leaf extension rates of twelve turfgrass species under progressive water stress condition and uniform cultural practices are listed in Tables 8 and 9, respectively.

All grass species showed lower ET rates under progressive water stress than under non-limiting soil moisture condition (Tables 3 and 8). This is probably due primarily to limited soil moisture availability (1,4,31,47), which resulted in a decreased soil water potential. Fig. 8 shows the decline in the average ET rate for all 12 turfgrass species as the soil moisture content decreased.

Significant differences were observed in ET rates at both the interspecies and intraspecies levels. The rankings of each grass species in terms of ET rates are very similar to that for non-limiting soil moisture condition, except for bahiagrass. Bahiagrass showed a major relative change in ET rate between non-limiting soil moisture conditions and progressive water stress conditions. Considering

Table 8. Comparative ET rates of twelve turfgrasses grown under progressive water stress conditions and uniform cultural practices (0.25 kg N are^{-1} growing $month^{-1}$ and 3.8 cm cutting height).

Turfgrass Species	Evapotranspiration Rate			
	(mm/day)	(inch/week)	(%)[1]	[2]
Common Buffalograss	2.71	0.75	0	│
Emerald Zoysiagrass	2.85	0.78	5	││
Argentine Bahiagrass	2.93	0.81	8	││
Common Centipedegrass	2.95	0.81	9	││
Common Bermudagrass	3.08	0.85	14	││
Tifgreen Bermudagrass	3.27	0.90	21	││
Meyer Zoysiagrass	3.31	0.91	22	││
Common Blue Grama	3.39	0.94	25	│││
Tifway Bermudagrass	3.51	0.97	29	││
Texas Common St.Augustinegrass	3.54	0.98	30	│
Adalayd Sand Knotgrass	3.61	0.99	33	│
Kentucky 31 Tall fescue	4.17	1.15	54	│

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[1] $\frac{\text{ET rate of the species - ET rate of Common Buffalograss}}{\text{ET rate of Common Buffalograss}}$

[2] Means linked with the same line are not significantly different at P=0.05 level in Duncan's multiple range test.

Table 9. Vertical leaf extension rates of twelve turfgrasses grown under progressive water stress conditions and uniform cultural practices (0.25 kg N are^{-1} growing month^{-1} and 3.8 cm cutting height).

Turfgrass Species	Vertical Leaf Extension Rate (mm/day)	[1]						
Common Blue Grama	6.31	|						
Argentine Bahiagrass	4.02		|					
Common Buffalograss	3.83		|	|				
Kentucky 31 Tall fescue	3.39		|	|	|			
Common Bermudagrass	2.78		|	|	|	|		
Tifway Bermudagrass	2.55			|	|	|		
Texas Common St.Augustinegrass	2.35				|	|	|	
Adalayd Sand Knotgrass	2.31				|	|	|	
Meyer Zoysiagrass	1.74					|	|	|
Tifgreen Bermudagrass	1.62					|	|	|
Common Centipedegrass	0.89						|	|
Emerald Zoysiagrass	0.77							|

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[1] Means linked with the same line are not significantly different at P=0.05 level in Duncan's multiple range test.

Fig. 8. Changes in the average ET rate for twelve turfgrasses when grown under progressive water stress and uniform cultural practices (0.25 kg N are^{-1} growing month^{-1} and 3.8 cm cutting height).

that bahiagrass is a native of subtropical eastern South America, is adapted to a low intensity of culture, and has excellent drought resistance (1), bahiagrass probably possesses an adaptive mechanism when under internal water stress that impairs the ET. Further studies are needed to identify the specific mechanism possessed by bahiagrass.

Buffalograss, Emerald zoysiagrass, bahiagrass, and centipedegrass showed low ET rates; while tall fescue, Adalayd sand knotgrass, St.Augustinegrass showed high ET rates. Tifgreen bermudagrass, Tifway bermudagrass, Common bermudagrass, Meyer zoysiagrass, and blue grama ranked intermediate in ET rate (Table 8).

