

SECOND YEAR  
PROGRESS REPORT

concerning

PHYSIOLOGICAL INVESTIGATIONS

in

DEVELOPING WATER CONSERVING,  
MINIMAL MAINTENANCE TURFGRASSES  
AND CULTURAL SYSTEMS

Volume II

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## I. EXECUTIVE SUMMARY

The original proposed time schedule for the major research objectives in developing water conserving, minimal maintenance turfgrasses and cultural systems is found on page 6. The current progress is reasonably close to the original schedule. Whether this will be sustained in the upcoming year as we start to address the drought resistance dimension in more detail is difficult to foresee. In terms of the specific subobjectives and their status, these are shown on page 7. Scientific papers that have been published are included in the Appendix. From research conducted over the first two years, the following conclusions have been drawn.

### A. Minimal Water Use Rates:

1. The major warm season turfgrass species vary substantially in water use rates.
2. The comparative interspecies water use rates are of a magnitude to have practical significance for field applications.
3. Initial data suggest that there may be as much variation among cultivars within a warm season species as there is at the interspecies level.
4. The primary plant parameters affecting the evapotranspiration rate are a high canopy resistance and a low leaf blade area.
5. These plant morphological parameters are valid in interpreting the differentials in water use rates among eleven major warm season perennial turfgrasses.
6. Fortunately, these morphological parameters can be easily and rapidly assessed for use in screening thousands of clonal plantings for low water use rates in a breeding program.
7. These morphological factors are subject to modification by a number of cultural practices; thus, the turf manager can significantly affect the water use rate of a given turfgrass species.
8. Both the warm and cool season turfgrass species possess significant differences in stomatal density.
9. Both warm and cool season turfgrasses vary significantly in stomatal distribution over the leaf. In the case of warm season turfgrasses, there is a distinct relationship between the stomatal arrangement and their associated subfamily classifications of Eragrostoideae and Panicoideae.
10. A significantly higher stomatal density was found on the adaxial side of the leaf in comparison to the density found on the abaxial side, with the exception of Kentucky 31 tall fescue.
11. There was no relationship between an increase in the evapotranspiration rate and a higher stomatal density. In fact, there was a trend to an inverse relationship.

12. Although, the stomatal characterization studies have not elucidated a component contributing to a reduced evapotranspiration rate, these results may be useful in the upcoming mechanistic studies of drought resistance.
13. It was found that the results of the potential evapotranspiration rate assessments across a range of warm season species can be reproduced in a water-heat stress simulation chamber that are representative of evapotranspiration rates monitored in the field, providing the canopy structure and leaf extension rates are comparable, as controlled by the cultural practices employed.
14. The water-heat stress simulation module can be used for the measurement of comparative evapotranspiration rates of turfgrasses.
15. The major cool season turfgrass species vary substantially in water use rates.
16. The comparative water use rate differentials of turfgrasses are of a magnitude that is practical for usage in field applications.
17. Initial data suggest that there may be as much variation among cultivars within a cool season species as there is at the interspecies level.
18. Growth inhibitors do possess a valid potential for use in reducing evapotranspiration rates of turfgrasses, with an effective period of up to 14 weeks and a significant order of reduction ranging from 17 to 28%.
19. The evapotranspiration rate increases as the cutting height is raised.
20. The evapotranspiration rate increases as the nitrogen nutritional level is increased.
21. The relative significance of an increased cutting height or nitrogen nutritional level on the evapotranspiration rate varies with the particular turfgrass species. In high nitrogen requiring turfgrasses, the evapotranspiration is most affected by changes in the nitrogen level, whereas in low nitrogen requiring turfgrasses, evapotranspiration is affected by changes in mowing height.
22. There is genetic diversity within the bermudagrass species that contributes to a variance in potential evapotranspiration (ET). This diversity can be measured and statistically analyzed.
23. Associated plant morphological characteristics of bermudagrasses can be correlated with potential evapotranspiration. Among the characteristics documented are leaf and shoot density, canopy orientation, leaf extension rate, and leaf width.
24. In general, bermudagrass cultivars with a low potential evapotranspiration under non-limiting water conditions had high shoot and leaf densities, horizontal or near horizontal canopy orientations, narrow leaves, and a low to moderate leaf extension rate. The converse was also demonstrated.

25. Visual assessment via the canopy resistance-leaf extension concept, with possible refinements through observer training, offers a rapid, economical approach for screening large numbers of bermudagrass clonal plantings under field conditions for low water use rates.
8. Enhanced Rooting/Water Absorption:
  1. Initial experiments suggest that the root hair dimension of turfgrass root characterization has been overlooked and that over the past three decades, far too much emphasis has been placed on total root mass and depth.
  2. The rooting depths and total root weights of the major warm season turfgrasses vary substantially in terms of interspecies rooting potentials.
  3. The greater rooting capability of the bermudagrasses shown in this study is no doubt a significant factor in the overall drought resistance mechanism.
  4. Preliminary data suggest that, based on the high correlation between both root weight and length with the shoot marker in selecting deep rooting plants, use of shoot biomass as a plant marker in selecting deep rooting plants, thereby avoiding time consuming root measurements. Much more research remains to be done to confirm this at the intraspecies level.
  5. Spring root decline (SRD) is a separate phenomenon rather than a result of other external stresses.
  6. There are two distinctly different dormancy phases for the root and shoot systems of warm season perennial grasses, with root growth sustained after short dormancy occurs.
  7. The spring root decline response has occurred in all ten warm season grasses investigated, which indicates that it is common to most warm season perennial grasses used for turfgrass purposes.
  8. Under controlled environment growth chamber conditions, the temperature threshold above which spring root decline is induced has been documented as 28°C (82°F). Temperatures above this threshold stimulate rapid shoot growth with probable redirection of carbohydrate reserves from the roots to the shoots, resulting in spring root decline. Temperatures below this level result in new root growth from the tips of existing roots with no evidence of spring root decline.
  9. Significant differences in rooting depth and root mass were found among the major cool season turfgrass species when grown under near optimum conditions.
  10. Certain cool season species, such as crested wheatgrass and the tall fescues, exhibited a stronger capability to sustain root growth under severe heat stress conditions.

11. There are variations in rooting among the major cool season species, but the differentials are not nearly as great as observed under near optimum growing conditions.

**C. Improved Drought Resistance:**

1. The major warm season turfgrass species vary greatly in drought avoidance and in drought resistance, with comparative rankings being much different than had been previously assumed.
2. Variations in drought avoidance and recovery is as great within most of the turfgrass species as the variation at the interspecies level.

**D. Physiological Basis of Minimal Maintenance Turfgrasses:**

1. Genetic diversity in terms of minimal maintenance turfgrasses can be observed as morphological, anatomical, and physiological plant parameters and can be statistically evaluated.

SCHEDULE OF RESEARCH ACTIVITIES BASED ON THE PROJECTED BUDGET LEVEL

1978	1980	1982	1984	1986	1988	1990	1992
	Minimal Water Use Rate						
	Enhanced Rooting/Water Absorption						
		Minimal Maintenance					
		Improved Drought Resistance					
				Heat Tolerance			
				Improved Water Stress Hardiness			
				Improved Wear Tolerance			

SUMMARY OF RESEARCH PROGRESS AT TEXAS A&M UNIVERSITY AFTER  
THE INITIAL TWO YEARS OF INVESTIGATION UNDER USGA FUNDING

Status of Study*	Number of Studies Under Each Major Research Objectives					Total
	Minimal Water Use Rate/ET (A)	Enhanced Rooting/Water Absorption (B)	Improved Drought Resistance (C)	Minimal Maintenance Turfgrasses (D)	Improved Heat Hardiness (E)	
Completed and submitted for publication	1	2	---	---	---	3
Research completed with data processing and report preparation underway	4	1	1	---	---	6
Research in second year	2	2	3	1	---	8
Research in first year or just initiated	4	4	1	---	---	9
On hold due to physical facility limitations	---	1	---	---	---	1
Scheduled in next year	2	2	5	2	1	12
Planned for future years **	2	4	12	7	7	32
<b>Total</b>	<b>15</b>	<b>16</b>	<b>22</b>	<b>10</b>	<b>8</b>	<b>71</b>

\* A research objective under a major research thrust may involve more than one study and a study may encompass one to several experiments.

\*\* Includes planned studies scheduled for future years under Objectives C, D, E, and F.



## II. INTRODUCTION

This annual report represents a summary of progress achieved through the second year of water conservation research funded jointly by the United States Golf Association and the Texas Agricultural Experiment Station under the direction of J. B. Beard. The initial date of funding for the USGA grant was March 30, 1983. More recently, the USGA Turfgrass Research Committee established a uniform annual reporting date of November 1. Thus, the annual report for the second year's research has been delayed from March 30th to November 1st. This is more realistic since we were not able to start on the official date due to a delay of several months in getting the funding allocations implemented through the Texas A&M Research Foundation and the Texas Agricultural Experiment Station.

The funding level for the water stress physiology investigation has been at a sufficient level so that excellent progress was made on the research objectives. These findings are summarized and specific data provided in Section IV. After two years, approximately 70% of the planned research on reducing evapotranspiration/water use rates; approximately 40% of the planned research on enhanced rooting/water absorption investigations; 10% of the planned research on improved drought resistance; and 5% of the planned research on the physiology of minimal maintenance turfgrasses have been completed.

No physiological-mechanistic investigations have been initiated concerning the improved heat stress and wear tolerance since initiation of research under these objectives is not scheduled until later, as shown on the schedule of research activities in the Executive Summary. These latter two research objectives must be delayed until the turfgrasses and associated characteristics are identified that contribute to low water use rates, deep rooting, drought resistance, and minimal maintenance requirements. Once this is accomplished, we can then pursue the heat hardiness and wear tolerance dimensions. It is important that this order of organizational structure be followed to ensure that we are investigating the types of grasses that will possess the anatomical, morphological, and physiological characteristics of a water conserving turfgrass. In other words, one could initiate research concerning the wear tolerance and heat hardiness of existing grasses but the results may not be valid on the new water conserving of grasses to be developed. Thus, the reason for a later scheduling of the wear and heat research objectives.

Objective A: Our progress on the Minimal Evapotranspiration/Water Use Rate research objective is well on schedule with the original projections. This investigator recognized that the potential for solving the mechanistic dimensions associated with this particular problem within a reasonable period of time was high since a significant amount of research had already been conducted at TAMU prior to receiving the USGA grant. In addition, the problem is not nearly as complex as the other research objectives, such as drought resistance.

Objective B: We are currently deeply involved in the second research objective concerning Enhanced Rooting/Water Absorption. Identifying plant markers that can be used in a breeding program for rapid screening is a difficult challenge. However, basic botanical studies into such aspects as root hairs, their description on different species, and how they are affected by environmental

and cultural factors could be a very significant aspect in addition to the relationship between the root hair characteristics and the rooting depth/ mass. At this stage in the rooting research effort, there is evidence that it may be possible to develop a rapid screening technique; although with our current level of knowledge the probability of success is not as high as that for the low water use rate objective.

Objective C: The third research objective involves Improved Drought Resistance. This is a very complex phenomena. The avoidance component of drought resistance encompasses the evapotranspiration rate and rooting dimensions. Thus, research on the earlier two objectives will contribute to our overall understanding of drought resistance as well as for the other objectives planned within the project. The complex nature of drought resistance and the lack of existing information on perennial turfgrasses does not allow one to make a reasonable estimate for a time frame in which the drought resistance mechanistic aspects can be solved to the point that potential plant markers for rapid screening in a breeding program are available. Our initial studies at the interspecies and intraspecies levels for the major warm season turfgrasses reveal that the comparative drought resistances are much different than what turfgrass specialists have predicted and shows just how little we know about the drought resistance of perennial turfgrass species. Thus, it is a very challenging area but one in which major contributions to water conservation can be made.

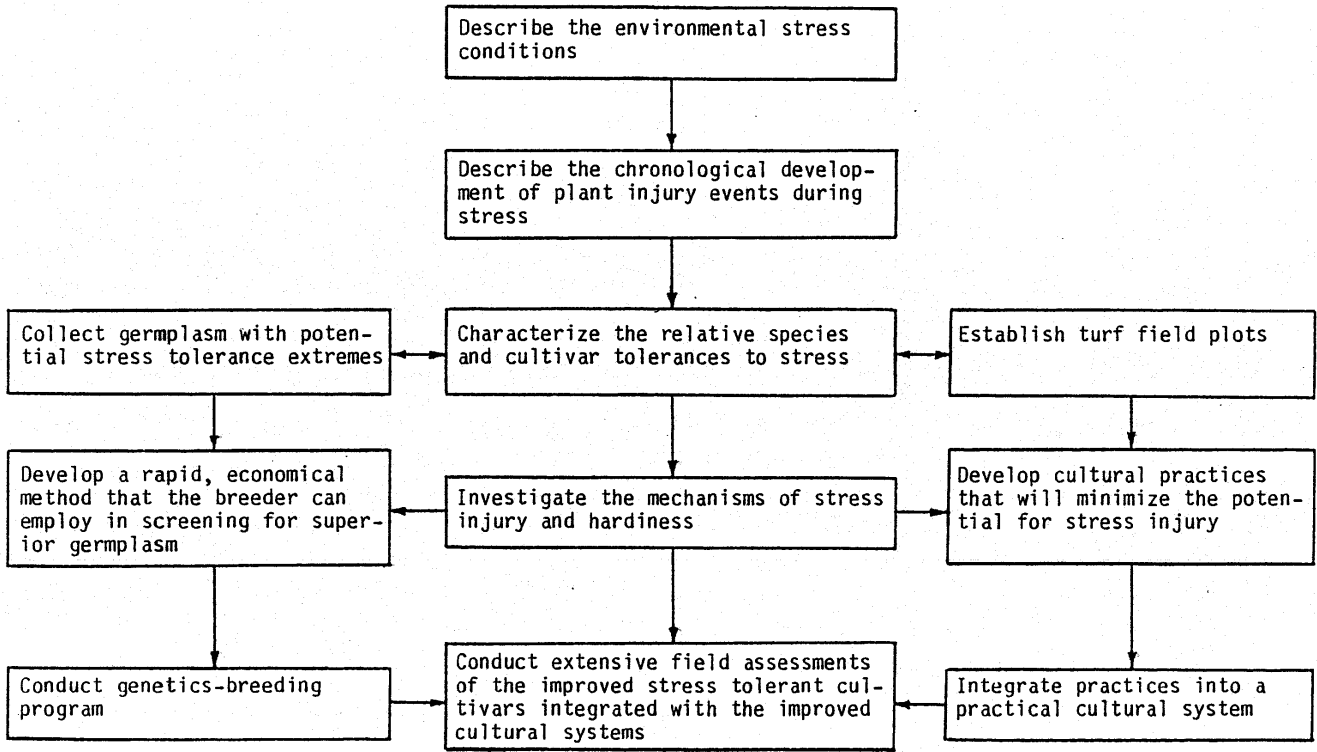
Objective D: The fourth research objective concerning the Physiological Basis of Minimal Maintenance Turfgrasses is a pioneering adventure. Based on the initial studies reported herein, there is a reasonable expectation of success, given adequate time and funding. The reason for this optimism is that the characteristics contributing to a low evapotranspiration rate also may be associated with turfgrasses which have a minimal maintenance requirement.

Objective E: The research on Heat Hardiness as it relates to water conserving turfgrasses is not scheduled to be initiated as yet. Water and heat stresses are closely interrelated. A turfgrass with a low water use rate may in turn possess less heat tolerance. Thus, the heat hardiness dimension will receive attention once adequate progress is made on Objectives A, B, and C.

Objective F: The complex subject of Internal Water Stress Hardiness is actually a component of drought resistance. Research on this aspect will be initiated when the descriptive and species comparison phases of the Improved Drought Resistance Objective are complete.

Objective G: The Improved Wear Tolerance Objective must be addressed once objectives A, B, C, and D are well advanced. It is suspected that turfgrasses with water conserving, minimal maintenance characteristics may also possess reduced wear tolerance. Thus, the need for this research objective as a part of the overall goal of Water Conserving, Minimal Maintenance Turfgrasses and Cultural Systems.

An environmental stress physiology - genetics model to improve stress tolerance in turfgrasses.



### III. IMPLEMENTATION

#### A. Organization

The research project organizational structure remains the same for the upcoming year as for the initial two years. With the projected reduction in funding for the fourth year, this structure will have to be changed substantially. There will be a reassignment of responsibilities with two key people assigned a greater range in types of research activities due to a reduction of one full-time position. This will result in substantially slower progress than had been projected in the original proposal.

#### B. Personnel

\* Concerning the current personnel status, the Postdoctoral position formally filled by Dr. David M. Casnoff was held open from March to September so that funds could be utilized for other needed aspects of the ongoing research. As of September 9th, Dr. Robert L. Green, formerly of Oklahoma State University, joined the USGA Water Conservation Research Project in the Postdoctoral position.

Robert L. Green received B.S. degrees in Biology from Florida State University in 1974 and in Ornamental Horticulture in 1977 from the University of Florida. He received his M.S. degree in Horticultural Science in 1979 and his Ph.D. degree in Agronomy in 1982 from the University of Florida. Dr. Green's major area of study and interest during his graduate program was turfgrass science-management and breeding-genetics. In 1982, He accepted a faculty position at Oklahoma State University as Assistant Professor and Ornamental-Turf Extension Specialist. For three years, he worked closely with the turfgrass industries in Oklahoma, providing them with technical and practical information. He also was responsible for the State Turfgrass Weed Control Recommendations.

Dr. Green joined the Turfgrass Stress Physiology Research Project at Texas A&M University in September of 1985 as a Postdoctoral Fellow working with Dr. James B. Beard. His experience in working on basic physiological problems and his practical insight will be a valuable addition to the Project. Dr. Green's research responsibilities will include the area of root hair characterizations and determining just how significant an overall description of root length and mass is versus the measurement of root hairs through which the absorption of water is actually occurring. It may be that most turf root research which has placed emphasis on the total mass and depth of roots may have overlooked an important aspect since a turf could possess a large root mass but very little functioning root hair zone. This is an important question to be answered in relation to maximizing water uptake, thus, contributing to maximum drought avoidance of turfgrasses.

\* A second personnel change occurred on September 1, 1985, with the resignation of Mr. Doug Dahms as Agricultural Research Technician in charge of turfgrass maintenance at the Turfgrass Field Research Laboratory. Mr. Dahms' performance record was excellent over the past four years, and he has returned to school to complete his undergraduate degree in the Turfgrass Option. This

position was immediately filled when Mr. John Walker accepted an offer of employment.

John R. Walker graduated from Texas A&M University in 1985 with a B.S. degree in Agronomy (Turfgrass Management and Soil Science Options). While attending college, he was actively involved with the American Society of Agronomy Student Chapter. He held the offices of Reporter and Vice-President and was elected President during his senior year. He also was a member of the 1984 Texas A&M Soil Judging Team which placed second in the regional contest and qualified for the National Contest where they placed thirteenth. He represented Texas A&M University in the National Student Speech Contest, held in conjunction with the Agronomy Society Annual Meetings, in 1984, and placed fourth. He was actively involved in the Texas A&M Turf Club. Mr. Walker has three years of experience in landscape installation and one summer of experience in golf course operations. That experience combined with his formal education at Texas A&M and having worked for the past four months at the Turfgrass Field Research Laboratory places him in a strong position to assume the responsibilities that are so critical to the operation of the Turfgrass Research Project.