The ET rate is not necessarily related to the drought tolerance of a turfgrass species (1). Maximov (34) reported that some xerophytes have a higher transpiration rate than certain mesophytes, and thus the transpiration rate cannot be considered a criterion of drought resistance. The results of this study confirm this concept. Tall fescue showed a high ET rate, although it is known to have a good drought resistance. On the other hand, centipedegrass showed a low ET rate, although it has poor drought resistance. In contrast, zoysiagrass, bermudagrass, buffalograss, and St.Augustinegrass exhibited strong association between their ET rates and drought resistances.

Effects Of Cultural Factors On ET Rates

Comparisons of the ET rates of nine turfgrasses between the Uniform Cultural System Study and the Optimum Cultural System Study are shown in Fig. 9 and Table 10. Table 11 shows a comparison of

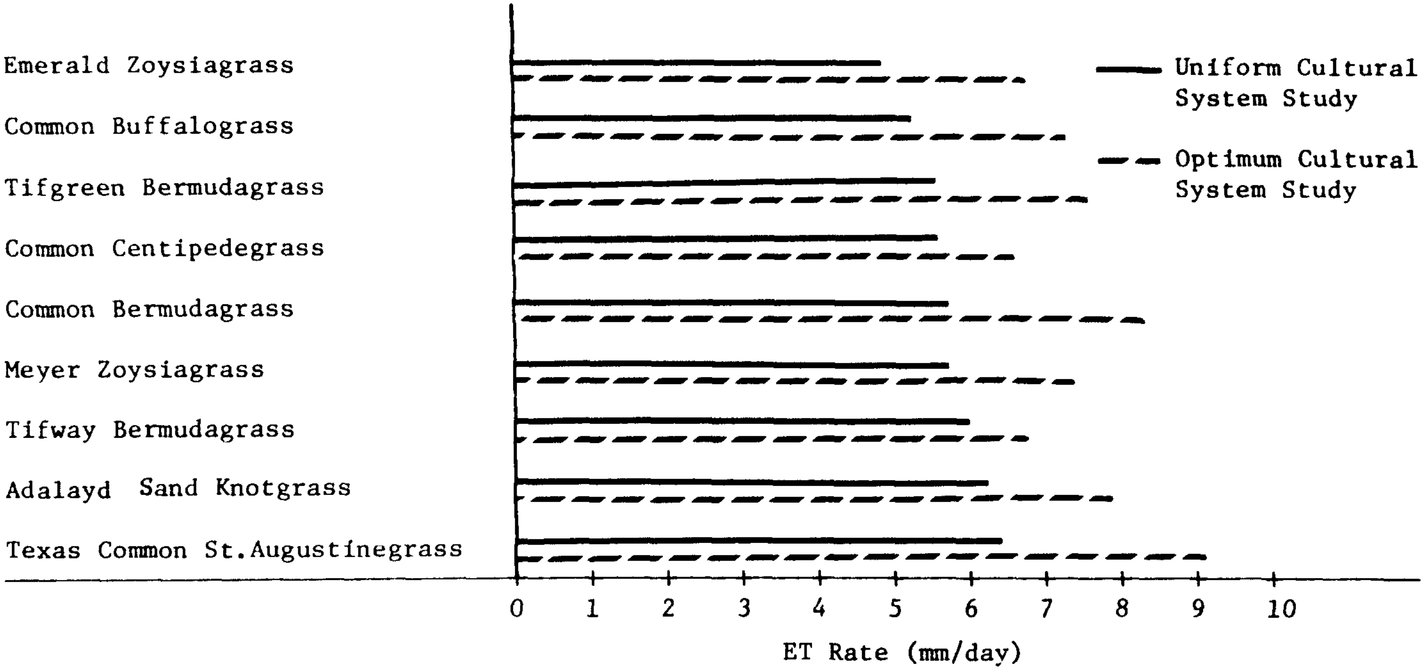

Fig. 9. Comparisons of ET rates of nine turfgrasses between the Uniform Cultural System Study and the Optimum Cultural System Study when grown under non-limiting soil moisture conditions.

Table 10. Comparative ET rates of nine turfgrasses with different nitrogen fertilization rates and cutting heights when grown under non-limiting soil moisture conditions.

Turfgrass Species	Uniform Cultural Practice			Optimum Cultural Practice		
	Nitrogen (g are^{-1} mon^{-1})	Cut Ht. (cm)	ET Rate (mm/day)	Nitrogen (g are^{-1} mon^{-1})	Cut Ht. (cm)	ET Rate (mm/day)
Common Bermudagrass	250	3.8	5.77^{b}[1]	500	2.5	8.18^{a}[1]
Tifway Bermudagrass	250	3.8	5.88^{b}	500	2.5	6.69^{a}
Tifgreen Bermudagrass	250	3.8	5.43^{b}	500	2.5	7.58^{a}
Adalayd Sand Knotgrass	250	3.8	6.15^{b}	500	2.5	7.87^{a}
Texas Common St.Augustinegrass	250	3.8	6.32^{b}	250	5.0	9.07^{a}
Meyer Zoysiagrass	250	3.8	5.82^{b}	125	5.0	7.17^{a}
Emerald Zoysiagrass	250	3.8	4.84^{a}	125	5.0	6.82^{a}
Common Buffalograss	250	3.8	5.26^{b}	125	5.0	7.34^{a}
Common Centipedegrass	250	3.8	5.50^{b}	125	5.0	6.58^{a}

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[1] Means with the same letter in the same row are not significantly different at P=0.05 level in Duncan's multiple range test.

Table 11. Comparison of the vertical leaf extension rates of nine turfgrasses between the Uniform Cultural System Study and the Optimum Cultural System Study when grown under non-limiting soil moisture conditions.

Turfgrass Species	Vertical Leaf Extension Rate (mm/day)		
	UCSS[1]	OCSS[2]	
Common Bermudagrass	3.17	7.10	*[3]
Tifway Bermudagrass	1.77	5.78	*
Tifgreen Bermudagrass	1.50	4.64	*
Adalayd Sand Knotgrass	3.85	7.46	*
Texas Common St.Augustinegrass	2.15	7.43	*
Meyer Zoysiagrass	2.74	3.92	
Emerald Zoysiagrass	1.56	4.49	*
Common Buffalograss	2.80	4.70	*
Common Centipedegrass	1.27	2.51	

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[1] Uniform Cultural System Study (0.25 kg N are^{-1} month^{-1} and 3.8 cm cutting height)

[2] Optimum Cultural System Study (optimum nitrogen fertilization rate and cutting height)

[3] Two means in the same row are significantly different at P=0.05 level in LSD.

vertical leaf extension rates of nine turfgrasses between the Uniform Cultural System Study and the Optimum Cultural System Study under non-limiting soil moisture conditions.

It is generally accepted that a raised cutting height increases the ET rates from plants (1,32) and notrogen fertilization increases the total water use of turfgrass (29,33). A reduction in the leaf area causes a decrease in the total transpiration rate, while an increased shoot growth rate resulting from nitrogen fertilization may cause an increase in the transpiration rate. However, Shearman (40) reported decreased ET rates after increasing the nitrogen fertility level of creeping bentgrass.

It was difficult to separate the effects of nitrogen fertility from cutting height as it influences the ET rates of turfgrasses. However,the data show that three bermudagrasses and Adalayd sand knotgrass possessed higher ET rates at the higher nitrogen fertility level which overshadowed the effects of a lower cutting height. The two zoysiagrasses, buffalograss, and centipedegrass exhibited lower ET rates at the lower cutting height which dominated the opposite response caused by the higher nitrogen fertility level. It should be noted that the four former species are quite responsive to nitrogen fertilization, while the latter four species are known to have a low nitrogen requirement.