\* The remaining research personnel continue as in past years.

- Mr. Sam I. Sifers is in charge of the growth chambers, greenhouse, and a portion of the stress physiology investigations.
- Mr. Steve D. Griggs is in charge of the stress physiology lab, computer operations, and statistical data processing.
- Kisun Kim, a graduate student, has completed course work for his Ph.D. and is conducting his dissertation research in the area of drought resistance mechanisms. He should complete this research phase within the next year.
- A new graduate student, Mr. Paul H. Vermeulen, is scheduled to arrive in January, 1986 and will most probably become involved in a portion of the USGA sponsored water conservation research. The exact problem area that he will pursue will not be identified until after his arrival.

### C. Facilities Development

The status of the physical facilities that are so important in conducting the stress physiology investigations is good. The water-heat stress simulator used in the evapotranspiration rate studies is operated 24 hours a day, 7 days a week, for 50 weeks a year. It continues to perform well after some major renovations and rebuilding of control parts during the first year. A compressor replacement was required on one of the controlled environment growth chambers utilized in the rooting studies, but fortunately the down time was less than three weeks.

A 60-cm deep sand root zone site of 22 x 22 meters was constructed for the drought studies and functioned well for the studies conducted during the summer of 1985. In addition, a 15 x 26-meter sand modified area of 25 cm in depth was completed; Tifway bermudagrass established; and a cutting height-nitrogen-potassium interaction study initiated in relation to evapotranspiration rates, rooting, and drought resistance.

Funds were provided from another source for purchase of a \$3,600 computerized data recorder, that will greatly speed up the field data collection and

processing dimensions of the research. In addition, \$14,000 was provided by the Texas Agricultural Experiment Station for construction of a 1.5-meter deep sand root zone combined with a linear gradient irrigation system installation. It has not yet been determined whether state funds will be available for conducting the seasonal minimal water requirement study that is planned. If not available, this area would be ideal for use during the second year of drought stress studies, as it has a much deeper permeable root zone and larger area to facilitate the investigations.

The current amount of work with root columns combined with all the plant material that is maintained in pots for the water balance technique used in the evapotranspiration studies have filled our greenhouse facilities to maximum capacity. We are hopeful that additional space can be obtained so this condition will be alleviated in the upcoming winter season. The greenhouse space situation is creating some difficulties, but it is not delaying our progress.

#### IV. STATUS REPORTS AND KEY RESULTS AFTER TWO YEARS OF INVESTIGATIONS

The three major research objectives addressed during the past two years were (A) Minimal Water Use Rates, (B) Enhanced Rooting/Water Absorption, and (C) Improved Drought Resistance. In addition, studies have been initiated more recently under Objective D, the Physiological Basis of Minimal Maintenance Turfgrasses. Good progress has been made on all four major research thrusts during the past year. Emphasis has been placed on completion of a number of subobjective studies; plus the statistical analysis, assessment, and writing of individual scientific papers for publication in research journals.

##### A. OBJECTIVES FOR MINIMAL WATER USE RATES AND THE RESEARCH STATUS

This major research thrust relates primarily to the development of low water use rates for turfs that are normally irrigated, therefore, contributing to water conservation. However, the development of turfgrasses and cultural systems possessing reduced evapotranspiration rates also will contribute one dimension to a drought avoidance strategy that is one component of drought resistance.

A-1. Determine the comparative potential evapotranspiration rates of eleven major warm season turfgrass species under non-limiting moisture conditions. Initiated in 1983.

Status - Two full years of field studies plus two laboratory studies in the controlled environment water/heat stress simulator have been conducted. The evapotranspiration rates of eleven major warm season turfgrasses were assessed by means of the water balance method using the mini-lysimeter technique. The scientific paper has been written and submitted for publication in Crop Science. (Species Comparison) K. Kim and S. Griggs.

Results - As a group, the warm season turfgrasses have a lower potential evapotranspiration rate than the cool season turfgrasses as shown in the following table. Potential evapotranspiration is the maximum rate that occurs under non-limiting moisture conditions. The range in potential evapotranspiration rates for the warm season turfgrasses assessed was from 5.5 to 8.5 mm per day. High density, low growing species such as buffalograss, centipedegrass, and the hybrid bermudagrasses exhibited low water use rates. Other warm season species, such as St. Augustinegrass, seashore paspalum, and bahiagrass exhibited medium evapotranspiration rates in comparison to the cool season turfgrasses, but ranked highest of the warm season species. These results represent the first definitive information regarding the comparative water use rates among the major warm season turfgrasses (Table A-1).

Table A-1. Relative Ranking of Potential Evapotranspiration (PET) Rates for the Major Cool and Warm Season Turfgrasses \*

Relative Ranking	PET Rate (mm/day)	Turfgrass	
		Cool Season	Warm Season
Very low	< 6		Buffalograss
Low	6 - 7		Bermudagrass hybrids Centipedegrass Bermudagrass Zoysiagrass Blue grama
Medium	7 - 8.5	Hard fescue Chewings fescue Red fescue	Bahiagrass Seashore paspalum St. Augustinegrass Zoysiagrass, Emerald
High	8.5 - 10	Perennial ryegrass	
Very high	> 10	Tall fescue Creeping bentgrass Annual bluegrass Kentucky bluegrass Italian ryegrass	

\* Grown in their respective climatic regions of adaptation and proper cultural regime.

#### Conclusions -

- a. The major warm season turfgrasses species vary substantially in water use rates.
- b. The comparative interspecies water use rates are of a magnitude to have practical significance for field applications.
- c. Initial data suggest that there may be as much variation among cultivars within a species as there is at the interspecies level.

\* \* \* \* \*



A-2. Assess the relationship of shoot morphology to the potential evapotranspiration rates of eleven major warm season turfgrasses. Initiated in 1983.

Status - Two full years of field studies plus one extensive controlled climate water/heat simulation chamber study have been completed. A scientific paper has been submitted for review. (Mechanistic Aspects and Development of Breeding Markers) K. Kim, S. Griggs, and S. Sifer.

Results - These mechanistic studies have revealed that certain types of plant morphology affect the resistance to water loss via evapotranspiration as does the surface from which evapotranspiration occurs. There are two major components: (a) a high canopy resistance to evapotranspiration which includes a high shoot density and a more horizontal leaf orientation and (b) a low leaf area from which evapotranspiration can occur, which includes a narrow leaf width and a slow vertical leaf extension rate.

These two morphological dimensions, when assessed over eleven major warm season species in relation to their respective evapotranspiration rates, fit very well in terms of the mechanistic interpretation of why the differential evapotranspiration rates have occurred at the interspecies level. The relative importance of each individual morphological component does vary depending on the particular species. Now that a definitive mechanistic interpretation for the differences in water use rates has been established at the interspecies level, the next step is to conduct comparable intraspecies studies such as Subobjectives A-8 and A-9.

In addition to being an easily, rapidly assessed marker for use in breeding programs, it is also evident that these plant morphological characteristics can be readily manipulated by the turf manager. Thus, the comparative evapotranspiration rates as reported under Subobjective A-1 can be altered substantially depending on the particular mowing, nutritional, and irrigation regime implemented by the turf manager. The degree of alteration in the evapotranspiration rate is sufficiently large that there could actually be shifts in the comparative interspecies rankings. Thus, the reason for Subobjectives A-7 and A-11.

#### Conclusions -

- a. The primary plant parameters affecting the evapotranspiration rate are a high canopy resistance and a low leaf blade area.
- b. These plant morphological parameters are valid in interpreting the differentials in water use rates among eleven major warm season perennial turfgrasses.
- c. Fortunately, these morphological parameters can be easily and rapidly assessed for use in screening thousands of clonal plantings for low water use rates in a breeding program.
- d. These morphological factors are subject to modification by a number of cultural practices; thus, the turf manager can significantly affect the water use rate of a given turfgrass species.

\* \* \* \* \*

A-3. Compare the stomatal characteristics and densities among ten major warm season and twelve major cool season turfgrasses under uniform growth chamber conditions. Initiated in 1983.

Status - Controlled environmental studies are completed for the ten major warm season turfgrasses and the twelve major cool season grasses. Statistical analyses have been completed on both the warm season turfgrasses and the cool season species. A scientific paper has been drafted for the warm season species and is now in the review process. (Mechanistic Study) D. Casnoff and S. Griggs.

Results - Ten warm season C<sub>4</sub> turfgrasses were characterized for stomatal density on both the adaxial and abaxial sides of the youngest, fully expanded leaf blade and for their associated water use rate. Water use was measured using a specially designed environmental chamber, wherein three replications of each cultivar were grown in 1 gallon mini-lysimeters pots.

Significant differences were found in water use rates and in stomatal densities on both sides of the leaf blade. Within any given species, there are usually more stomates per given area on the adaxial compared to the abaxial side of the leaf. Highest overall stomatal densities were found in Meyer and Emerald zoysiagrasses; followed by Tifgreen, Tifway, and Common bermudagrasses, Common buffalograss, Texas Common St. Augustinegrass, Adalayd seashore paspalum, Common centipedegrass, and Argentine bahiagrass. The highest potential evapotranspiration rates under non-limiting soil moisture and uniform cultural conditions were found for Emerald zoysiagrass; followed by Argentine bahiagrass, Texas Common St. Augustinegrass, Adalayd seashore paspalum, Meyer zoysiagrass, Common centipedegrass, Common bermudagrass, Tifgreen bermudagrass, Tifway bermudagrass, and Common buffalograss. Correlations between stomatal density on the abaxial side of the leaf blade and the water use rate were significant, but also negative and low in value ( $r = -0.43^*$ ). When comparing stomatal density on the abaxial and adaxial sides of the leaves, a correlation of  $0.87^{**}$  was found. There was a relationship found between stomatal arrangement and the two subfamilies, Eragrostoideae and Panicoideae, represented by the turfgrass species used in this study (Table A-3.1)

Of the cool season turfgrasses studied thus far, there are significant differences in the stomatal densities on the adaxial sides of the leaf blade. The highest densities have been found for sheep and hard fescues; followed by chewings fescue, perennial ryegrass 'Manhattan II', annual bluegrass (subsp. reptans), Kentucky bluegrass 'Majestic', and tall fescue 'Rebel' and 'Kentucky 31'. Some samples of Kentucky 31 had higher stomatal densities on the abaxial side of the leaf blade rather than the adaxial side. This is the only exception to the usual case where more stomates are found on the adaxial side than the abaxial side. There are some very striking differences in stomatal arrangements on the abaxial sides of those cool season turfgrass species studied. Perennial ryegrass has stomates only adjacent to both sides of the mid-rib. Chewings fescue, sheep fescue, and hard fescue had no stomates on the abaxial side. All other species studied had stomates found on the entire abaxial surface. Relationships between the stomatal densities and evapotranspiration rates of these cool season turfgrasses will be analyzed as soon as the data collection phase is complete.

Table A-3.1 The comparative stomatal densities on the adaxial and abaxial sides of a leaf blade of ten warm season turfgrass species and their potential evapotranspiration (PET) rates and vertical leaf extension rates after 24 hours under non-limiting soil moisture conditions and maintained at 30°C air temperature and with a 10°C dew point.

Turfgrasses	Stomatal Density*		Mean PET (mm d <sup>-1</sup> )	Mean Daily Vertical Leaf Extension Rate (mm d <sup>-1</sup> )
	Adaxial ---- (per 1 mm <sup>2</sup> )	Abaxial -----		
<u>Subfamily Eragrostoideae</u>				
Meyer zoysiagrass	468 a**	284 ab	7.8 b	3.2 cd
Emerald zoysiagrass	432 ab	256 b	9.4 a	4.4 cd
Common bermudagrass	404 ab	308 ab	6.4 cd	9.3 a
Tifgreen bermudagrass	400 ab	344 a	6.3 cd	2.4 d
Tifway bermudagrass	400 ab	348 a	5.8 d	3.2 cd
Common buffalograss	344 b	236 b	5.7 d	9.3 a
<u>Subfamily Panicoideae</u>				
Texas Common St. Augustinegrass	240 c	92 c	8.1 b	2.5 d
Adalayd seashore paspalum	220 c	116 c	8.1 b	5.6 bc
Common centipedegrass	112 d	92 c	7.4 bc	4.1 cd
Argentine bahiagrass	96 d	84 c	8.2 b	7.1 ab

\* Counts were made prior to potential evapotranspiration measurements.

\*\* Means followed by the same letter are not significantly different at the 5% level according to Duncan's Multiple Range Test.

Table A-3.2. The Comparative Stomatal Densities on the Adaxial and Abaxial Leaf Blades of Twelve Cool Season Turfgrass Species

Turfgrass Species and Cultivar	Adaxial per 1 mm <sup>2</sup>	Abaxial per 1 mm <sup>2</sup>
Hard Fescue, Waldina	50.83 a	0.00 d
Creeping Bentgrass, Penncross	44.00 ab	25.00 a
Sheep Fescue	36.83 abc	0.00 d
Chewings Fescue	35.50 abcd	0.00 d
Annual Bluegrass	33.83 bcde	17.83 ab
Kentucky Bluegrass, Bensun	31.17 bcdef	10.18 bcd
Perennial Ryegrass, Manhattan II	31.17 bcdef	4.17 cd
Tall Fescue, Rebel	21.90 cdef	11.43 bcd
Rough Bluegrass, Sabre	21.83 cdef	0.00 d
Kentucky Bluegrass, Majestic	19.87 def	9.33 bcd
Kentucky Bluegrass, Merion	18.33 ef	6.00 bcd
Tall Fescue, Kentucky 31	17.00 f	13.70 bc

### Conclusions -

- a. Both the warm and cool season turfgrass species possess significant differences in stomatal density.
- b. Both warm and cool season turfgrasses vary significantly in stomatal distribution over the leaf. In the case of warm season turfgrasses, there is a distinct relationship between the stomatal arrangement and their associated subfamily classifications of Eragrostoideae and Panicoideae.
- c. A significantly higher stomatal density was found on the adaxial side of the leaf in comparison to the density found on the abaxial side, with the exception of Kentucky 31 tall fescue.
- d. There was no relationship between an increase in evapotranspiration rate and a higher stomatal density. In fact, there was a trend to the inverse relationship.
- e. Although, the studies of stomatal characterizations have not elucidated a component contributing to reducing evapotranspiration rates, these results may be significant and useful in the upcoming mechanistic studies of drought resistance.

\* \* \* \* \*

A-4. Establish the accuracy with which the water-heat stress simulation module reproduces representative evapotranspiration rates typically observed in the field. Initiated in 1983.

Status - A series of two field studies and three controlled environment water/heat stress simulation chamber experiments have been completed. Currently, a scientific paper is in the process of being written. (Interspecies Comparison Study) S. Griggs and K. Kim.

Results - Potential evapotranspiration (PET) rates of ten warm season turfgrasses and 1 cool season turfgrasses were assessed to compare the validity of results obtained from the simulation experiments relative to the results obtained in the field. As shown in the accompanying table, there was a strong relationship between the results obtained in the field and those obtained in the simulation chamber provided the specific cultural practices were the same as in the field in order to achieve a comparable canopy structure and leaf extension rate. The results indicate that assessments of the evapotranspiration rates for twelve cool season turfgrasses can be conducted in the simulation chamber.

Table A-4. Comparative Potential Evapotranspiration Rates as Determined in the Stress Simulation Chamber vs Field Conditions for Nine Warm Season Turfgrasses and One Cool Season Turfgrasses. (Chamber at 30°C temperature and 10°C dew point).

Simulation Growth Chamber		Field Plot Conditions	
Turfgrass	PET (mm/day)	Turfgrass	PET (mm/day)
Kentucky 31 Tall Fescue	9.70	Kentucky 31 Tall Fescue	7.13
Argentine Bahiagrass	8.20	Tx Common St. Augustinegrass	6.32
Tx Common St. Augustinegrass	8.09	Argentine Bahiagrass	6.25
Adalayd Seashore Paspalum	8.09	Adalayd Seashore Paspalum	6.15
Meyer Zoysiagrass	7.84	Tifway Bermudagrass	5.88
Common Centipedegrass	7.37	Meyer Zoysiagrass	5.82
Common Bermudagrass	6.43	Common Bermudagrass	5.77
Tifgreen Bermudagrass	6.32	Common Centipedegrass	5.50
Tifway Bermudagrass	5.80	Tifgreen Bermudagrass	5.43
Texoka Buffalograss	5.73	Common Buffalograss	5.26

#### Conclusions -

- a. It was found that the results of the potential evapotranspiration rate assessments across a range of warm season species can be reproduced in a water-heat stress simulation chamber that are representative of evapotranspiration rates monitored in the field, providing the canopy structure and leaf extension rates are comparable as controlled by the cultural practices employed.

- b. The water-heat stress simulation module can be used for the measurement comparative evapotranspiration rates of turfgrasses.

\* \* \* \* \*

- A-5. Determine the comparative potential evapotranspiration rates of twelve major cool season turfgrasses. Initiated in 1983.

Status - The characterization of potential evapotranspiration rates among twelve major cool season turfgrasses have now been completed in the controlled environment simulation chamber. The data have been statistically analyzed in preparation for drafting a scientific paper. (Species Characterizations) S. Griggs.

Results - As a group, the cool season turfgrasses are characterized by water use rates that are significantly higher than the rates found for warm season species as described under Subobjective A-1 (Table A-1). The potential evapotranspiration rates monitored among the twelve cool season turfgrass species ranged from 7.4 to 12.4 mm per day. The highest evapotranspiration rates were exhibited by the Kentucky bluegrasses, annual bluegrass, creeping bentgrass, and tall fescue. Perennial ryegrass ranked intermediate and the fine-leaved fescues ranked the lowest. In comparison with warm season species, the fine-leaved fescues would rank in the medium category. As with the warm season turfgrasses, plant morphology parameters, such as a high canopy resistance and a low leaf area, were strongly associated with a low water use rate. The potential for turfgrass breeders to make rapid field assessments for low water use plants using these plant parameters is promising. This approach must be confirmed by studies conducted on cultivars and/or selections at the intraspecies level for each species. These results represent the first definitive information regarding the comparative water use rates among the major cool season turfgrasses.

Conclusions -

- a. The major cool season turfgrasses species vary substantially in water use rates.
- b. The comparative water use rate differentials of turfgrasses are of a magnitude that is practical for usage in field applications.
- c. Initial data suggest that there may be as much variation among cultivars within a species as there is at the interspecies level.

Table A-5. The Comparative Potential Evapotranspiration (PET) Rates of Twelve Cool Season Turfgrasses Assessed in the Water-Heat Stress Simulator at 22°C Temperature and 12°C Dewpoint.

Turfgrass	PET (mm d <sup>-1</sup> )
Kentucky Bluegrass, Merion	12.42 a
Kentucky Bluegrass, Bensun	12.39 a
Kentucky Bluegrass, Majestic	11.93 ab
Tall Fescue, Rebel	11.42 abc
Creeping Bentgrass, Penncross	10.10 abcd
Tall Fescue, Kentucky 31	9.87 abcde
Annual Bluegrass	9.76 bcde
Sheep Fescue	9.29 cde
Perennial Ryegrass, Manhattan II	9.14 cde
Rough Bluegrass, Sabre	8.42 de
Chewings Fescue	7.72 de
Hard Fescue, Waldina	7.42 e

\* \* \* \* \*

A-6. Determine the potential for using turfgrass leaf growth inhibitors in water conservation. Initiated in 1983.

Status - Three field experiments and one greenhouse experiment have been completed under this objective. A scientific paper is being written. (Mechanistic and Cultural Studies) W. Menn.

Results - Based on earlier mechanistic investigations of plant morphological factors affecting resistance to evapotranspiration, a hypothesis was developed regarding the potential to use growth regulators in slowing vertical leaf extension rates of turfgrasses and thereby reduce evapotranspiration. Studies were conducted on Texas Common St. Augustinegrass and Tifway bermudagrass over a three-year period in the field, plus one greenhouse study.

Results show that the hypothesis was valid and that water use rates could be reduced in the order of 17 to 28% for a period of up to 14 weeks, depending on the particular turfgrass species and the environmental growing conditions in the field. Species with a more rapid leaf extension rate, such as St. Augustinegrasses, or a more favorable environmental condition for growth which enhances the leaf extension rate, resulted in a greater percentage reduction in evapotranspiration when an effective growth regulator was used. The two materials successfully used in these studies were flurprimidol and mefluidide. These were the first investigations to demonstrate the additional benefit of achieving water use conservation via the use of an effective growth inhibitor and thereby also increase the cost-benefit effectiveness of these materials.

## Conclusion

- a. Growth inhibitors do possess a valid potential for use in reducing evapotranspiration rates of turfgrasses, with an effective period of up to 14 weeks and a significant order of reduction from 17 to 28%.

\* \* \* \* \*

- A-7. Compare the influence of cutting height and nitrogen rate on the evapotranspiration rates of eleven major warm season turfgrasses. Initiated in 1983.

Status - A series of field studies over two years have been completed utilizing eleven major warm season species and a scientific paper has been submitted for review. (Improved Cultural Systems) K. Kim and S. Sifers.

Results - The approach in this study involved an assessment of evapotranspiration rates by the water balance method under field condition on two major study areas. One study area had all species maintained at a uniform cutting height of 3.8 cm and a nitrogen nutritional level of 0.2 kg/are per growing month. In the second study area, all species were maintained at their respective optimum cutting heights and nitrogen nutritional levels. Both experimental areas were irrigated to maintain a non-limiting moisture environment. Very consistent results from these areas revealed that those species with a high nitrogen requirement had their evapotranspiration rates affected to the greatest extent by changes in the nitrogen fertilization level. In contrast, those species having a low nitrogen requirement had their evapotranspiration rate most affected by changes in the cutting height. In case of the former, the evapotranspiration rate increased with increases in the nitrogen fertilization rate, while in the case of the latter, the evapotranspiration rate increased when the cutting height was raised. Whether affected by an increase in the nitrogen fertilization level or an increase in the mowing height, the evapotranspiration rate increase was associated with an increase in leaf area, primarily via a more rapid leaf extension rate.

## Conclusions -

- a. The evapotranspiration rate increases as the cutting height is raised.
- b. The evapotranspiration rate increases as the nitrogen nutritional level is increased.
- c. The relative significance of increased cutting height or nitrogen nutritional level on the evapotranspiration rate varies with the particular turfgrass species. In high nitrogen requiring turfgrasses, the evapotranspiration is most affected by changes in the nitrogen level, whereas in low nitrogen requiring turfgrasses, evapotranspiration is affected by changes in mowing height.

\* \* \* \* \*



A-8. Determine the comparative potential evapotranspiration rates of twenty-four bermudagrass cultivars under non-limiting moisture conditions. Initiated in 1984.

Status - This two-year study and the results are in the final stages of analysis. The preparation of a scientific paper will be initiated soon. (Intraspecies Comparison and Breeding Markers) S. Sifers and K. Kim.

Results - Potential evapotranspiration rates were assessed for twenty-four bermudagrass cultivars grown under field conditions. The approach involved the use of the water balance method with mini-lysimeters inserted into the turfgrass variety plots at the TAMU Turfgrass Field Laboratory on a modified sand root zone. One cultivar was added in the fall of 1984; thus, the results for this cultivar encompasses only one year. The plots were mowed at 2.18 cm and received 0.5 kg nitrogen per growing month.

The accompanying table illustrates the relative rankings of the bermudagrass cultivars. The cultivars varied significantly in potential evapotranspiration rates. Also included in the table are the mean leaf extension rate, mean shoot density, leaf width, and canopy orientation for each cultivar. There is an association between the relative evapotranspiration rate of each cultivar and its morphological characteristics. The relative importance of each individual characteristic varies among the turfgrass species, with leaf orientation and shoot density appearing to be associated with the evapotranspiration rate across the full range of twenty-four cultivars.

Conclusions -

- a. There is genetic diversity within the bermudagrass species that contributes to a variance in potential evapotranspiration (ET). This diversity can be measured and statistically analyzed.
- b. Associated plant morphological characteristics can be correlated with potential ET. Among the characteristics documented are leaf and shoot density, canopy orientation, leaf extension rate, and leaf width.
- c. In general, bermudagrass cultivars with a low potential ET under non-limiting water conditions had high shoot and leaf densities, horizontal or near horizontal canopy orientations, narrow leaves, and a low to moderate leaf extension rate. The converse was also demonstrated.

\* \* \* \* \*

A-9. Assess the validity and relative accuracy of visual estimates of evapotranspiration rates using the canopy resistance-leaf extension concepts as would be applied in a turfgrass breeding program. Initiated in 1984.

Status - This two-year study has been completed for bermudagrass and zoysiagrass species. Visual rankings are completed for the bermudagrass for two years and compared to statistical data. One visual ranking has been made for zoysiagrass and will be analyzed when data from C-10 is available. (Breeding Markers) S. Sifers, M. Engelke, and G. Horst.

Table A-8. Comparative analysis of potential evapotranspiration (PET) rate of 24 bermudagrass cultivars versus associated plant parameters, under non-limiting moisture conditions and mowing at 1 inch, during 1984 and 1985 at College Station, Texas using Duncan's Multiple Range Test for Variable.

Cultivar	PET Mean for 2 Years mm day <sup>-1</sup>	Leaf Extension Rate Mean mm	Shoot Density per dm <sup>2</sup>	Leaf Width mm	Canopy Orientation 0 = Horizontal 9 = Vertical
Sunturf	5.51 a*	6.49 abc*	70.1 bcd*	1.8 abcd*	6.3 ab*
A-29	5.43 a	5.21 bcd	64.3 def	1.8 abcd	6.0 abc
Santa Ana	5.37 ab	6.16 abc	70.2 bcd	1.8 abcd	5.0 bcdef
Ormond	5.36 ab	5.27 bcd	65.9 cdef	2.1 ab	5.6 abcd
Tufcote †	5.23 ab	6.22 abc	68.8 cde	2.2 a	5.0 bcdef
Common	5.21 abc	9.63 a	44.5 f	2.1 a	7.0 a
Tifgreen	5.13 abc	5.39 bcd	70.9 bcd	1.5 cde	4.7 cdef
Tifway II	5.10 abcd	5.55 abcd	94.5 ab	2.0 abc	5.3 bcde
Texturf 1F	5.10 abcd	7.63 ab	62.1 ef	1.9 abc	5.3 bcde
A-22	5.01 abcde	6.64 abc	70.0 bcd	1.9 abc	5.0 bcdef
Tifway	5.01 abcde	5.57 abcd	115.2 ab	1.6 bcde	4.7 cdef
Tiffine	4.99 abcde	6.26 abc	79.2 abc	1.7 bcd	4.7 cdef
Tifgreen II	4.99 abcde	4.77 cde	84.7 abc	1.7 bcd	4.7 cdef
FB 119	4.94 abcdef	6.81 abc	68.0 cde	2.1 ab	5.0 bcdef
U-3	4.93 abcdef	5.52 abcd	83.7 abc	1.8 abcd	4.7 cdef
Tiflawn	4.89 abcdef	6.17 abc	88.4 ab	1.9 abc	4.7 cdef
Pee Dee	4.86 bcdef	5.51 abcd	89.9 ab	1.4 de	4.0 efg
Texturf 10	4.79 bcdef	5.95 abc	65.9 cdef	2.5 a	5.0 bcdef
Vamont	4.69 cdef	4.73 cde	84.7 abc	2.2 a	3.7 fg
Midway	4.68 cdef	7.24 ab	85.0 abc	1.8 abcd	4.3 defg
Midiron	4.65 cdef	7.15 ab	84.2 abc	2.2 a	4.3 defg
Tifdwarf	4.63 def	3.04 e	126.6 a	1.3 e	3.0 g
Everglades	4.55 de	7.25 ab	88.6 ab	1.7 bcd	4.0 efg
Bayshore	4.43 e	6.59 abc	82.1 abc	1.8 abcd	4.3 defg

\* Means with the same letter are not significantly different at the P=0.05 level in the Duncan's Multiple Range Test.

† Based on one year's data.

Results - A study was conducted on field plots at the TAMU Turfgrass Research Laboratory which contained twenty-four bermudagrass cultivars. The turfs were established in 1978. They had been maintained at a cutting height of 2.5 cm and received 0.5 kg nitrogen per 1,000 square feet per growing month, as well as irrigation as needed to prevent visual wilt. The potential evapotranspiration measurements were accomplished using the water balance method with mini-lysimeter technique. At the same time measurements were taken, visual ratings of comparative evapotranspiration rates were made based on the high canopy resistance-low leaf area concept. The visual estimates were made directly on the turfs growing in the mini-lysimeters by four observers: Drs. Beard, Casnoff, Engelke, and Horst. Visual rankings based on canopy orientation, leaf extension rate, leaf width, and leaf-shoot densities correlated at a 75% accuracy level with the actual potential evapotranspiration measurement for the 1984 data. In May of 1985, a similar study resulted in an accuracy level of 72%. The highest score achieved was 74% and the lowest was 66%. This range in variation suggests that training of the evaluators is needed to ensure the best possible accuracy, as the highest accuracy level was achieved by the individual most experienced with the canopy resistance-leaf area concepts as related to evapotranspiration rates.

Conclusions -

- a. Visual assessment via the canopy resistance-leaf extension concept, with possible refinements through observer training, offers a rapid, economical approach for screening large numbers of bermudagrass clonal plantings under field conditions for low water use rates.

\* \* \* \* \*

A-10. Determine the comparative potential evapotranspiration (PET) rates for seven zoysiagrasses that had a diverse array of canopy densities, leaf orientations, and leaf extension rates as related to the visual prediction technique. Initiated in 1985.

Status - The first year of a two-year study has been partially completed, and the initial results are in the final stages of analysis. This study will compare the potential evapotranspiration (ET) rates of eleven zoysiagrasses maintained in the greenhouse and assessed in the water-heat stress simulator, as well as in the field. Plant types being evaluated ranged from a narrow leaf, dense canopy zoysiagrass to a broad leaf, open canopy zoysiagrass with several cultivars between these two extremes. One field evaluation was completed in the fall of 1985. The greenhouse and water-heat stress simulator testing will occur simultaneously during the winter of 1985-86 with replicate testing scheduled for 1986. One visual ranking was completed by Dr. J. B. Beard, Dr. M. Engelke, and S. Sifers on October of 1985. (Interspecies Comparison and Breeding Markers) S. Sifers, S. Griggs, and M. Engelke.

\* \* \* \* \*

A-11. Investigate more critically the influence of cutting heights and nitrogen nutritional levels on evapotranspiration rates. Initiated in 1984.

Status - Sand root zone modification to USGA specifications including a root zone of 25 cm placed over a drain line system has been installed and a Tifway

bermudagrass turf established. In the spring of 1985, cultural treatments were imposed across the plot area in all possible combinations including:

- (a) Three cutting heights of 1.3, 2.5, and 3.8 cm;
- (b) Three nitrogen nutritional levels of 0.5, 1.0, and 1.5 kg ha<sup>-1</sup>;
- (c) Three potassium nutritional levels of 0.5, 1.0, and 1.5 kg ha<sup>-1</sup>.

It is important to allow the turf to establish a root system. Subsequently, this cutting height/nitrogen/potassium interaction study will be used in future investigations of water use rates, rooting potential, and drought resistance. Obviously, each of these subobjectives will have to be assessed during a separate growing season. Initial studies are projected to be conducted on the evapotranspiration rates using the mini-lysimeter technique/water balance method. (Improved Cultural Systems) W. Menn and J. Walker.

## B. OBJECTIVES FOR ENHANCED ROOTING/WATER ABSORPTION AND THE RESEARCH STATUS

Developing an enhanced rooting capability will allow the turfgrass plant to draw moisture from a greater portion of the soil profile. The relationship of rooting to the rate of moisture withdrawal must be quantified. Delineation of the rooting dimensions will contribute to both a reduced water use rate and to the avoidance dimension of drought resistance. Thus, these rooting investigations interface closely with two of the other concurrent research objectives A and C being investigated.

\* \* \* \* \*

B-1. Characterize the root systems of eleven major warm season turfgrass species under non-limiting and water stressed conditions. Initiated in 1984.

Status - Initial studies on turfgrass root hairs and their activity involved growing Adalayd seashore paspalum and Tifway bermudagrass in 5-gallon buckets containing an aerated nutrient solution. Following 5 to 6 weeks of growth and again at 11 to 12 weeks, plants were transferred to a nutrient solution containing neutral red, a vital stain which selectively stains living plant tissue. Only those root hairs that absorb the red stain are alive and are assumed functional. At the two sampling dates, a portion of the root system was harvested and observed microscopically for the presence of root hairs and absorption of stain.

In response to a recent, intensive literature review, it has become apparent that our initial work with the root hair dimension of root characterization should be expanded. Secondly, it would be desirable to grow the turfgrasses in a more natural environment than a nutrient solution. Thus, the methods for characterization of the roots and especially the root-hair zone are being expanded and modified.

Techniques have been developed recently to determine total shoot weight, total root weight, total root length, average root radius, root hair length, root hair diameter, number of root hairs per centimeter of root, and percent viable root hairs. Experimentation will be initiated in November of 1985. Turfs will be grown under greenhouse conditions in PVC columns filled with a sandy loam. The PVC columns will be sectioned as described in B-2 in order to evaluate successive individual depths for the above parameters. Initially, the techniques for root hair characterizations will be tested on a few selected species, and then a full scale study will be conducted on the eleven major warm season and the twelve major cool season turfgrasses. (Interspecies Comparison and Mechanistic Study) D. Casnoff and R. Green.

Results - Observations of root hairs harvested from turfs maintained in nutrient solution show that Adalayd seashore paspalum has root hairs evenly distributed over the entire length of its roots (26.67 cm). We observed a gradual decrease in percent functional root hairs from the apex of the root (apex - 2.54 cm = 100% root hairs absorbed dye) to 26.27 cm from the apex (20.32 cm - 26.26 cm = 15 to 20% root hairs absorbed dye). Tifway bermudagrass had root hairs distributed in a random arrangement along the entire length of

its roots. Unlike Adalyd, root hairs of Tifway more than 1.27 cm away from the root apex did not absorb dye.

A fairly detailed literature review on root hairs is completed and written. This provides some baseline information to compare and to help interpret our findings.

#### Conclusions -

- a. Initial experiments suggest that the root hair dimension of turfgrass root characterization has been overlooked and that over the past three decades, far too much emphasis has been placed on total root mass and depth.

\* \* \* \* \*

B-2. Assess the interspecific rooting potentials of eleven major warm season turfgrasses under non-limiting moisture conditions. Initiated in 1984.

Status - This study conducted under greenhouse conditions using the root column facility has been completed. An associated study utilizing lower nitrogen and moisture levels was conducted as a follow-up and has also been completed. Subsequently, the data processing and analyses have been completed. A scientific paper has been submitted for review. (Interspecies Characterization Comparison and Mechanistic Aspects) D. Casnoff and S. Sifers.

Results - The interspecific rooting potential of eleven major warm season species was assessed under non-limiting moisture conditions in the greenhouse using root columns filled with sand. In both studies, the data collected consisted of (a) the number of roots intersecting the 30, 60, 90, 120, 150, and 180 cm depths and (b) the weights of roots found from the 0-30, 30-60, 60-90, 90-120, 120-150, and 150-180 cm sections of the 210 cm long column.

Results showed that after 70 days of growth, Texas Common St. Augustine-grass and two bermudagrasses, Texturf 10 and FB 119, had the longest root extensions and the most total root weight. After 130 days of growth, FB 119 bermudagrass had more roots and more total root weight in all levels of the soil profile than the other cultivars investigated. Meyer zoysiagrass, Texoka buffalograss, and Common centipedegrass had the least developed root systems after 70 and 130 days of growth. Interspecies correlations between all variables measured were found to be highly significant. It was found that correlations between shoot weight and total root weight (0.88\*\*) and shoot weight and longest root length (0.77\*\*) were both highly significant and high in value. Note that if these correlations would hold true within a given species, the breeder might be able to utilize shoot characteristics as selection criteria for drought resistance rather than the more time consuming root characterizations.

An allied experiment was conducted in which six turfgrasses requiring a low intensity of culture were grown with a lower nutritional and moisture regime than used in the study described above. The regime included 2.4 kg ha<sup>-1</sup> per growing month each of N, P<sub>2</sub>O<sub>5</sub>, and K<sub>2</sub>O in the form of a 14-14-14 granular fertilizer. In addition, each column was irrigated with 300 ml of distilled water per day. The turfgrasses used in this study were Texturf 10

bermudagrass, Texas Common St. Augustinegrass, Common centipedegrass, Meyer zoysiagrass, Texoka buffalograss, and Pensacola bahiagrass. The bermudagrasses produced long, extensive root systems at all depths, while Meyer zoysiagrass and Texoka buffalograss produced shallow systems. Thus, the rooting responses were similar under both the moderate and the very low nutritional and moisture levels.

Table B-2. The comparative mean extension of the longest root and the mean total root weight for eleven warm season turfgrasses after 130 days of growth under near-optimum growing conditions.