The vertical leaf extension rates of all grass species, except Meyer zoysiagrass and Common centipedegrass,in the Optimum Cultural System Study were higher than those in the Uniform Cultural System Study. Considering the demonstrated relationship between increased

ET rates in respond to increased vertical leaf extension rates, it is assumed that the optimum cultural practices for each grass species caused a higher shoot growth rate and thus resulted in higher ET rates. Shearman's reports (40) that a 0.25 kg N are^{-1} fertility levels on creeping bentgrass caused higher ET rates supports this assumption. Further studies are needed to determine the effects of individual cultural practices on ET rates in the field.

Effects Of Environmental Factors On ET Rates

The climatological data collected during both the Uniform and Optimum Cultural System Studies and the Water Stress Study are summarized in Tables 12 and 13. Correlations between ET rates and selected environmental parameters, including air temperature, soil temperature, pan evaporation, net radiation, and relative humidity under non-limiting soil moisture conditions and uniform cultural practices are listed in Table 14.

Highly significant correlations were found between ET rates and air temperature for all grasses. This corresponds to previous reports (22,45). However, soil moisture did not show any significant correlation with ET rates for all grass species. While air temperature directly influences the ET rate of plants by changing the water vapor pressure, the soil temperature influences water uptake by plants in terms of the capability of roots to absorb water. In addition, the resistance to water movement through the soil is temperature-dependent (30). While ET from plants is very sensitive to changes in air temperature, the soil temperature does not influence ET. In a study conducted by Tew et al. (45), the

Table 12. Climatological data during both the Uniform and Optimum Cultural System Studies under non-limiting soil moisture conditions.

Environmental Parameters	Rep I				Rep II				Rep III			
	8/11	8/12	8/13	8/14	8/17	8/18	8/19	8/20	8/24	8/25	8/26	8/27
Ta[1,2]	27.8	27.8	29.4	-	31.1	32.2	27.2	29.4	29.4	29.4	30.0	30.0
Ts	27.8	27.8	28.3	-	28.9	29.4	28.9	31.1	28.9	28.3	28.9	28.9
Pr	1.3	3.6	1.3	1.8	1.5	0.8	0	0	0	0	1.3	0.8
Ep	6.4	5.6	8.6	-	8.9	8.4	6.6	8.6	10.7	10.9	9.7	8.4
Rn	412	271	-	-	565	505	297	555	550	566	844	503
RH	73.6	80.2	67.2	63.3	58.9	54.9	75.7	61.8	62.3	53.6	61.1	62.0

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[1] Ta: Air Temperature (°C) Ts: Soil Temperature (°C) Pr: Precipitation (mm)
Ep: Pan Evaporation (mm) Rn: Net Radiation (Watt/m^2) RH: Relative Humidity (%)

[2] All data were obtained from the Turf Weather Station, except Rn which was obtained from the Miniature Net Radiometer installed on the ET Experimental Area.

Table 13. Climatological data during the Water Stress Study under progressive water stress.

Environmental Parameters	Rep I					Rep II					
	9/6	9/7	9/8	9/9	9/10	9/25	9/26	9/27	9/28	9/29	9/30
Ta[1,2]	25.6	27.2	28.3	27.2	27.2	_	22.2	25.6	26.7	25.6	25.6
Ts	26.7	27.8	27.8	27.8	27.8	_	24.0	25.0	25.0	25.6	25.6
Pr	0	0	0	0	0.8	0	0	0	0	0	0
Ep	6.1	6.9	8.9	9.1	7.6	7.9	8.4	8.9	5.6	14.0	7.1
Rn	428	439	391	495	467	471	_	458	439	446	351
RH	54.3	57.1	54.5	52.3	50.3	53.9	41.4	51.1	68.0	70.8	71.1
Wv	1.2	0.9	0.8	0.9	1.0	1.2	1.2	2.4	2.1	1.7	1.4

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[1] Ta: Air Temperature (°C) Ts: Soil Temperature (°C) Pr: Precipitation (mm)
Ep: Pan Evaporation (mm) Rn: Net Radiation (Watt/m^2) RH: Relative Humidity (%)
Wv: Wind Velocity (m/sec)

[2] All data were obtained from the Turf Weather Station, except Rn which was obtained from the Miniature Net Radiometer installed on the ET Experimental Area.