Turfgrass Species/Cultivar	Extension of Longest Root (cm)	Total Root Weight (g)
Bermudagrass - FB 119	183 a*	9.10 a*
Bermudagrass - Tifgreen	155 ab	5.10 b
Bermudagrass - Tifway	122 bcd	4.50 bc
Bermudagrass - Texturf 10	138 bc	4.10 bc
Seashore paspalum - Adalayd	90 def	3.30 bcd
St. Augustinegrass - Texas Common	100 cde	2.80 cde
Zoysiagrass - Emerald	92 def	2.50 cde
Bahiagrass - Argentine	78 efg	1.70 de
Centipedegrass - Common	57 fgh	1.40 de
Zoysiagrass - Meyer	46 gh	1.10 de
Buffalograss - Texoka	35 h	0.70 e

\* Means within each column followed by the same letter do not differ significantly ( $P = 0.5$ ) by Duncan's Multiple Range Test.

#### Conclusions -

- a. The rooting depths and total root weights of the major warm season turfgrasses vary substantially in terms of interspecies genetic rooting potentials.
- b. The greater rooting capability of the bermudagrasses shown in this study is no doubt a significant contribution to the overall drought resistance mechanism.
- c. Preliminary data suggest that, based on the high correlation between both root weight and length with the shoot weight, there is a potential for the use of shoot biomass as a plant marker in selecting deep

rooting plants, thereby avoiding time consuming root measurements. Much more research remains to be done to confirm this at the intraspecies level.

\* \* \* \* \*

B-3. Investigate the relationships of rooting to water use rates under water stress conditions. Initiated in 1984.

Status - This complex problem has been on hold due to the lack of a safe, functional rhizotron facility. We are hopeful that the moisture stress studies just described under Objective B-2 will provide further information that will contribute to an understanding of this research objective. Based on current projections, it is not anticipated that a rhizotron/lysimeter/rainout shelter facility will be in place and operational before 1987. In fact, at this time, no specific funds have been identified for this purpose. However, the site has been established and the soil site development completed. (Mechanistic Study) S. Sifers.

\* \* \* \* \*

B-4. Conduct exploratory studies of root enhancing agents. Initiated in 1984.

Status - After several attempts, the first study has been completed on root enhancement of Penncross creeping bentgrass. The results are mixed, with no significant differences found among the seven chemical treatments tested. The results, although not significant have still given some leads as to different types of experiments using many of these same chemicals. Thus, another experiment has been started using individual plants grown in root columns in a controlled environment growth chamber. This experiment will of be short duration in an attempt to evaluate the effects on rooting in the early root development stages under 90° to 95°F (32° - 35°C) heat stress conditions. (Mechanistic and Cultural Studies) S. Griggs.

\* \* \* \* \*

B-5. Determine the cause of spring root decline (SRD) of warm season turf-grasses as well as methods to minimize its potentially negative effects. Initiated in 1984.

Status - The initial phase of the investigation has been completed and two research papers written (see Appendix). One paper summarizing the overall research data was presented by S. Sifers at and published in the Proceedings of the Fifth International Turfgrass Research Conference. A second paper has been completed on the induction of spring root decline and is now in the review process.

The new series of experiments will utilize radioactive <sup>14</sup>C to follow carbohydrate distribution and partitioning that occurs prior to, during, and after spring root decline. A growth chamber study will be initiated in the fall of 1985. This research has been partially funded by the O.J. Noer Research Foundation. (Mechanistic Study) S. Sifers and R. Green.



### Conclusions -

- a. Spring root decline (SRD) is a separate phenomenon rather than a result of other external stresses.
- b. There are two distinctly different dormancy phases for the root and shoot systems of warm season perennial grasses, with root growth sustained after short dormancy occurs.
- c. The SRD response has occurred in all ten warm season grasses investigated, which indicates that SRD is common to most warm season perennial grasses used for turfgrass purposes.
- d. Under controlled environment growth chamber conditions, the temperature threshold above which spring root decline is induced has been documented as 28°C (82°F). Temperatures above this threshold stimulate rapid shoot growth with probable redirection of carbohydrate reserves from roots to shoot, resulting in spring root decline. Temperatures below this level result in new root growth from the tips of existing roots with no evidence of SRD.

\* \* \* \* \*

- B-6. Assess the interspecific rooting potential of twelve major cool season turfgrasses under non-limiting moisture conditions. Initiated in 1985.

Status - This study has been completed. The final measurements were taken on June 7, 1985, which represented 98 days of growth. The types of plant parameters assessed were similar to those for the study of the interspecific rooting potentials of eleven major warm season turfgrasses; i.e., number of root inter-sections at 30, 60, 90, and 120 cm depth; longest root length; total root weight; shoot weight; and number of tillers. (Species Comparison and Mechanistic Studies) S. Griggs and D. Casnoff.

Results - After 98 days of growth, Fairway crested wheatgrass had the longest root extension of the cool season grasses tested. Kentucky 31 tall fescue and Rebel tall fescue exhibited the next longest root extensions. Within the bentgrasses assessed, Highland colonial bentgrass had longer roots than Penncross creeping bentgrass. Among the three Poa species evaluated, Poa pratensis 'Merion' had the longest roots while Poa annua subsp. reptans had longer roots than Poa annua subsp. annua. Total root weight assessments showed no differences statistically. Correlations between the root/shoot ratios and shoot weights were very high (0.96) and highly significant.

Other correlations between shoot weight and root weight were low and not significant. Correlations in the warm season grasses were generally higher than for the cool season species. This single correlation could help guide the breeder with further enhancement of turfgrasses for drought resistance/avoidance and lower water use rates (Table B-6).

Conclusion -

- a. Significant differences in rooting depth were found among the major cool season turfgrass species when grown under near optimum conditions.

Table B-6. The Comparative Mean Extension of the Longest Root and the Mean Total Root Weight for Twelve Cool Season Turfgrasses After 98 days of Growth Under Non-Limiting Moisture Conditions

Turfgrass Species/Cultivar	Longest Root Extension (cm)	Total Root Weight (g)
Crested Wheatgrass, Fairway	86.1 a*	1.7 a
Tall Fescue, Kentucky 31	80.9 ab	1.2 a
Tall Fescue, Rebel	55.2 bc	1.3 a
Colonial Bentgrass, Highland	55.0 bc	1.2 a
Creeping Bentgrass, Penncross	43.8 c	1.4 a
Hard Fescue, Scaldis	42.0 c	1.5 a
Perennial Ryegrass, Manhattan II	41.3 c	0.2 a
Chewings Fescue, Jamestown	40.5 c	0.6 a
Kentucky Bluegrass, Merion	34.7 c	1.5 a
Rough Bluegrass, Sabre	31.7 c	0.6 a
Annual Bluegrass (perennial)	29.9 c	0.7 a
Annual Bluegrass (annual)	26.5 c	0.4 a

\* Means followed by the same letter are not significantly different at the 0.05 level for the Duncan's Multiple Range Test for significance.

\* \* \* \* \*

- B-7. Assess the interspecific rooting potentials of twelve major cool season turfgrass species under heat stress and non-limited moisture conditions. Initiated in 1984.

Status - This greenhouse study was completed in September, 1984. The data are being statistically analyzed and interpreted. (Species Comparison and Mechanistic Studies) D. Casnoff and S. Griggs.

Results - Twelve cool season turfgrasses were evaluated for root and shoot growth characterizations when grown in a greenhouse under heat stress. The methodology used was the same as that for the interspecific rooting potential studies. Those cultivars investigated included: Fairway crested wheatgrass, Rebel tall fescue, Kentucky 31 tall fescue, Highland colonial bentgrass, Penncross creeping bentgrass, Merion Kentucky bluegrass, Manhattan II perennial

ryegrass, Poa annua subsp. reptans, Poa annua subsp. annua, Scaldis hard fescue, Jamestown chewings fescue, and Sabre rough bluegrass. The data taken were root weight, shoot weight, percent verdure, number of tillers per main shoot, and longest root length.

The most root dry matter produced under heat stress was by Fairway crested wheatgrass, followed by Rebel and Kentucky 31 tall fescues. All other cultivars studied had less root dry matter and were not significantly different from each other. The longest root length produced under heat stress was by Fairway crested wheatgrass, followed by Rebel and Kentucky 31 tall fescues. Ranking lower, in order, were Manhattan II perennial ryegrass, Penncross creeping bentgrass, Scaldis hard fescue, Merion Kentucky bluegrass, Poa annua subsp. annua, Sabre rough bluegrass, Jamestown chewings fescue, and Poa annua subsp. reptans.

The most shoot dry matter was produced by Kentucky 31 and Rebel tall fescues; followed by crested wheatgrass and Penncross creeping bentgrass. All other cultivars studied produced less shoot dry matter than the above and were not significantly different from each other. The highest percent verdure found after 130 days of growth under heat stress was for Penncross creeping bentgrass, Poa annua subsp. reptans, Kentucky 31 tall fescue, and Scaldis hard fescue; followed by Manhattan II perennial ryegrass, Jamestown chewings fescue, Merion Kentucky bluegrass, Fairway crested wheatgrass, Poa annua subsp. annua, Highland colonial bentgrass, and Rebel tall fescue. The smallest percent verdure was produced by Sabre rough bluegrass.

#### Conclusions -

- a. Certain cool season species, such as crested wheatgrass and the tall fescues, exhibited a stronger capability to sustain root growth under severe heat stress conditions, than do other species.
- b. There are variations in rooting among the major cool season species, but the differentials are not nearly as great as observed under near optimum growing conditions.

### C. OBJECTIVES FOR IMPROVED DROUGHT RESISTANCE AND THE RESEARCH STATUS

Following the onset of soil drought, a grass plant exhibits leaf rolling, firing of the outer lower leaves, and eventually a cessation of growth and total browning of the aboveground shoot tissues. At this point, it is defined as being in a state of dormancy. Once rainfall occurs, most perennial turfgrasses have varying degrees of ability to reinitiate new shoot growth, depending on the particular species and duration of drought stress. Drought resistance is broadly defined as the ability of a plant to survive an extended soil drought. Note that a turfgrass that has a low water use rate may not be drought resistant. These are two entirely different physiological parameters.

An important component of drought resistance is termed as drought avoidance. It encompasses such characteristics as a reduced evapotranspiration rate and deeper rooting which, respectively, slows the rate of water loss from the shoots and increases the ability to absorb moisture from a greater portion of the soil profile. As a result, the point at which the plant enters dormancy is delayed and, therefore, the potential period of time when a plant is subjected to severe moisture stress during dormancy is shortened. Thus, it can be seen that Objective A, concerning Minimal Water Use Rates, and Objective B, concerning Enhanced Rooting/Water Absorption, will provide important information concerning the dimensions of drought avoidance. This is the reason we initiated Objectives A and B first rather than the drought resistance studies of Objective C. However, these are only a few of the five major components of drought resistance which must be investigated.

C-1. Characterize the comparative drought avoidance and drought resistance of eleven major warm season turfgrass species and their cultivars. Initiated in 1984.

Status - A preliminary study was conducted in 1984. Then a new field plot area was established during the spring of 1985. This area is a modified sand root zone, 60 cm in depth, with associated irrigation and drainage. Over fifty turfgrass cultivars were assessed for comparative drought avoidance and resistance. Data collection is completed and the findings are now being analyzed. A second study is scheduled for 1986. (Interspecies Comparison) K. Kim and S. Sifers.

Results - The study was expanded from the original eleven warm season turfgrass species, which were segregated in one portion of this new area, to include separate areas for twenty-three bermudagrass cultivars, five St. Augustinegrass cultivars, six zoysiagrass cultivars, and six centipedegrass cultivars. All of the turfgrasses were planted as four-inch plugs of turf during the spring of 1985, and allowed to establish for two months under non-limiting moisture conditions. Irrigation was terminated on July 29, 1985 for this entire area, and parameters listed in C-2 were observed.

Data are still being analyzed; however, preliminary results indicate several cultivars within each species have a good drought avoidance mechanism and recovery potential. Turfgrasses with a good combined drought avoidance, resistance, and recovery were Tiffine and Texturf 10 bermudagrasses; Floratam and FA 108 St. Augustinegrasses; Emerald, Meyer, FC 13521, and El Toro zoysiagrasses; and Common and Oklawn centipedegrasses. Many of the cultivars

Table C-1. Comparative recovery of warm season turfgrass observed 18 days after 48 days of drought stress in the summer of 1985.

Interspecies	Bermudagrass	St. Augustinegrass	Zoysiagrass	Centipedegrass
High*	Very High*	High*	High*	High*
Emerald Zoysiagrass	Tiflawn	FA 108	FC 13521	Common
Meyer Zoysiagrass	Tiffine	Florata	Emerald	Oklaw
Texturf 10	Tifcote		Meyer	
Bermudagrass	Bayshore	Medium	El Toro	Low† (Med.?)
Tifgreen	Texturf 1F	Tx 8262	Belair	AC 17
Bermudagrass			Korean Common	Tenn Hardy
Centipedegrass	Medium High	Low		AC 26
Common Bermudagrass	FB 119	Raleigh		AC 44
	Tifgreen II	Texas Common	All cultivars	
Medium	Midway		showed over 95%	†over 70%
Adalayd	U-3		green recovery	green recovery
Buffalograss	Texturf 10			
Bahiagrass	Midiron			
Low	Medium			
Tifway	Sunturf			
Bermudagrass	Common			
St. Augustinegrass	Ormond			
	Pee Dee			
	Tifgreen			
	Vamont			
	Medium Low			
	Tifdwarf			
	Everglades			
	Tifway			
	Very Low			
	Santa Ana			
	Tifway II			

\* Classification is good only within each column.

tested had an excellent subsequent recuperative potential, although they entered severe drought stress and dormancy early. Buffalograss was one example. The following table lists the comparative recovery of these turfgrasses as observed on the 18th day of the recovery phase.

Conclusions -

1. The major warm season turfgrass species vary greatly in drought avoidance and in drought resistance, with comparative rankings being much different than had been previously assumed.
2. Variation in drought avoidance and recovery is as great within most of the turfgrass species as the variation at the interspecies level.

\* \* \* \* \*

C-2. Characterize the morphological, anatomical, and physiological plant parameters associated with drought avoidance among eleven major warm season turfgrass species and their cultivars. Initiated in 1984.

Status - One preliminary field study was conducted in 1984, followed by an extensive, but detailed, field study in 1985. The data are now being analyzed and interpreted. A second detailed field study is planned for 1986 to confirm the 1985 results. (Mechanistic Study) K. Kim and S. Sifers.

Results - Field studies were conducted from July through September, 1985 using replicated four-inch plugs of turf in a three-foot deep modified sand root zone. These plugs were allowed to root for two months under non-limiting water conditions, then irrigation was withheld and the turfs allowed to progress into severe drought stress. This phase was continued for 48 days and was terminated due to the onset of rain. Air and canopy temperatures, leaf rolling or folding, and leaf firing or browning were observed daily. Leaf water potential, stomatal changes, leaf blade length, vertical leaf extension and lateral shoot growth measurements were made periodically. This field study was expanded from the original eleven warm season turfgrasses to include twenty-two bermudagrass cultivars, five St. Augustinegrass cultivars, six zoysiagrass cultivars, and six centipedegrass cultivars.

Data from this diverse array of descriptive parameters and cultivars is being analyzed for leads to future in-depth studies concerning the mechanisms of drought resistance. This analysis should be completed by January of 1986. The following table is a comparative listing of leaf browning with data taken on the 35th day of the test. A low percentage of leaf browning would indicate resistance to drought stress. Cultivars that had a low percentage of firing were Texturf 10, Common and Tiffine bermudagrass; Floratam and FA 108 St. Augustinegrass; Meyer, FC 13521, El Toro, and Emerald zoysiagrass; and Common and Oklawn centipedegrass. There was an inconsistency between the bermudagrasses and zoysiagrasses which may be due to their location in the plot area. This first test will be repeated during the summer of 1986, with emphasis on those cultivars that showed specific drought resistant mechanisms.

\* \* \* \* \*

Table C-2. Comparative leaf firing percentage of warm season turfgrasses observed after 35 days of drought stress during the summer of 1985.

Interspecies	Bermudagrass	St. Augustinegrass	Zoysiagrass	Centipedegrass
High*	Very High*	High*	High*	High*
St. Augustinegrass	Tifway II	Texas Common	Korean Common	AC 17
Tifway Bermudagrass	Santa Ana	Raleigh	Meyer	AC 26
Buffalograss	Tifdwarf			Tenn Hardy
				AC 44
Medium	Medium High	Medium	Medium	
Adalayd	Tifway	Tx 8262	Belair	Low
Bahiagrass	Pee Dee			Common
Centipedegrass	Everglades	Low	Low	Oklawm
Tifgreen		Floratom	FC 12521	
Bermudagrass	Medium	FA 108	El Toro	
	Tifgreen		Emerald	
Low	Ormond			
Texturf 10	Sunturf			
Bermudagrass	Common			
Common	Vamont			
Bermudagrass	Midiron			
Emerald	FB 119			
Zoysiagrass	U-3			
Meyer	Texturf 10			
Zoysiagrass				
	Medium Low			
	Midway			
	Tufcote			
	Bayshore			
	Tifgreen II			
	Tiflawn			
	Texturf 1F			
	Low			
	Tiffine			

\* Classification is good only within each column.

- C-3. Characterize the morphological, anatomical, and physiological plant parameters associated with the drought resistance (i.e., recuperative ability) of eleven major warm season turfgrass species following subjection to severe drought stress. Initiated in 1984.

Status - This field study was expanded to include the turfgrasses studied in C-1 and C-2. The initial detailed study has been completed and the data are being analyzed to identify turfgrass plant characteristics as they are candidates for more in-depth study. A more detailed, second-year confirmation study is planned for the root column research facility during the winter of 1985 followed by both field and root column studies in 1986. (Mechanistic Study) K. Kim and S. Sifers.

\* \* \* \* \*

- C-4. Assess the relationship between rooting characteristics and drought resistance of twelve major warm season perennial turfgrasses. Initiated in 1984.

Status - The twelve turfgrasses investigated include the eleven warm season turfgrasses previously assessed for genetic rooting potential (B-2), plus Pensacola bahiagrass. The turfgrasses were allowed to grow for 80 days in the root column facility. Then irrigation was discontinued and the plants were allowed to harden off, enter dormancy, and/or die. Once it was determined how each turfgrass responded to progressive water stress, irrigation was resumed to assess recovery. Unfortunately, we were not able to get reliable data from the first experiment due to a problem with the heating system in the greenhouse when outside temperatures dropped well below freezing.

The initial study was terminated and restarted on May 30, 1985. The rooting columns were disassembled, cleaned, and replanted. Irrigation was discontinued on August 19, 1985. Presently, drought stress has been imposed for 63 days. Common centipedegrass and Meyer zoysiagrass show the most severe symptoms of drought stress, while the three bermudagrasses and two bahiagrasses show the least severe symptoms of water stress to date. Data to be taken are: the number of root intersections/depth, root weights, and depth of the longest root. These data will then be correlated to (a) the number of days after irrigation is discontinued until the first signs of moisture stress, i.e., leaf rolling or folding, appear, (b) the number of days after irrigation is discontinued until entering total dormancy when all leaves have browned, and (c) the total dry weight of shoot biomass after full browning. (Mechanistic Study) D. Casnoff.



D. OBJECTIVES FOR PHYSIOLOGICAL BASIS OF MINIMAL MAINTENANCE TURFGRASSES AND THE RESEARCH STATUS

- D-1. Investigate the morphological, anatomical, and physiological plant parameters associated with minimal maintenance characteristics of bermudagrass cultivars. Initiated in 1984.

Status - Initial field and greenhouse studies have been completed. Morphological and anatomical data showed that characteristics which have been identified as contributing to low water use rates were also important in contributing to low nitrogen requirements. Water use rate, leaf extension rate, clipping dry weight, shoot density, canopy orientation and visual quality ratings have been documented as useful parameters. Analyses for nitrogen content of the tissue materials collected during this study are now being conducted. A scientific research paper is planned following completion of these analyses. Results of the drought resistance and recuperative potential studies will be used to select turfgrasses for follow-up studies under this objective. (Interspecies Comparisons and Mechanistic Study) S. Sifers.

Conclusions -

- a. Genetic diversity contributing to minimal maintenance turfgrasses can be observed as morphological, anatomical, and physiological plant parameters and can be statistically evaluated.

## V. BUDGET STATUS

Emphasis on cost containment during the past twelve months has ensured that expenditures fall within the annual budget projections. The cost for conducting the field drought resistance studies was much higher than projected as it required two full-time professionally trained scientists working for more than three months to complete the work. As a result, the Postdoctoral position, previously filled by Dr. David M. Casnoff, was held open from April 1 to September 9, 1985. The position was then filled by Dr. Robert L. Green. This allowed flexibility in achieving the research objectives outlined during the year within the planned budget. It is anticipated that costs for the drought resistant studies during the upcoming year will not be any greater than they were for the past year. Our specific costs for the detailed root hair investigations are still unclear. Otherwise, it is anticipated that the planned budget should be adequate to complete the objectives.

## VI. PUBLICATIONS

After two years of intensive research, the first technical papers published in peer reviewed scientific journals are appearing. The reader is referred to the Appendix for copies of the actual publications as they appeared in the scientific journals. In addition, three drafts of scientific papers are in the review process, and two additional papers are in the advanced writing stage.

A second aspect involves publication of the USGA sponsored research results in a popular version entitled "Texas Turfgrass Research 1985 - TAES Consolidated Progress Reports". Four progress reports were published in 1985. They include the following:

- PR-4314 Assessment of the Genetic Potentials for Root Growth of Eleven Warm Season Perennial Turfgrasses under Nonlimiting Moisture Conditions. D. M. Casnoff and J. B. Beard. pp. 10-14.
- PR-4315 Leaf Blade Stomatal Characterizations of Ten Warm Season C-4 Perennial Grasses and Their Association to the Water Use Rate. D. M. Casnoff, J. B. Beard, D. G. Verwers, and S. D. Griggs. pp. 15-18.
- PR-4316 Spring Root Decline (SRD): A Research Summary. S. I. Sifers, J. B. Beard, and K. S. Kim. pp. 19-30.
- PR-4331 Comparative Assessment of the Wilting Tendency of Warm Season Turfgrasses. K. S. Kim and J. B. Beard. pp. 143-148.

Oral reports and associated abstracts on research supported by the USGA include (1) three papers presented at the International Turfgrass Research Conference in Avignon, France (see Appendix), and (2) three papers which were presented at the American Society of Agronomy Meetings in December of 1984. Included were :

- (1) a keynote address by J. B. Beard entitled "Water Use Rate by Turfgrasses";

- (2) a second paper by D. M. Casnoff and J. B. Beard entitled "Assessment of the Genetic Potential in Root Growth of Nine Warm Season Turfgrass Species under Non-Limiting Moisture Conditions; and
- (3) a third paper by S. D. Griggs, D. M. Casnoff, and J. B. Beard entitled "Stomatal Characteristics and Densities of Four Cool Season (C-3) and Ten Warm Season (C-4) Turfgrasses as Correlated to Water Use Rate".

Current plans are to present two papers at the upcoming American Society of Agronomy Meetings scheduled in Detroit during December of 1985.

It also should be mentioned that an article summarizing the water use rate studies will appear in the September-October issue of the USGA Green Section Record and subsequently in Grounds Maintenance.

#### VII. DISSEMINATION OF RESEARCH RESULTS

Visibility of the USGA's support of our turfgrass water conservation program has been achieved through speaking at key national and regional turfgrass conferences during the past year. The general topic is usually in the area of water conservation strategies and research updates related to rooting, water use rates, and drought stress. Addresses have been given before the following:

- a. Professional Lawn Care Association of America Annual Meeting - Tampa, Florida in November, 1984.
- b. Annual Texas Turfgrass Conference - San Antonio, Texas in December, 1984.
- c. Annual Michigan Turfgrass Conference - East Lansing, Michigan in January, 1985.
- d. International Conference of the GCSAA - Washington, D.C. in February, 1985.
- e. American Sod Producers Association National Conference - Orlando, Florida in February 1985.
- f. Midwest Regional Turfgrass Conference - Lafayette, Indiana in March, 1985.
- g. Arizona Turf Seminar - Phoenix, Arizona in March, 1985.
- h. Water Conservation Seminars - Palm Springs and Los Angeles, California in September, 1985.
- i. GCSAA-USGA Turfgrass Research Conference - Indianapolis, Indiana in September, 1985.

Current plans are to reduce the number of presentations by about one-half for the 1985-86 period, particularly in view of my responsibilities as President of the Crop Science Society of America. The emphasis will be placed primarily on national conferences and reduce the number of state conferences during this time frame.

## VIII. APPENDIX

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Proceedings of the Fifth International Turfgrass Research Conference. Avignon, France. July 1985.

Chapter | **An environmental genetics model  
for turfgrass improvement :  
physiological aspects <sup>(1)</sup>**

1 | J.B. BEARD and M.C. ENGELKE

**ABSTRACT**

A coordinated team effort for the development of turfgrass cultivars with tolerance to specific environmental stresses has not been attempted in turfgrass improvement. The major types of turfgrass stresses, the components and resultant complexity of each type of stress, and the potential for success in cultivar improvement are discussed. A physiological model is presented with water use rate reduction being used as the example. Included in the model are a description of the environmental conditions, the chronology of plant responses, characterizations at the inter- and intraspecies level, and mechanistic studies leading to feasible plant prediction parameters. A hypothesis concerning the most effective plant predictive parameters is established. Using turfgrass selections possessing a full range of a plant predictive characteristic, the hypothesis is tested. If confirmed, the next phase involves studies of inheritance and methods for incorporating the desirable traits into an improved cultivar.

Additional key words : Tolerance, Stress, Inheritance

(1) A contribution from the Department of Soil and Crop Sciences, Texas A&M University, College Station, TX 77843. U.S.A., Texas Agric. Exp. Sta. Journal, Article n°TA 20477

## INTRODUCTION

Turfgrass science, especially the breeding/genetic aspects, is a young science compared to most of the traditional field and horticultural crops. For many years, most turfgrass cultivars were developed through field selection and subsequent replicated field plot evaluations over time to characterize the most desirable selections. Emphasis was placed on better turf characteristics such as a lower growth habit, higher density, good color, and uniformity. Any improvements in environmental stress tolerance that may have occurred in the development of these earlier cultivars were purely by chance. Since the mid-1960's, a few turfgrass breeding efforts have evolved utilizing a team approach that consisted of a breeder-geneticist and a plant pathologist. As a result, a number of new cultivars of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) have been released with improved disease resistance. Currently there is a great need to develop a team approach, consisting of a geneticist and a stress physiologist, with the primary thrust being to develop turfgrass cultivars with improved tolerance to specific environmental stresses (Engelke, Beard and Colbaugh, 1985). At the same time, similar team inputs must be encouraged from plant pathologists and entomologists (Colbaugh and Engelke, 1985).

Even in the more traditional crops, the number of team oriented programs devoted to improving stress tolerance has been limited. Among those teams that have been formed, the success ratio has been low. The yield component greatly complicates the potential for success. One example of a successful program involves the incorporation of improved low temperature hardiness into wheat (*Triticum aestivum* L.) by Everson and Olein of Michigan. The less complex nature of low temperature hardiness is probably a factor in the success of this program. Fortunately, yield is not a factor in the case of turfgrasses. Rather, survival while at the same time sustaining a degree of quality, in terms of functional cover, is the main concern.

With the need to reduce costs and resource inputs in the maintenance of turfgrasses, the development of more stress tolerant cultivars is a high priority. Reduced water use rates, drought resistance, cold hardiness, heat tolerance, shade adaptation, and wear tolerance are of concern. Water conservation, shade adaptation, and wear tolerance are major problems regardless of the climatic region. Solving these problems through the development of improved stress tolerant cultivars will require a closely coordinated team effort between the turfgrass breeder-geneticist and the stress physiologist. This paper will address a team oriented approach for improving the environmental stress hardiness of perennial turfgrasses.

## PROBLEM PERSPECTIVE

In crop production, the basic principle is to select a set of climatic and soil conditions where yield can be maximized. In this case, breeding for stress tolerance is oriented to the objective of widening the adaptive zone wherein yields can be maximized. Unfortunately, these concepts are not applicable in turfgrass culture. Urban centers are selected based on commercial, economic, political, and/or strategic geographical bases. The area is then extensively disrupted during the construction of buildings, residential areas, roads, and drainage ways.

Many times the typical soil profile is completely destroyed in the process. Then the landscapers are expected to establish a turf under a broad array of adverse situations. Subsequently, the groundskeeper is responsible for sustaining a vegetative cover with a specified degree of density, color, and uniformity depending on the particular use.

Most of the stress physiology/breeding research teams have concentrated on annual species, such as cold stress in small grains. More recently, there has been emphasis on water stress problems in sorghum [*Sorghum bicolor* (L.) Moench], an annual grass. Additional research is needed concerning the stress tolerance components of most significance for the long-lived perennial grasses which possess an elaborate lateral stem system consisting of rhizomes and/or stolons. Also, the culture of an annual crop includes planting schedules and production techniques which are devised to avoid anticipated stress periods. In contrast, perennial grasses may survive the stress, enter a dormancy phase, or be killed. The unique problems and characteristics associated with perennial turfgrasses further emphasize the importance of detailed stress research involving a team approach of a stress physiologist and a breeder devoted to the development of stress tolerant cultivars.

#### ENVIRONMENTAL STRESSES

The major environmental stresses of concern in the culture of perennial turfgrasses include high water use, drought, heat, cold, shade, and wear (Table 1). Many of these stresses are interrelated. Thus, improvements in the tolerance to one stress may positively or negatively alter the severity or proneness to an associated stress. For example, reduced water use rates achieved by a slower leaf extension rate plus greater internal and external plant resistances to water loss may greatly reduce the transpirational cooling capability. This could cause increased proneness to heat stress in some species if heat survival depends on an avoidance dimension, such as transpirational cooling. Thus, at the time a reduced water use rate is being incorporated into a cultivar, research should be conducted to insure the introduction of improved internal tissue tolerance to heat. This paper presents our current state of knowledge concerning the components of each individual stress of turfgrasses and the potential for achieving realistic cost-effective selection parameters for use in a turfgrass breeding program to select for tolerance to a particular stress.

#### Water Use Rate

The reduction of water use rates is a concept oriented toward irrigated turfs, as contrasted to drought resistance. Many types of turfgrasses will by necessity, require irrigation in order to sustain the recuperative potential needed on intensely trafficked sports field and recreational turfs. Secondly, the beneficial transpirational cooling dimension that contributes to an improved environment for both plant survival and human activities in densely populated urban areas must be considered. Finally, the appearance of turfs that is so desirable in intensely populated urban centers and resort locations requires supplemental water applications. The biological components controlling evapotranspiration include (1) canopy resistance, (2) vertical leaf extension rate, (3) stomatal resistance, (4) internal tissue resistance, and (5) the rooting characteristics. A good base of research information has been developed

Table 1. A summary of the major environmental stresses of turfgrasses, the respective known components for each stress and the research information available of turfgrasses.

Types of Stress	Known Stress Components	Research Information Available on Turfgrasses
Excessive water use rate (Irrigated turfs)	Canopy resistance Leaf extension rate Stomatal resistance Internal resistance Rooting	Good base
Drought	Evapotranspiration resistance - avoidance Rooting - avoidance Xeromorphic shoot characteristics Dormancy survival Internal tissue hardness	Very limited
Heat	Transpirational cooling - avoidance Internal tissue tolerance	Limited
Cold	Chill stress Non-equilibrium freezing Equilibrium freezing	Good base
Shade	Disease resistance Light energy capture and utilization Dark respiration Lateral stem orientation	Fair to good base on cool season species
Wear	Lignin content of shoots Amount of verdure Percent sclerified tissue in leaf	Fair base on cool season species



for a selected group of turfgrass species concerning the comparative importance of the various resistances to evapotranspiration as well as the comparative potential evapotranspiration rates at the inter- and intraspecies levels (Johns, Beard, and Van Bavel, 1983; Kim, 1983; Kim and Beard, 1983). The combination of a high canopy resistance plus a slow vertical leaf extension rate are the major factors controlling evapotranspiration from turfs. Recent evidence suggests that these traits can be rapidly assessed in a breeding program to develop future turfgrass cultivars with reduced water use rates. The heritability of agronomic traits associated with canopy resistance is being studied through controlled hybridization with selected parents.

#### Drought Resistance

Drought resistance is needed in species/cultivars used on extensive locations where irrigation facilities are not physically available or budgetary restraints do not permit irrigation. Components of drought resistance that have been identified in other plant species include the evapotranspiration resistance and rooting dimensions which are essentially drought avoidance factors (Beard, 1973). Other components are the xeromorphic shoot characteristics, dormancy survival mechanisms, and internal tissue hardiness to water stress. Detailed studies of these various components and their relative importance are lacking for the turfgrass species. In fact, investigations of the relative drought resistance at both the inter- or intraspecies levels are lacking. Thus, much research needs to be done in this area of environmental stress.

#### Heat Stress

Heat stress is closely interrelated to summer water stress and, in fact, they are frequently difficult to separate experimentally. Two specific components of heat stress have been identified (Beard, 1973). One consists of evapotranspirational cooling, which, as now practiced, is essentially an avoidance mechanism requiring supplemental irrigation. The second dimension involves various types of internal tissue hardiness to supraoptimal temperatures. Both shoot and root tissues must be considered. The basic pool of research data available on heat tolerance is somewhat limited. The research conducted on turfs has been done primarily with the *Agrostis* and *Poa* species. Unfortunately, most field studies have been confounded by a number of summer stress dimensions other than heat. In fact, the data in many studies should not have been described as heat tolerance, but rather as summer survival. During heat tolerance studies, it is very critical to sustain the proper energy balance while specific levels of heat stress are imposed on the grass plant. While the amount of research information on direct heat stress of turfgrass species is somewhat limited, the problem area is far less complex than drought resistance and the potential for progress in developing a more complete description of the stress phenomenon and allied inter- and intraspecies tolerances are achievable. However, a rapid cost-efficient method for screening large numbers of plants in a breeding population is yet to be developed.

#### Cold Stress

There are three components to cold stress: (a) chilling, (b) non-equilibrium freezing, and (c) equilibrium freezing. Chill stress is

unique to subtropical C<sub>4</sub> perennial turfgrasses, whereas the other two components can occur in both cool and warm season species. Which type of freezing stress occurs depends on the rate of freezing and the degree of cold hardiness in the individual species or cultivar (Beard, 1973). There is a good base of knowledge on both types of freezing stress that is applicable to turfgrasses. There also are some techniques in advance stages of development that have potential for modification of specific turfgrass species. The number of species that can be screened by this method on a cost effective basis is limited, but acceptable if integrated into a breeding program at a more advanced stage. In the case of chill stress of C<sub>4</sub> warm season species, screening can now be readily accomplished in the field by visual assessment.

#### Shade Stress

Stress tolerance to tree shade is a very complex phenomenon involving a combination of disease resistances, light energy capture and utilization, dark respiration, lateral stem orientation, and rooting. Resistance to various diseases is by far the most significant factor in shade adaptation for the C<sub>3</sub> cool season turfgrass species (Beard, 1965). This is the component which should be emphasized initially. There also is a fairly reasonable base of knowledge on the physiological components of shade stress (Wilkinson and Beard, 1974 and 1975). However, a comprehensive screening technique has not been developed and the potential for developing economically feasible methods appears to be a challenging problem.

#### Wear Stress

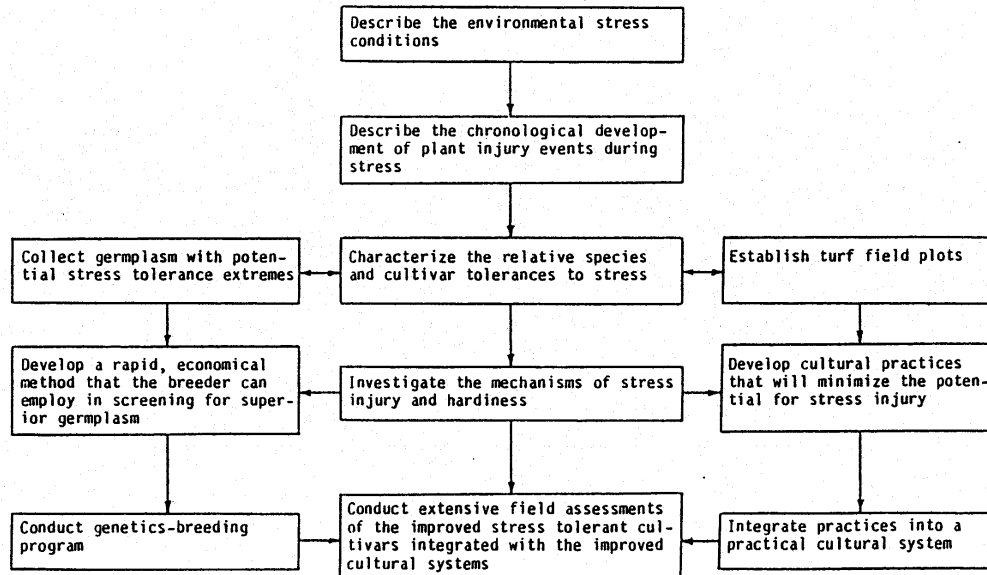
The known components of wear tolerance include the shoot lignin content, the amount of verdure, and the percent of sclerified tissue in the leaves (Shearman and Beard, 1975). There is a fair base of knowledge on the components of wear tolerance at both the inter- and intraspecies levels for cool season species. The development of acceptable screening techniques for a breeding program has a reasonable potential for success in certain grass species.

### AN ENVIRONMENTAL STRESS - GENETICS MODEL FOR TURFGRASS

The first step (Figure 1) is to describe the environment in which each stress occurs so that it can be duplicated under controlled environment greenhouse and/or growth chamber conditions to facilitate year round in-depth investigations. The second step is to describe the chronological development of plant injury symptoms during the onset and progression of stress injury. This involves anatomical, morphological, and physiological aspects. Subsequently, it is important to characterize the relative stress hardiness among the major turfgrass species as well as at the intraspecies level among the available cultivars and selections being emphasized in the breeding program.