Table 13. Continued.

Environmental Parameters	Rep III							
	10/14	10/15	10/16	10/17	10/18	10/19	10/20	10/21
Ta	18.9	18.9	-	20.0	20.0	22.8	16.1	13.9
Ts	23.8	23.8	-	21.7	21.7	21.7	20.6	18.9
Pr	0	0	0	0	0	0	0	0
Ep	5.6	5.1	5.1	5.1	4.6	8.6	5.3	3.0
Rn	427	464	419	405	416	367	388	-
RH	69.3	68.4	65.3	65.9	81.3	76.6	59.3	56.8
Wv	1.2	0.4	1.1	1.1	1.1	1.4	2.4	1.8

Table 14. Correlations between the ET rates of twelve turfgrasses to the environmental parameters and leaf height when grown under non-limiting soil moisture conditions and uniform cultural practices (0.25 kg N are^{-1} growing month^{-1} and 3.8 cm cutting height).

Turfgrass Species	Correlation Coefficient					
	[1] ET/Ta	ET/Ts	ET/Ep	ET/Rn	ET/RH	ET/LH
Common Buffalograss	.43*[2]	-.16	.25	.50**[3]	-.27	-.15
Common Blue Grama	.62**	-.00	.62**	.76**	-.61**	.07
Common Bermudagrass	.70**	.14	.72**	.81**	-.73**	.14
Tifway Bermudagrass	.69**	.13	.75**	.86**	-.74**	.06
Tifgreen Bermudagrass	.62**	.05	.68**	.82**	-.63**	.33*
Adalayd Sand Knotgrass	.61**	.09	.68**	.74**	-.63**	.92
Meyer Zoysiagrass	.66**	.06	.66**	.74**	-.64**	.03
Emerald Zoysiagrass	.58**	-.02	.48**	.73**	-.50**	.42*
Texas Common St.Augustinegrass	.64**	.16	.73**	.83**	-.53**	.21
Common Centipedegrass	.57**	-.08	.51**	.67**	-.50**	.42*
Argentine Bahiagrass	.36*	-.02	.35*	.66**	-.34*	.07
Kentucky 31 Tall fescue	.57**	.25	.81**	.76**	-.73**	.12

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[1] ET: Evapotranspiration Rate Ta: Air Temperature Ts: Soil Temperature
Ep: Pan Evaporation Rn: Net Radiation RH: Relative Humidity LH: Leaf Height

[2] Significant at P=0.05 level.

[3] Significant at P=0.01 level.

soil temperature range was from 10 to 40°C, which were wide enough to influence ET. The range from 27.8 to 31.1°C reported in this was very narrow and favorable for root activity, since the optimum soil temperature is 27°C for turfgrass root growth of warm season grasses (1). This concept can be supported by the significant correlation of ET rates to soil temperature, which ranged from 18.9 to 27.8°C in the Water Stress Study.

Pan evaporation showed significant correlations with ET rates for all grass species, except buffalograss, while net radiation showed highly significant correlations with ET rates for all grass species. These responses of buffalograss may be due to the hairs on the leaf surface. The long, dense hairs on buffalograss leaves may have increased the boundary layer so that the resistance to outward diffusion of water vapor from the stomata was increased. Relative humidity also showed significant correlation with ET rates for all grasses, except buffalograss. This could be explained by the above mechanism as well.

No correlation was found between accumulative leaf height and ET rate,except Tifgreen bermudagrass, Emerald zoysiagrass, and Common centipedegrass which have very low leaf extension rates and ET rates. It has been reported that an increased leaf height usually increases the ET rate from turfgrasses (22). In this field study, it was assumed that the enhancing effect of leaf height on ET rate at the interspecies level was overshadowed by the strong effects of environmental factors, such as air temperature, net radiation, and atmospheric vapor pressure. From these results, it can be concluded that under non-limiting soil moisture conditions, the ET rates from grasses were increased primarily by higher air temperature, higher net radiation, and low atmospheric vapor pressure.