Subsequently, the mechanisms of stress injury and stress hardiness are pursued. These mechanistic investigations should be oriented to concepts that will provide a sound basis for the development of screening methods for stress tolerance in a grass breeding program, as well as for

Figure 1. An environmental stress physiology - genetics model to improve stress tolerance in turfgrasses.



the development of cultural strategies to minimize the potential for stress injury.

Depending on the type of stress and the complexity of the problem, the next step is to develop a rapid economic method which the grass breeder can employ in screening the germplasm collection for superior stress tolerance. At the same time, cultural studies should be initiated that emphasize the development of approaches which minimize the potential for stress injury. Finally, there remains the task of integrating the newly developed, stress tolerant turfgrass cultivars resulting from the breeding program and the newly developed or altered cultural strategies and soil management systems into a total cultural system best adapted for the newly introduced cultivar. The integrated cultural system for the newly developed cultivar must, of course, be tested and implemented on a practical basis under typical field conditions.

#### APPLICATION OF THE MODEL

An example of the application of an environmental stress model is the research program being conducted at Texas A&M University in identifying low water use rate turfgrasses for irrigated regimes, and, thereby, conserving water. The characterization of environments under which high water use rates occur is well described in the literature. Furthermore, the physiological activities are well detailed in the literature (Beard, 1973). Studies are being conducted concerning the stomatal frequencies and characteristics for the major turfgrass species and cultivars (Griggs, Casnoff, and Beard, 1984). Since much of the literature from other crops was directly applicable, the initial thrust in this research program involved characterization of water use rates at the inter- and intraspecies levels.

The water use rates of eleven major warm season species were characterized by Kim and Beard (1983) under non-limiting soil moisture conditions which simulated potential evapotranspiration. Subsequently, the evapotranspiration rates were assessed for the same eleven grasses under progressive water stress conditions. The evapotranspiration assessments were conducted in mini-lysimeters under field conditions using the water balance method. The turf plots were constructed to insure a natural environment surrounding each mini-lysimeter. All grasses were mowed at a 3.8 cm cutting height and fertilized with 0.25 kg nitrogen  $\text{are}^{-1}$  growing month $^{-1}$ .

The range in potential evapotranspiration rates among the eleven species was in the order of 45% with significant differences observed at both the interspecies and intraspecies levels. Emerald zoysiagrass (Zoysia japonica x Z. tenuifolia Willd. ex. Trin.), Texoka buffalograss [Buchloe dactyloides (Nutt.) Engelm], Tifgreen bermudagrass (Cynodon dactylon x C. transvaalensis Davy), and Common centipedegrass [Eremochloa ophiuroides (Munro.) Hack.] exhibited the lowest potential evapotranspiration rates; while Kentucky 31 tall fescue (Festuca arundinacea Schreb.), Texas Common St. Augustinegrass [Stenotaphrum secundatum (Walt.) Kuntz.], Argentine bahiagrass (Paspalum notatum Flugg.), and Adalay seashore paspalum (Paspalum vaginatum Sw.) were characterized by high rates. Common bermudagrass (C. dactylon (L.) Pers.), Tifway bermudagrass, Meyer zoysiagrass (Z. japonica Steud.), and Common blue grama [Bouteloua gracilis (N.B.K.) Lag. ex. Steud.] ranked intermediate in potential evapotranspiration rates. This study was repeated a second growing season with similar findings.

When the same eleven species were subjected to progressive water stress, the relative rankings in terms of evapotranspiration rate did not change among the species, with one exception. Bahiagrass had a very high evapotranspiration rate under non-limiting moisture conditions, but exhibited a very low evapotranspiration rate under progressive water stress. This suggests that an internal adaptive mechanism exists in bahiagrass that may be of significance when studying water conservation strategies related to drought resistance.

More recently seven cool season turfgrasses have been assessed in terms of potential evapotranspiration. Comparisons were made among perennial ryegrass, Kentucky bluegrass, turf-type tall fescue, forage-type tall fescue, and creeping bentgrass (*Agrostis palustris* Huds.) when mowed at 3.8 cm. All seven grasses ranked very high in terms of potential evapotranspiration. The assessment of a broader range of cool season species is continuing.

Mechanistic studies by Johns, Beard, and Van Bavel (1980, 1981, and 1983) concerning the relative magnitudes of the resistance components controlling evapotranspiration were conducted in a stress simulation chamber under non-limiting water conditions. Investigations revealed that external resistances ( $r_a + r_c$ ) were two to four times greater than the leaf resistance ( $r_l$ ). The resistance values found for St. Augustinegrass were comparable to those reported earlier for barley (*Hordeum vulgare* L.). It was concluded that under well watered conditions stomata exhibited limited control of evapotranspiration. In other words, the evapotranspiration rate is controlled to a large extent by factors external to the plant that can be manipulated through morphological characteristics rather than through internal anatomical or physiological components of the plant. These external factors were found to include the number and position of leaves and stems within the turfgrass canopy. Turfs with a high leaf and stem density plus a substantial horizontal leaf orientation exhibited greater impairment of the normal upward movement of water vapor and, at the same time, reduced turbulent eddy movements within the canopy. These data suggest that a greater potential exists for enhancing resistance to evapotranspiration through manipulation of canopy structure and density rather than alterations in leaf resistances.

Investigations conducted by Kim and Beard (1984) concerning the morphological characteristics of the major turfgrasses that were associated with high and low water use rates revealed a consistent trend at the interspecies level. Those species possessing low water use rates also are characterized by a slower vertical leaf extension rate and a high canopy resistance in terms of a high shoot density, more horizontal leaf orientation, and a narrower leaf texture. All these are plant characteristics that can be rapidly assessed visually in the field by a plant breeder. This approach to rapid visual assessment of canopy resistances to evapotranspiration has been tested at the intraspecies level with 22 bermudagrass genotypes. Drs. Horst, Engelke, Casnoff, and Beard conducted visual estimates of comparative water use rates among replicated sets of the 22 selections. This initial series of visual ratings resulted in a 70+% accuracy in ranking them as to their relative water use rate. For an initial attempt, this success level suggests a promising new approach that can be used effectively by breeders in the field. A wide diversity of zoysiagrass canopy resistance and leaf extension types has been identified by Engelke. These are now being

established as turfs for quantitative assessments of water use rates to predict the effectiveness of this technique on a different species.

The significant influence of the vertical leaf extension rate on evapotranspiration has introduced a fundamental concept that may be applied to various cultural practices. Investigations by Shearman and Beard (1972) and by Kim and Beard (1983 and 1984) showed that close mowing and a low nitrogen rate could significantly reduce the evapotranspiration from both cool and warm season turfgrasses. The combined cutting height-nitrogen nutritional regime that produced the most rapid leaf growth rate also was associated with the highest evapotranspiration rate regardless of the species involved. Those species with a high nitrogen requirement were more sensitive to nitrogen fertility than to mowing heights in terms of effect on evapotranspiration rates. In contrast, those species with a low nitrogen requirement were characterized by evapotranspiration rates which were more affected by mowing than by the nitrogen nutritional level (Kim and Beard, 1984).

The significant influence of leaf extension rate also suggested investigations regarding the use of growth inhibitors in water conservation (Johns and Beard, 1981 and 1982). Both field and greenhouse studies were conducted on St. Augustinegrass and bermudagrass utilizing two growth inhibitors: flurprimidol and mefluidide. All four experiments confirmed the hypothesis that growth inhibitors have potential as a cultural technique to achieve water conservation. Reductions in the evapotranspiration rate in the order of 15 to 35% were found, depending on the specific experimental conditions and the inherent shoot growth rate of the species involved. The reductions in water use rate were sustained for a period of 12 to 14 weeks. It should be indicated that the use of growth inhibitors as a water conservation strategy is associated primarily with irrigated turfs. Additional studies are being conducted on other cultural practices that might affect the canopy resistance, leaf extension rate and, thereby, evapotranspiration. This brief review of an extensive series of studies that have been conducted on water use rates is an example of the successful application of an environmental stress-genetics model to turfgrasses.

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#### SUMMARY IN FRENCH

Un modèle génétique-milieu pour l'amélioration du gazon  
Aspects physiologiques

Un programme pluridisciplinaire pour la création de cultivars de gazon tolérants à des stress spécifiques d'environnement n'est pas encore mis en place pour améliorer les gazons. Ici nous discutons les principaux types de stress chez le gazon, les facteurs et la complexité résultante de chaque type de stress, et le potentiel de réussite dans l'amélioration des cultivars. Un modèle physiologique est présenté, en prenant comme exemple la réduction de la consommation d'eau. Le modèle inclut une description des conditions d'environnement, la chronologie des réponses de la plante, une caractérisation au niveau inter et intra spécifique et des études de mécanismes conduisant à des méthodes pratiques de prédiction. Une hypothèse concernant les paramètres les plus importants intervenant dans la prévision a été établie. En utilisant des sélections de graminées à gazon possédant une gamme complète des caractéristiques prévisibles, l'hypothèse sera vérifiée. Si elle se confirme, la prochaine phase inclura des études d'héritabilité et des méthodes permettant l'incorporation des caractères désirables dans les cultivars améliorés.



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## Key Events in the Seasonal Root Growth of Bermudagrass and St. Augustinegrass<sup>1</sup>

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*Additional index words.* turf, lawngrass, *Poaceae*, *Cynodon* spp., *Stenotaphrum secundatum*

**Abstract.** Root growth of St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] and bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Davy] (C-4 plants), show distinct seasonal patterns different from those of the cool-season perennial grasses (C-3 plants). Root growth continued after winter shoot dormancy occurred, and at soil temperatures below 10°C. Severe browning of the entire root system was observed just after spring shoot greenup followed by a delay of about 3 weeks in new root initiation and replacement, even though significant shoot development was occurring prior to this period of root initiation.

Difficulties involved in making continuous, nondestructive root system evaluations have resulted in the development of turfgrass, forage, and pasture cultural systems based on the responses of the grass shoot. Because of this, the potential importance of root system characteristics and seasonal behavior in such cultural systems has yet to be fully investigated. Many cultural difficulties, including turfgrass establishment and unusual pesticide phytotoxicity, could be manifestations of a weakened grass plant resulting from a poorly developed root system (9, 10, 11, 12).

Earlier rooting studies on perennial grasses were conducted with cool season, C-3 species (3) using periodic evaluation methods

(13, 14, 15, 16). This investigation is the first to utilize continuous (daily) root observation procedures to study the seasonal behavior of 2 major perennial warm season C-4 grass species. This report covers the first 2 years of a continuing investigation conducted in the Texas A&M University Turfgrass Rhizotron. The rhizotron consisted of 2 rows of 24 root observation boxes, each having dimensions of 25 cm wide x 30 cm long x 75 cm deep. Details pertaining to the rhizotron construction and design were reported earlier (4, 5, 6, 7, 8).

'Floritam' St. Augustinegrass and 'Tifgreen' bermudagrass sods were transplanted into the root observation boxes in August 1976. Phosphorus (P) was applied annually to the turfs as superphosphate at a rate of 148 kg of actual P per hectare. The initial application of phosphate (August 1976) was incorporated into the upper 10 cm of the soil. All turfs received nitrogen (as KNO<sub>3</sub> and (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>) and potassium (as KNO<sub>3</sub>) at a rate of 49 kg of actual nutrient (N or K) per ha-growing month. The turf was mowed weekly at a 5-cm cutting height for 'Floritam' and a 2.5-cm cutting height for 'Tifgreen'. Irrigation was applied as needed to prevent wilting. Treatments were replicated 4 times. Soil temperatures were recorded continuously at 10- and 30-cm depths with a 2-pen Foxboro temperature recorder beginning in October 1977, while previous soil temperatures were periodically monitored us-

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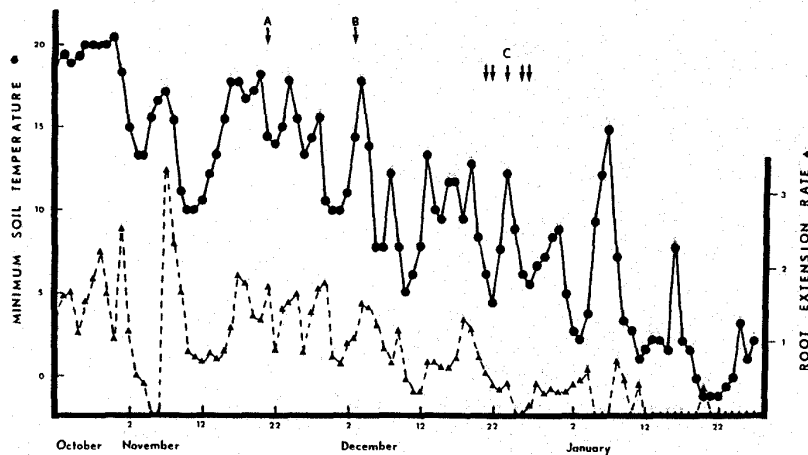


Fig. 1. St. Augustinegrass mean root extension rate (cm/day) and the minimum soil temperature (°C) at a 10-cm depth from Oct. 23, 1977, through Jan. 27, 1978. (A) Chilling injury was first observed on Nov. 21, 1977. (B) No further shoot growth occurred after Dec. 3, 1977. (C) The first 5 frosts occurred at the end of December.

ing copper-constantan thermocouples. Root extension lengths were recorded daily by tracing root growth on clear acetate sheets which were pressed against the glass plate of the root observation boxes.

**Summer rooting responses.** Individual root extension rate of both species averaged 2.8 cm/day during the warm summer months. Daily root extension rates ranged from 0 to 10 cm/day for individual roots. Daytime cloud cover resulted in reduced nocturnal root extension rates in a previous greenhouse investigation (4). The average daily root extension rate for these 2 warm season species

was 5 times greater than the rate reported by Beard (1, 2) for creeping bentgrass (*Agrostis palustris* Huds.) and Weaver (15) et al. for winter wheat (*Triticum aestivum* L.), both cool season species.

New root initiation, root maturation, and death of older roots continued through the summer months. Rooting depths for both species were in excess of 70 cm; however, the majority of the root system was located in the upper 30 cm of the soil (Table 1). 'Floritam' roots were substantially fewer in number per unit area of sod and larger in diameter than those of 'Tifgreen'. St. Au-

Table 1. St. Augustinegrass and bermudagrass root system profiles as sampled in November 1976, about 3 months after establishment.

Soil layer depth (cm)	St. Augustinegrass		Bermudagrass	
	Root dry wt (mg)	% of total	Root dry wt (mg)	% of total
0-10	256 e <sup>z</sup>	52	387 c	62
10-20	123 cd	25	139 b	22
20-30	77 bc	16	69 a	11
30-40	35 ab	7	29 a	5

<sup>z</sup>Means separation within columns by Duncan's multiple range test, 5% level.

gustinegrass had up to 28 actively growing roots visible through the grass facing of the root observation boxes, while the bermudagrass turfs had up to 60 actively growing roots visible per plate.

**Fall rooting responses.** Root extension rates of 'Floritam' gradually decreased as fall soil temperatures declined (Fig. 1). The root extension rate averaged 1.3 to 1.5 cm/day during the last 2 weeks in October 1976 and 1977. Respective soil temperature means at a 10-cm depth for these 2-week periods were 15.5 and 20.1°C.

Chilling symptoms (initially appearing as a purple leaf coloring) were observed on the 'Floritam' turfs on Oct. 26, 1976, and Nov. 21, 1977. The mean soil temperatures at a 10-cm depth were 15.3 and 17.2°C, respectively. 'Tifgreen' developed chilling injury symptoms about 3 days later than 'Floritam' in 1977. 'Tifgreen' shoot growth essentially ceased after Oct. 1, 1976, and Dec. 3, 1977. Root growth continued for almost 30 days after shoot growth ceased in 1977.

**Winter root responses.** During the period between the last day of measurable root growth in early winter and the initiation of new shoot growth the following spring, the roots of both species remained a white to light-tan color. As such, they were assumed to be alive and capable of functioning. No root growth occurred after Jan. 21, 1978, until the occurrence of spring new root initiation. The mean soil temperature at a 10-cm depth for the remaining portion of January, February, and March 1-21 were 1.9, 5.4, and 11.4°C, respectively. New root initiation was not observed during the winters of 1976-1977 and 1977-1978.

**Spring root responses.** The first new leaves initiated from 'Tifgreen' were observed on March 21, 1978, while those of 'Floritam' were visible on March 22, 1978 (Fig. 2). On March 26, the roots of both species underwent a rapid color change from white-light tan to brown. A similar color change of the roots was also observed during leaf-greenup in early spring for 1977 and 1979. After March 26, 1978, both the 'Floritam' and 'Tifgreen' turfs produced significant amounts of new green leaves without any outward signs of new root initiation. 'Tifgreen' shoots and roots developed earlier in the spring than those of 'Floritam' (Fig. 2). New spring roots of 'Tifgreen' did not reach

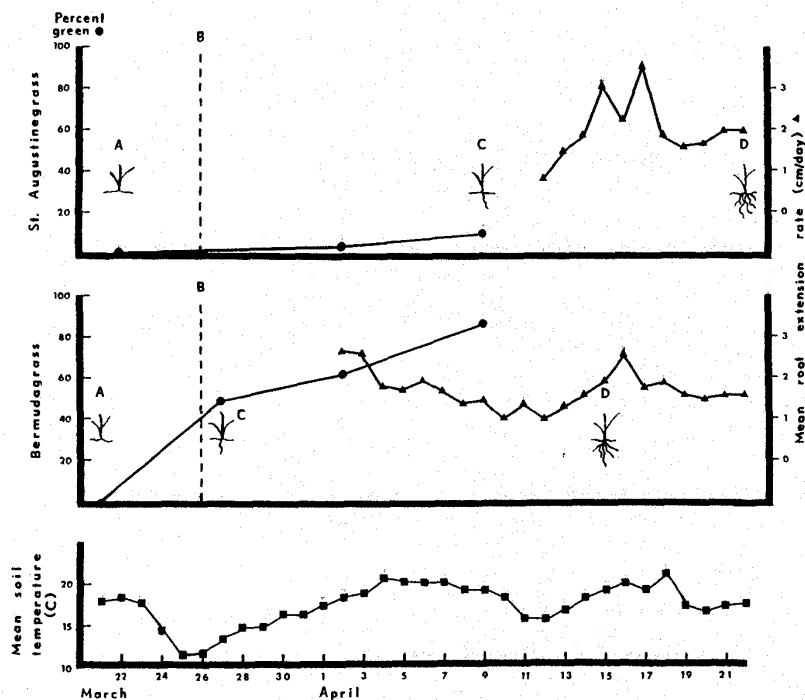


Fig. 2. Key events in the shoot and root development of 'Tifgreen' bermudagrass and 'Floritam' St. Augustinegrass and soil temperature during spring of 1978. (A) Appearance of the first new leaves, (B) root browning, (C) new root initiation, and (D) the first root reaches a 30-cm depth.

a depth of 30 cm until mid-April of 1978, while 'Floritam' roots did not achieve this depth until late April.

Three previously unknown seasonal root growth characteristics of 2 warm season (C-4) perennial grasses have been observed during this investigation. First, fall root growth occurred at surprisingly low soil temperatures. Although the amount of growth was small, its occurrence at soil temperatures below 10°C for these warm-season, perennial grass species was not expected, nor previously reported in the literature. Second, root growth continued in the fall after shoot growth ceased and conditional shoot dormancy had occurred. There appear to be distinct shoot and root dormancy phases during the fall-early winter months, rather than a general plant dormancy. This finding is in direct contrast to a report by Weaver et al. (15) with a C-3 annual grass, 'Kanred' red winter wheat. Root growth of 'Kanred' winter wheat was observed to cease simultaneously with that of the aboveground parts. Third, severe browning of the entire observable root systems of both grasses occurred just after spring shoot greenup was observed. 'Tifgreen' exhibited a 1-day delay, while 'Floritam' had a 2-week delay before new root initiation occurred following the spring root senescence phenomenon. This rooting delay was actually longer from a practical standpoint, since it took about 20 and 15 days for any newly initiated 'Tifgreen' and 'Floritam' root, respectively, to reach a soil depth of 30 cm. Thus, the effective spring rooting delay for both grasses in 1978 was about 3 weeks.

It can be speculated that the restricted spring root growth is at least partially the result of internal plant factors such as carbohydrate

availability to the root and hormonal concentrations. Evidence for such speculation is seen in the observation that root growth continued in the fall but not during the early spring, even though soil temperatures at those times were comparable.

The limited root system during this late winter-early spring period could increase the proneness to injury from low-temperature stress, desiccating winds, traffic, diseases, and insect pests. Periodic reports from throughout the southern United States have noted such problems during this period (9, 10, 11, 12). Furthermore, pesticide applications at normal rates, which result in no observable injury when applied at other times during the growing season, have caused phytotoxicity problems if applied during this spring root loss period (9, 10, 11). The inability of grasses to root adequately during this spring greenup period is probably a major contributing factor to these winterkill, pesticide, and establishment problems.

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Chapter | **An environmental genetics model  
for turfgrass improvement :  
developmental aspects <sup>(1)</sup>**

3 | M.C. ENGELKE, J.B. BEARD  
and P.F. COLBAUGH

ABSTRACT

Development of functional and persistent turfgrass cultivars adapted to natural environmental conditions will require an intense, systematic, multidisciplinary approach. The genotypes developed will be directed to a more conservative and often stressful environments. Assessment of species best suited for the natural environment will be closely associated with acquisition and evaluation of existing germ plasm resources. Primary consideration must be directed toward gaining a better understanding of the biological mechanisms associated with performance and survival under stress conditions. A team approach to systematic breeding programs must develop and utilize techniques which identify the genetics of important biological characteristics and which enhance the genetic diversity and integrity of the base population. Comprehensive turfgrass breeding efforts are discussed detailing the interdisciplinary approach to developing turfgrasses for use under natural environmental conditions.

Additional key words : Natural environment, Stress, Germ plasm resources

INTRODUCTION

America became painfully aware of energy considerations in 1973 when petroleum prices increased dramatically. In 1978 and again in 1980, record droughts prevailed across the United States reminding us of yet another of our most treasured natural resources - WATER. Of the global supply of water, less than 1 percent is potable. The remainder is tied up in glaciers, oceans and other high-salt-content supplies not readily available for human consumption (National Geographic, 1980).

The potable water supply is limited, while population growth and water demands are projected to increase by 35 percent in the United States by year 2000 (Carter, 1980). Water use during 1980 in Texas alone was 17.3 million acre-feet; 78 percent of that was for agricultural irrigation, 12 percent for municipal water use, and 10 percent for industrial use (Clarke, n.d.). Nearly 60 percent of the municipal supply is being used for landscape and general-purpose turf areas in the arid southwest United States. Restrictions on the use of our water resources, especially potable water, will be greatly increased over the next few decades and may exclude turfgrasses and ornamentals regardless of their purpose. The cost of water, nutrients, and energy will continue to increase the cost of turf maintenance.

(1) A contribution from Texas Agricultural Experiment Station, Texas A&M University System, Dallas, College Station, U.S.A.

Energy costs for pumping water have become a significant portion of the total operating budget of many institutions with irrigated landscapes. Water availability is not the only concern of present day turf managers and scientists; however, without supplemental water few if any on the present-day turfgrass cultivars would persist.

The "environment" according to Billings (1952) "includes all external forces and substances affecting growth, structure, and reproduction of the plant." A "stress environment" according to Levitt (1980) is one which is unfavorable to living organisms. Boyer (1982), Beard (1973) and Ward (1969), in their analysis of factors limiting plant adaptation, production, survival, and efficiency, identify environmental stress factors such as extremes in temperature, moisture, light, and wind as major selection criteria. Considering day-to-day fluctuations in weather, brief periods of stress occur frequently. Fortunately the biological constitution of most plant species buffer against these brief extremes.

The physiological state of plants also changes in response to the weather, seasons, and edaphic conditions. If the environmental changes are gradual, the plants physiological mechanisms will adjust, within limits, and become "conditioned" or "harden-off". In contrast, if these changes are abrupt, or too severe, the plant becomes stressed. Nearly all living organisms can survive moderate levels of stress for brief time periods. A plant's ability to adapt to a region is thus dependent upon its ability to tolerate individual and multiple influences of the environment (Wilsie, 1962). A plant is considered adapted as long as the critical limits of its biological system are not exceeded for a prolonged period of time. The critical biological limits and physical performance of a plant are controlled by its genetic composition and the environment in which it grows. Changes in either will result in changes in the plants expression.

The intensity of cultural practices required to maintain quality turf is a function of the specific cultivar in use and the natural climatic conditions of the region. Monthly 30 year average precipitation patterns (Figure 1) presented for precipitation received. Variability exists also in the minimum and maximum temperature extremes and the duration of occurrence. Ward (1969) identified major growth regions and zones of plant adaptation based on long term weather records, specifically relative precipitation and ambient temperatures. Because of this wide variation in natural environmental conditions, it is reasonable to expect that different varieties and/or species will be best adapted to the different regions of the country.

Many of the commercially available turfgrasses in use today are poorly adapted to the natural environment, and in many cases in the environments where they are presently being used. They have a large number of favorable genes for quality turf in an environment with relatively mild temperatures, abundant water, and extensive cultural inputs, such as frequent fertilization, mowing, and pesticide application, as they were developed for an optimized environment. Full utility of these cultivars often requires the turf manager modify the environment in order to compensate for the biological deficiencies of the plant. When these plants are introduced into a different environment such as where water resources are limited, the plants performance will also change according its genetic makeup. If the environmental change is too great, the plant may be unable to compensate due to its genetic

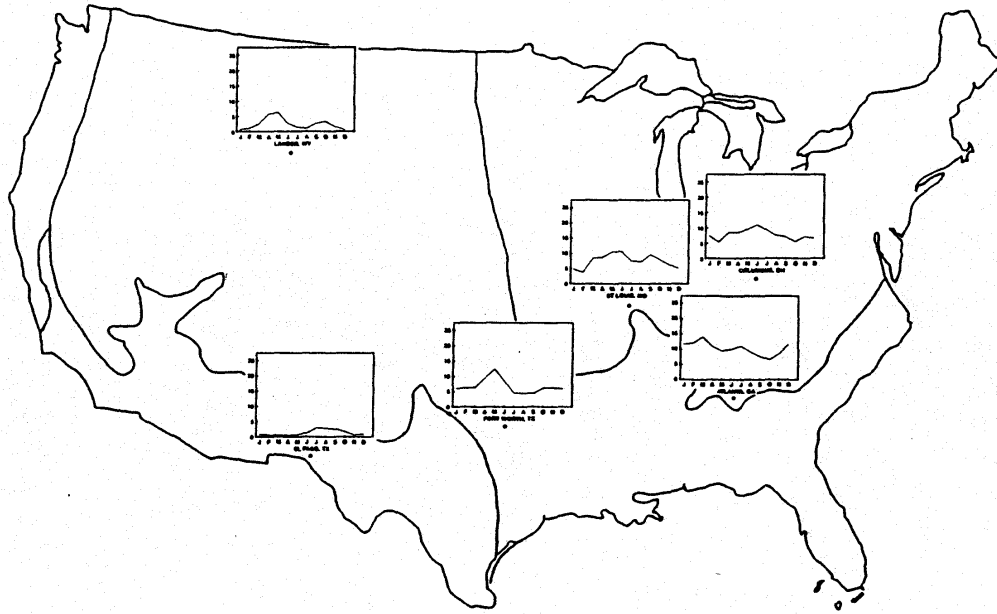


Fig.1: Precipitation patterns for selected cities in the United States(cm)

limitations and become stressed. Its performance is then less than desirable.

Considerable genetic potential exists for improving most plant species for a specific type of environment. Ward (1969) and Boyer (1982) recognized the biological limitations and regionalization of certain species, although Boyer contends that marginally adapted species can be improved through selection and genetic manipulation. However, the full genetic potential of the species must first be recognized in order to accomplish significant change. The best way of assessing this potential is by determining plant performance under conditions that are nonlimiting, rather than under a natural environment which would limit full expression of its genetic potential. It is important to make the distinction that the genetic potential of the plant is independent of environmental influence, but that the expression of this genetic potential is dependent on the environment. As stated by Allard (1966):

"Genes cannot cause a character to develop unless they have the proper environment, and no amount of manipulation of the environment will cause a characteristic to develop unless the necessary genes are present."

Therefore, the phenotypic potential of the plant, which we see in the field, is the product of its genetic potential interacting with the environment.

Once the genetic potential of a species is defined, the selection process must be conducted with emphasis on the limiting factor(s) in order to increase the frequency of favorable genes in the population. In addition, genetic improvements should be closely coupled with the proper management practices in order to create a phenotype which is close to its genetic potential for the selected environment. In this way the resulting cultivars will be better adapted to the intended environment.

#### OBJECTIVES

The ultimate success of the breeding program depends on the investigator's ability to identify and manipulate biologically important agronomic and physiological characteristics.

Such planning must consider numerous factors including:

- 1) primary utility (recreation, erosion, esthetics, etc.) of the particular turf;
- 2) its intended region (area) of utilization;
- 3) projected intensity (traffic) of utilization;
- 4) anticipated environmental and cultural limitations (climatic, moisture, nutrition);
- 5) primary biological limitations (diseases, insects, salinity); and
- 6) degree of genetic diversity available within the species.

The function of future turfs will be similar to their use today in providing erosion control from wind and rain, reducing glare and noise in the urban environment, providing a safer playing area on athletic and recreational areas, dissipating heat, and yielding a certain aesthetic appeal for the domestic environment. New cultivars must utilize existing and alternate water and energy resources more efficiently and be able to survive and perform under more natural conditions with minimal environmental modifications. The species utilized for future turf will depend on the availability of genetically diverse germ plasm, heritability of desirable characteristics, and the cultural limitations under which they are to be produced and utilized. It is reasonable to expect that numerous cultivars among several species will be developed to fill the broad array of environmental, sociological, and economic "niches" presently recognized in the turf industry. Likewise, the multiple cultivars will expand the functional product line available to both the consumer and the producer, thereby stimulating competition, improving product quality and availability, and increasing the probability of success.

A flow diagram is presented to aid in the discussion of the many facets of a comprehensive turfgrass breeding program (Figure 2).

#### Identification of Plant Species

The primary and secondary regions of adaptation are generally defined for any given species based on the principal environmental factors of temperature, moisture and geographic factors of relative latitude and altitude. As Boyer (1982) suggested, a species which is marginally adapted to a climatic niche may be improved through genetic manipulation. The real concern is - does the probability of success and environmental and economic impact warrant introduction of "exotic" plant species?

To answer these questions, information and research efforts must be directed to determining the level of genetic diversity available to the plant breeder either through existing germ plasm collections, or what may be available at their Center-of-Origin and obtainable (physically and politically) through intensive plant collection trips. The remaining question must be concerned with the species ultimate turf potential which is directly concerned with persistence, performance and production.

#### Germ Plasm Acquisition

Germ plasm acquisition and development of the Germ Plasm Introduction Nursery (GPIN) is a continuing process by which the breadth of diversity is assembled, evaluated and concentrated throughout the life of the program. The importance and extent of germ plasm acquisition must not be under-estimated as this represents the total accumulation of genetic variability available to the breeding program and ultimately determines the rate and extent of varietal development. The introduction of new plant into the GPIN provides the genetic diversity needed in every breeding program. The initial inputs to the first cycle GPIN should include existing germ plasm resources such as:



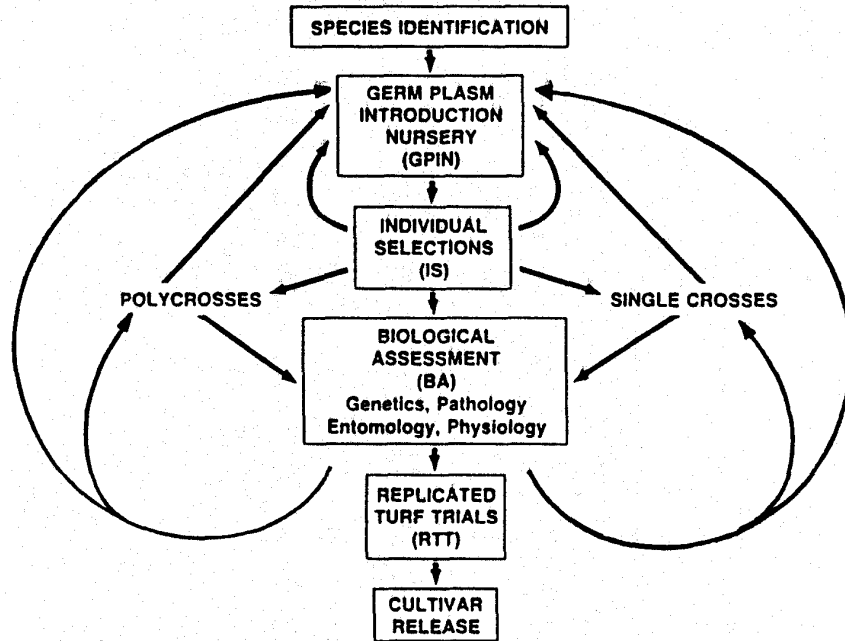


Fig.2: Flow diagram depicting major elements and events in developing grasses into acceptable turfgrass cultivars

- a.) the USDA Plant Introduction Collection;
- b.) existing germ plasm in cooperative breeding programs;
- c.) local ecotypes;
- d.) domestic collection trips;
- and
- e.) collection trips to the "Center-of-Origin"

As the program matures, plant materials possessing undesirable characteristics must be eliminated while simultaneously recycling desirable genotypes back into the GPIN. This elimination and recycling will increase the frequency of desirable genes within the population, maintain and enhance the degree of genetic diversity within the population, increase the frequency of desirable genes and through intercrossing (natural and controlled) provide for genetic recombination and emergence of more desirable genotypes, thereby improving the probability of success.

#### Germ Plasm Assessment

Germ plasm assessment is the most important, labor intensive, and expensive phase of any breeding program. As suggested by Boyer (1982), the initial assessment of plant materials should be done under non-limiting conditions in order to identify the full genetic potential of the plant materials available. In the case of the program in Texas, the development of the GPIN is staged under greenhouse and laboratory conditions, and on native soils which consist of a relatively heavy Houston Black Clay series. Considerable extremes exist in the natural environment in Texas especially with respect to temperature and moisture. If the initial evaluations were conducted only under field conditions, a considerable sum of the germ plasm would be lost immediately. Recognizing the limitations on greenhouse and laboratory space, interior selection and screening procedures are confined to those problem areas which afford the greatest probability of success. Once the potential of the population has been identified, and the realization that the desirable genes are present in the population, the actual selection and evaluation occurs in the field under more natural (adverse) conditions so the genotypes capable of exploiting limited resources can be identified (Boyer 1982). Reference is made to companion chapters within these proceedings (Beard and Engelke, 1985; Colbaugh and Engelke, 1985) which discuss both the interdisciplinary link and technical procedures to germ plasm identification and characterization.

Discussions in these chapters will include techniques for screening populations for:

- a.) tissue and root tolerances to high temperatures
- b.) rooting characteristics related to efficient use of water resources
- c.) identifying plant materials with salt tolerance
- d.) etiology and resistance to major pest organisms with special emphasis on diseases

Superior genotypes identified through field, greenhouse, and laboratory screening procedures will be recycled into the GPIN and be directed to the hybridization program.

### Species Hybridization

Species hybridization is the physical and biological phase of combining the favorable genes into an identifiable population, family or individual. This phase follows the identification of unique genetic characteristics, and depending on the nature of the trait(s) will be manipulated through either singel crosses or polycrosses.

Single crosses are intermatings between two selected plants where both the maternal and paternal parents are known. The procedure requires pollen control to ensure integrity of parental lines (self vs cross pollination). This technique is more laborious; however, it is particularly beneficial in studying the genetics of simply inherited characters and in examining the genetic linkage between traits. In some cases inbreeding, backcrossing and top-crossing are used to provide specific family relations in studying heritabilities and genetic linkages.

Polycrosses result for the intermating of several plants with no attempt to control the pollen source. The maternal identity of progeny can be maintained by harvesting seed from individual mother plants. Polycrosses are less effective in studying specific genetic relationships, however, in many species the polycross method permits greater genetic recombination, the generation of larger populations. Polycross family structures are used extensively in developing populations with traits having low heritabilities and under multigenic control.

In addition to using the resulting progenies in heritability studies, desirable progeny are:

- a.) included in subsequent GPIN's to increase gene frequency in base population,
- b.) recycled through all phases of GERM PLASM ASSESSMENT, and
- c.) included in replicated field performance trials (RTT)

### Replicated Turf Trials (RTT)

Replicated turf trials (RTT) are established initially at one or two locations within the climatic region of interest. As with germ plasm assessment, field trials are labor intensive and expensive to establish, maintain and evaluate. The early field performance trials include several advanced generation experimental varieties - EXPERVARS - and common cultivars. The more advanced trials limited in the numbers of entries in order to provide more locations and more complete information over several years with a reasonable expenditure of financial, land, and labor resources.

Regionally replicated turf trials provide information on areas of adaptation, and cultural inputs required by each EXPERVAR to provide minimal and optimal performance. Such trials are established on a linear gradient irrigation field design (LGIS) and provides for definition of minimum, maximum and optimum levels of supplemental irrigation required for each expervar. They system is used for defining the water uptake and consumptive use of each experimental under field conditions, and permits defining other cultural inputs required by each new experimental variety.

Advanced turf trials are coordinated with cooperators throughout the United States enabling us to accurately define the geographic limits of cultivar adaptations and performance. Such information is essential to the development and release of any new turfgrass.