Significant correlations between air temperature and soil temperature, air temperature and pan evaporation, air temperature and net radiation, air temperature and relative humidity, pan evaporation and relative humidity, and net radiation and relative humidity were also shown during this study (Table 15). Slatyer (43) stated that of all the variables which influence evaporation only solar radiation could be regarded as at all independent of the others. These correlations indicated the primary effect of net radiation over the others, except relative humidity.

Correlation between ET rate and some environmental parameters, which included air temperature, soil temperature, pan evaporation, net radiation, relative humidity, wind velocity, and accumulative leaf height, under progressive water stress condition and uniform cultural practices are shown in Table 16.

There was a wide range in soil temperatures from 18.9 to 27.8°C during the Water Stress Study. Turfgrass root activities could be influenced by this wide range of soil temperature and in turn affect the ET rates. This is shown by the highly significant correlations between the ET rate and soil temperature for all grass species during this Water Stress Study period. Air temperature, pan evaporation, net radiation, and relative humidity showed highly significant correlations with the ET rates for all grasses.

The effect of accumulative leaf height on ET rate was overshadowed

Table 15. Correlations between the environmental parameters monitored during the Uniform and Optimum Cultural System Studies when under non-limiting soil moisture conditions.

Environmental Parameters	Correlation Coefficient				
	[1] Ta	Ts	Ep	Rn	RH
Ta	1.00	.39 *[2]	.54 **[3]	.57 **	-.83 **
Ts		1.00	.28	.32	-.43 *
Ep			1.00	.75 **	-.84 **
Rn				1.00	-.70 **
RH					1.00

[1] Ta: Air Temperature Ts: Soil Temperature Ep: Pan Evaporation
Rn: Net Radiation RH: Relative Humidity

[2] Significant at P=0.05 level.

[3] Significant at P=0.01 level.

Table 16. Correlations between the environmental parameters under progressive water stress conditions and uniform cultural practices (0.25 kg N are^{-1} growing month^{-1} and 3.8 cm cutting height).

Turfgrass Species	Correlation Coefficient									
	[1] D/ET	D/LWP	ET/LH	ET/LWP	ET/Ta	ET/Ts	ET/Ep	ET/Rn	ET/RH	ET/Wv
Common Buffalograss	-.37**	-.44**	-.36**	.50**	.69**	.77**	.39**	.46**	-.50**[2]	-.32*[3]
Common Blue Grama	-.19	-.43**	-.16	.35**	.69**	.66**	.48**	.45**	-.38**	-.21
Common Bermudagrass	-.23	-.33*	-.10	.09	.77**	.85**	.47**	.52**	-.55**	-.19
Tifway Bermudagrass	-.31*	-.26*	-.36**	.38**	.81**	.89**	.51**	.51**	-.57**	-.20
Tifgreen Bermudagrass	-.26*	-.39**	-.39**	.10	.78**	.83**	.52**	.51**	-.57**	-.11
Adalayd Sand Knotgrass	-.27*	-.27*	.04	.09	.75**	.81**	.51**	.52**	-.57**	-.09
Meyer Zoysiagrass	-.33*	.23	.25	.45**	.76**	.84**	.50**	.54**	-.61**	-.19
Emerald Zoysiagrass	-.23	-.35**	-.29*	.14	.68**	.73**	.48**	.50**	-.53**	-.07
Texas Common St.Augustinegrass	-.24	.33*	.03	.03	.76**	.83**	.52**	.51**	-.55**	-.15
Common Centipedegrass	-.34**	-.15	.08	.05	.72**	.81**	.51**	.57**	-.59**	-.20
Argentine Bahiagrass	-.24	.04	.08	.26	.72**	.79**	.47**	.44**	-.48**	-.20
Kentucky 31 Tall fescue	-.39*	-.26	-.48**	.36*	.75**	.92**	.49**	.65**	-.62**	-.14

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[1] D: Days after Irrigation LWP: Leaf Water Potential LH: Leaf Height Ta: Air Temperature Ts: Soil Temperature ET: Evapotranspiration Ep: Pan Evaporation Rn: Net Radiation RH: Relative Humidity Wv: Wind Velocity

[2] Significant at P=0.01 level.

[3] Significant at P=0.05 level.

by the above environmental factors, plus a decreasing soil moisture level.

Soil moisture level is reported to be the primary factor influencing the ET rate from plants when subjected to limited water conditions (4,14,19,31,47). In this study, the relationship between the number of days after irrigation (D) and the ET rate was found only in 7 species, which could be attributed to the limited period of observation, 8 days. Biran et al. (4) found that the ET rate declined after being grown under a limited water supply conditions for 12 days. A decline in the average ET rates of twelve species is shown in Fig. 7.

Average water potentials for each grass species during the Water Stress Study are listed in Table 17. No significant relationship was found between the ET rates and leaf water potential. Clark and Levitt (11) reported that drought resistant plants are more able to conserve water, possibly through the development of thicker cuticles and deeper roots. Although more anatomical assessments are needed, it may be noteworthy that the drought resistant grasses, such as bahiagrass, tall fescue, blue grama, and buffalograss, showed very high water content in the leaves.

Wind velocity did not influence the ET rate in this study. The average wind velocity was monitored over a 24 hour period during this study. The wind velocity can influence ET rates of turfgrasses along with the other environmental factors. However, the effects of wind velocity vary according to the situation (37,38), for example, in the dark versus light. During the daytime, wind

Table 17. Average leaf water potentials of twelve turfgrasses grown under progressive water stress and uniform cultural practices (0.25 kg N are^{-1} growing month^{-1} and 3.8 cm cutting height).

Turfgrass Species	Leaf Water Potential (bar)	[1]					
Meyer Zoysiagrass	- 9.3	│					
Texas Common St.Augustinegrass	- 8.9	│					
Common Centipedegrass	- 8.2		│				
Emerald Zoysiagrass	- 7.7		│	│			
Tifway Bermudagrass	- 7.1			│	│		
Adalayd Sand Knotgrass	- 6.9				│		
Common Buffalograss	- 6.8				│	│	
Common Bermudagrass	- 6.8				│	│	
Tifgreen Bermudagrass	- 6.5				│	│	
Common Blue Grama	- 6.2					│	
Kentucky 31 Tall fescue	- 5.4						│
Argentine Bahiagrass	- 4.9						│

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[1] Means linked with the same line are not significantly different at P=0.05 level in Duncan's multiple range test.

decreases the transpiration rate, while it increases the transpiration rate at night (17). Therefore, a significant relationship between wind velocity and the ET rate could not be found in this study.

SUMMARY AND CONCLUSIONS

As the cost and availability of irrigation water becomes a greater factor in turfgrass maintenance, it will be necessary to use turfgrass species which have low water use rates (WUR). Thirteen turfgrass species were evaluated under both non-limiting soil moisture and progressive water stress conditions. Uniform cultural practices and optimum cultural practices were superimposed in this field study. Correlations between ET rates and selected cultural and environmental parameters were investigated.

The conclusions of this study were:

1. Emerald zoysiagrass, buffalograss, centipedegrass, and Tifgreen bermudagrass showed low ET rates, while tall fescue, St.Augustinegrass, bahiagrass, and Adalayd sand knotgrass exhibited high ET rates.
2. Centipedegrass, buffalograss, and zoysiagrass are promising turfgrass species where a water conservation strategy is a high priority.
3. Those grass species which had a slow vertical leaf extension rate, high shoot density, low leaf area, and prostrate growing habit tended to have low ET rates.
4. All grass species showed higher ET rates when maintained at their respective optimum nitrogen level and cutting height, primarily due to the resultant more rapid shoot growth rates.

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