#### Cultivar Release

The development and release of new turfgrasses require considerable investment in financial resources, equipment and labor. With the multidisciplinary approach, an understanding of the biological mechanisms involved in the plant's performance expedites the identification of desirable and essential characteristics within the germ plasm pool regardless if it is water-use-rates, characters controlling osmotic adjustment, heat tolerance, rooting characteristics, disease or insect resistance, or shade or salinity tolerance. The combined efforts of these interrelated disciplines improve the probability of developing cultivars which are able to better adapt and perform under natural environmental conditions with minimal resource inputs.

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## SUMMARY IN FRENCH

Un modèle génétique-milieu pour l'amélioration du gazon.  
Aspects du développement.

Le développement de variétés cultivées fonctionnelles et persistantes adaptées à des conditions naturelles d'environnement demandera une approche approfondie, systématique et multidisciplinaire. Les génotypes créés seront voués à des environnements plus pénibles et difficiles. L'évaluation des espèces les mieux adaptées à un environnement naturel sera étroitement associée à l'acquisition et à l'évaluation des ressources génétiques existantes. Priorité doit être donnée à l'acquisition d'une meilleure compréhension du mécanisme biologique associé à la performance et la pérennité sous des conditions d'extrême rigueur. Un travail d'équipe d'un programme d'amélioration doit développer et utiliser les techniques qui intègrent la génétique de caractéristiques biologiques importantes et qui augmente la diversité génétique en conservant l'intégrité de la population de base. Les efforts dans la compréhension de l'amélioration du gazon sont discutés donnant en détail l'approche interdisciplinaire pour créer des cultivars de gazon destinés à être utilisés dans des conditions naturelles.

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## Resistances to Evapotranspiration from a St. Augustinegrass Turf Canopy<sup>1</sup>

D. Johns, J. B. Beard, and C. H. M. van Bavel<sup>2</sup>

### ABSTRACT

A controlled environment study of evapotranspiration from St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] turf showed that, under adequately watered conditions, evapotranspiration was influenced to a greater extent by environmental factors which were external to the plants rather than by disposition of leaf stomata. Using an Ohm's Law analogue to define a resistance network for the turfgrass canopy, magnitudes of resistances to water loss were measured and compared. Internal resistance was defined as aggregate diffusive resistance of the foliage and was determined from porometer measurements of diffusive resistance of leaves. External resistance was defined as the sum of aerodynamic resistance and resistance to air mass exchange within the canopy and was measured by three different methods. Internal resistance was found to be only one-fourth to one-half the external resistance. Under wind speed conditions of 0.6 m/sec, actual evapotranspiration rates of St. Augustinegrass were only slightly lower than potential evapotranspiration rates. It is concluded that chemical or genetic control of stomatal resistance would not result in appreciable savings of irrigation water.

*Additional index words:* *Stenotaphrum secundatum* (Walt.) Kuntze, Diffusive resistance meter.

IN 1978, 2.3 billion m<sup>3</sup> of water was used by municipalities and rural communities of Texas (Texas Dep. of Water Resources, 1979). This amount is expected to double by the year 2000. It has been estimated that over 30% of urban water use is for irrigation of lawns and ornamental plants (Milne, 1976). During summer months, this percentage is much higher, perhaps as high as 50%. Accordingly, turf culture should be oriented toward balancing the conflicting interests of water conservation and maintaining superior turf quality. Ultimately, turf irrigation systems must provide water to turfgrass areas with maximum efficiency. These goals can be achieved only with a thorough understanding of the fundamental processes governing evapotranspiration and further development of methods by which evapotranspiration can be accurately estimated.

Evapotranspiration from a canopy of leaves can be expressed in an equation which is analogous to Ohm's law:

$$E = \frac{-(\chi_s - \chi_a)}{r_t} \quad [1]$$

in which

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E = evapotranspiration rate [g/(m<sup>2</sup> sec)]  
 $\chi_s$  = vapor density of interior of the leaves (g/m<sup>3</sup>),  
 $\chi_a$  = vapor density of the air above canopy (g/m<sup>3</sup>), and  
 $r_t$  = total resistance to evapotranspiration between interior of the leaves and bulk air (sec/m).

By convention, E is given a negative sign to denote that the direction of flux is away from the canopy.

Total resistance to evapotranspiration is equal to

$$r_t = r_a + r_c + r_i \quad (\text{sec/m}) \quad [2]$$

in which

$r_a$  = turbulent exchange resistance between canopy and bulk air (sec/m), also known as "aerodynamic resistance",

$r_c$  = resistance to air mass exchange within the canopy (sec/m), referred to as "canopy resistance", and

$r_i$  = aggregate diffusive resistance of the foliage, or "internal resistance" (sec/m).

Internal resistance,  $r_i$ , also known as "surface resistance" (Szeicz and Long, 1969), is the harmonic average of values for individual leaf surfaces divided by the leaf area index (Monteith, 1963). The term "leaf" will be understood to be synonymous with "lamina". Thus,  $r_i$  is a function of the resistances to diffusion of the epidermis and stomata. Aerodynamic resistance and resistance to air mass exchange within the canopy are resistances imposed by factors other than interiors of the foliage. The combination of these two resistances,  $r_a + r_c$ , will be referred to as "external" resistance to evapotranspiration.

This study was designed to determine the extent to which flux of water vapor from a turfgrass canopy is controlled by stomata, or internal resistance, even under adequately watered conditions (i.e., field capacity). The study was conducted in a controlled environment chamber so that different humidity and air temperature regimes could be imposed on the turf. Further, mowing height of the turf was varied in an attempt to vary external resistance. Wind speed and light were held constant throughout the study.

## MATERIALS AND METHODS

### (a) Measuring Resistances

#### Total Resistance

Total resistance can be determined from Eq. [1] using measurements of evapotranspiration rate E, vapor density in the leaves ( $\chi_s$ ), and vapor density of the air ( $\chi_a$ ).  $\chi_a$  can be deter-

mined from measurement of canopy temperature, assuming it to equal the dewpoint temperature of air within the leaves (Slatyer, 1967).

#### Internal Resistance

Internal resistance,  $r_i$ , can be determined from porometer measurements of diffusive resistance and measurements of leaf area indices using the following equation:

$$r_i = n/[L \sum_{i=1}^n (1/r_{ab} + 1/r_{ad})_i] \quad (\text{sec/m}) \quad [3]$$

in which

- L = leaf area index,
- i = number of an individual leaf,
- n = total number of leaves sampled,
- $r_{ab}$  = abaxial diffusive resistance (sec/m), and
- $r_{ad}$  = adaxial diffusive resistance (sec/m).

Alternatively, if total resistance and external resistance are known, internal resistance can be estimated by the difference (see Eq. [2]).

#### External Resistance

External resistance can be found by three different methods determining:

- (1) resistance to water loss from a wetted canopy,
- (2) resistance to enthalpy loss from a wetted canopy, and
- (3) resistance to sensible heat loss from the canopy.

For the water loss method, an assumption is made that the aggregate diffusive resistance of a wetted canopy is zero (Linacre, 1972). Thus:

$$r_a + r_c = \frac{-(\chi_s^0 - \chi_a)}{E} \quad (\text{sec/m}) \quad [4]$$

where  $\chi_s^0$  is the saturation vapor density of the wetted canopy.

To determine resistance to enthalpy loss, the energy balance of the wetted canopy is assumed to be

$$RN + H + \lambda E = 0 \quad (\text{W/m}^2) \quad [5]$$

in which

- RN = net radiant flux density ( $\text{W/m}^2$ ),
- H = sensible heat flux density ( $\text{W/m}^2$ ), and
- $\lambda$  = latent heat of vaporization of water [ $\text{J}/(\text{kg C})$ ].

Sensible heat flux density (H) can be expressed as

$$H = \frac{-\rho c_p (T_s - T_a)}{r_h} \quad (\text{W/m}^2) \quad [6]$$

in which

- $\rho$  = density of dry air ( $\text{kg/m}^3$ ),
- $c_p$  = specific heat of air at constant pressure [ $\text{J}/(\text{kg C})$ ],
- $T_s$  = temperature of canopy surface (C),
- $T_a$  = temperature of the air (C), and
- $r_h$  = resistance to sensible heat flux (sec/m).

The resistance to sensible heat flux,  $r_h$ , can be assumed to equal  $r_a + r_c$ . Latent heat flux density ( $\lambda E$ ) from the wetted canopy, can be expressed

$$\lambda E = \frac{-\lambda(\chi_s^0 - \chi_a)}{r_a + r_c} \quad (\text{W/m}^2), \quad [7]$$

By substituting Eqs. [6] and [7] into the energy balance equation (Eq. [5]), one can solve Eq. [7] for external resistance:

$$r_a + r_c = \frac{\rho c_p (T_s - T_a) + \lambda(\chi_s^0 - \chi_a)}{RN} \quad (\text{sec/m}). \quad [8]$$

The third method is a determination of resistance to sensible heat transfer from the canopy and is described fully in a paper

**Table 1. Time sequences and environmental conditions for evapotranspiration studies from St. Augustinegrass turf.**

Time Sequence of Events:			
Day 0	Day 1	Day 2	Day 5
2100 hours Mow Irrigate Set conditions	Allow drainage	Take measurements	Take measurements Begin Day 0 of next sequence at 2100 hours
Environmental conditions:			
Series	Mowing height cm	Temperature	
		Dewpoint C	Air C
1	8.0	19.6	34.5
2	8.0	23.9	34.5
3	8.0	29.0	34.5
4	5.0	19.6	34.5
5	5.0	23.9	34.5
6	5.0	29.0	34.5
7	6.5	19.6	34.5
8	6.5	23.9	34.5
9	6.5	29.0	34.5
10	6.5	13.1	25.4
11	6.5	23.9	26.9

by Johns et al. (1981). The method involves measuring change in temperature of an abruptly shaded canopy, and by using Newton's law of cooling, calculating a heat transfer coefficient the reciprocal of which can be equated to the external resistance of the canopy.

#### (b) Procedures

All experiments were conducted in a controlled environment chamber. The chamber was 1.0 m long, 0.37 m wide, and 0.57 m high with a root zone 0.2 m deep. Air flowed horizontally along the chamber at an average speed of 0.6 m/sec, measured at 0.15 m above the canopy with a hot-wire anemometer (Hastings, Model B-22). Air temperature and humidity were controlled by a conditioning module (Scientific Systems, Inc., Model THC-300) which was a modification of the unit described by Shearman and Beard (1973). Light was applied by three, 1 kW metal-halide lamps suspended 0.33 m above the chamber. The short-wave irradiance measured with an Eppley pyranometer was 300  $\text{W/m}^2$  and the daylength was 15 h (0700 hours to 2200 hours).

St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] turf covered the floor of the chamber. The root zone medium was fritted clay (Van Bavel et al., 1978). Three removable pots of turf, 0.22 m in diameter and 0.20 m deep, were embedded in the floor so that the turf in the pots was contiguous with the surrounding turf. The pots could be removed and weighed to determine water loss.

The time sequence and environmental conditions for 11 series of experiments are shown in Table 1. At the beginning of each series, the turf canopy was clipped at 2100 hours to desired height, then irrigated to saturation with a nutrient solution described by Moore (1974). Thirty-six hours elapsed between irrigation and the first measurements to allow drainage to cease. Approximately 1.0  $\text{cm}^3$  of nutrient solution was added per  $\text{cm}^2$  of chamber floor area each night during a series to maintain adequate soil moisture conditions. Each series lasted 5 days.

The following were measured during four days of each series: rate of evapotranspiration, air temperature, dewpoint temperature, canopy temperature, and epidermal diffusive resistance. Evapotranspiration rate was measured three times per day by weighing the pots at 3-hour intervals with a Mettler balance (Model P10N). Air temperature was measured hourly with two shielded copper-constantan thermocouples positioned 0.2 m above the center of the canopy. Dewpoint was measured hourly with

**Table 2. Comparisons of internal resistances ( $r_i$ ) of St. Augustinegrass obtained with a diffusive resistance porometer and 3 residual methods [ $r_t - (r_a + r_c)$ ] based on: evaporation from a wetted canopy (Method 1), enthalpy loss from a wetted canopy (Method 2), and sensible heat loss (Method 3).**

Mowing height cm	Temperature		$r_i$			
	Dewpoint	Air	Porometer	$r_t - (r_a + r_c)$		
	C		sec/m			
8.0	19.6	34.5	18 b*	17 b	13 b	51 a
8.0	23.9	34.5	15 b	12 b	8 b	36 a
8.0	29.0	34.5	13 b	16 b	21 b	28 a
5.0	19.6	34.5	87 a	33 b	58 ab	62 ab
5.0	23.9	34.5	44 ab	32 b	37 b	57 a
5.0	29.0	34.5	36 a	29 a	33 a	30 a
6.5	19.6	34.5	37 b	17 c	15 c	55 a
6.5	23.9	34.5	25 ab	14 c	21 bc	33 a
6.5	29.0	34.5	23 a	12 b	21 a	18 ab
6.5	13.1	25.4	37 b	23 c	28 c	83 a
6.5	23.9	26.9	26 b	14 c	23 b	41 a

\* Means followed by the same letter within a row are not significantly different (alpha level = 0.05) according to Duncan's Multiple Range Test.

a dewpoint hygrometer (EG & G, model 660), using air pumped from the downstream end of the chamber at 0.2 m above the canopy. Canopy temperature of each of the three pots in the chamber was measured hourly with an infrared thermometer (Barnes, model IRT-3) calibrated in the manner described by Holman (1978).

Epidermal diffusive resistance was measured twice daily on leaves from two pots with a LI-COR diffusive resistance meter (LI-60) and a sensor with a  $3.5 \times 20$  mm aperture (LI-205A). The porometer was calibrated in the manner described by McCree and Van Bavel (1977). Measurements were taken on a minimum of seven leaves from each pot. Wide leaves were selected to facilitate use of the narrow-aperture porometer. Diffusive resistance of the adaxial side of a leaf was measured first, then the abaxial side. Temperature of the same leaf was then measured by pressing a fine copper-constantan thermocouple to the shaded side of the leaf. Equation [3] was then used to calculate  $r_i$ .

To determine external resistance to evapotranspiration (method 1) and resistance to enthalpy loss (method 2) from a wetted canopy, the turf was thoroughly wetted with a water-surfactant mist applied with a small hand-squeezed spray gun. Surfactant (Big Blue) was mixed with distilled water in a 1:100 ratio. Pots were weighed and repositioned carefully in the chamber. Air temperature, canopy temperature, and dewpoint were measured five times in the next 30 min. At the end of 30 min, pots were removed and reweighed. The entire procedure was repeated. These procedures were conducted each day after 9 hours of evapotranspiration measurements.

Chamber roof temperatures ( $T_r$ ) were measured with thermocouples. An Eppley pyranometer was used to measure the short-wave radiation (RS) above the canopy and albedo ( $\alpha$ ) of the canopy. Net radiant flux density was then calculated from

$$RN = RS(1 - \alpha) + \sigma(T_r^4 - T_c^4) \quad (W/m^2) \quad [9]$$

in which  $\sigma$  = Stefan-Boltzman constant [ $5.67 \times 10^{-8}$  W/(m<sup>2</sup> K<sup>4</sup>)]. Emissivities of the chamber roof and turf canopy were assumed to be 1.0.

To determine resistance to sensible heat loss (method 3), the infrared thermometer was positioned quickly over an abruptly shaded pot and temperatures were recorded with a strip-chart recorder (Soltec, Model 252). The canopy was shaded by placing a large cardboard sheet over the roof of the chamber. When the shaded canopy reached a constant temperature, usually requiring 90 to 150 sec, the cardboard and thermometer were

removed. Within a few minutes, the canopy temperature had returned to its former value. The entire procedure was repeated three times for each of the two pots from which epidermal resistances were obtained. Least squares fitting was used to find the heat transfer coefficient (Johns et al., 1981).

Leaf area indices were obtained in parallel sequences of experiments conducted at the end of each series of experiments. As before, the turf was mowed and irrigated at the beginning of each series. On each afternoon of days two through five of a series, a 0.01 m<sup>2</sup> sample of turf canopy was extracted from a pot. The green, living leaf blades were separated from the sheaths at the collar, weighed, and then measured for total area (one side only) with a LI-COR area meter (Model LI-3000). Leaf area index was calculated from the ratio of total leaf area to 0.01 m<sup>2</sup>. These values were used in the calculation of  $r_i$  (Eq. [3]). Mass of leaf per unit area of ground was calculated and used in method 3 for determining external resistance.

An analysis of variance was conducted to determine differences among internal resistance and the residuals of total minus external resistance. For each set of conditions, the ratio of internal resistance to the residual of total minus surface resistance [ $r_i/(r_t - r_i)$ ] was used to calculate the ratio of actual to potential evapotranspiration. The equation for potential evapotranspiration rate ( $E_p$ ), as defined by Van Bavel (1966), and the equation for the actual evapotranspiration rate ( $E$ ), as defined by Monteith (1965), were used to obtain

$$\begin{aligned} E/E_p &= \frac{(\nabla/\gamma) + 1}{(\nabla/\gamma) + 1 + r_i/(r_t - r_i)} \\ &= \frac{(\nabla/\gamma) + 1}{(\nabla/\gamma) + 1 + r_i/(r_a + r_c)} \end{aligned} \quad [10]$$

in which

$\nabla$  = slope of the saturation vapor pressure curve (Pa/C), and  $\gamma$  = the psychrometric "constant" (Pa/C).

## RESULTS

Values of internal resistance obtained with the porometer were compared in Table 2 with three values obtained from residual methods (Eqs. [4], [8], and method 3). Leaf area indices ranged from 2.7 on the 2nd day after mowing to a value of 4.0 on the 5th day after mowing. Values for the four methods of determining  $r_i$  were similar in all sets of conditions tested. The values obtained with the porometer most closely resembled residual values obtained by determining resistance to enthalpy loss (method 2). The residuals of  $r_i$  minus resistance to sensible heat flux (method 3) were, in general, least similar to values of  $r_i$  obtained by the other methods. Internal resistance values reported here for St. Augustinegrass were similar to values reported for barley (*Hordeum vulgare* L.) (Szeicz and Long, 1969), alfalfa (*Medicago sativa* L.) (Van Bavel, 1967), sorghum (*Sorghum vulgare* L.) (Van Bavel and Ehrler, 1968), and sugar beet (*Beta vulgaris* L.) (Brown and Rosenberg, 1973).

Magnitudes of  $r_i$  are compared with  $r_t$  and  $r_t - r_i$  (total minus internal) in Table 3. Also shown in Table 3 are actual evapotranspiration rates for each of the conditions studied. Evapotranspiration rates ranged from 99 to 173 mg/(m<sup>2</sup> sec) with a mean of 135 mg/(m<sup>2</sup> sec) and a standard deviation of 19. Calculated ratios of actual evapotranspiration to potential evapotranspiration were greater than 0.9 in 8 of the 11 sets of conditions. In two of the remaining sets, the ratios were 0.88. In only one set was the magnitude of  $r_i$  large enough to significantly reduce the ratio of actual to potential evapotranspiration.



Table 3. Comparison of interior resistance ( $r_i$ ) measured with a porometer with the magnitudes of total ( $r_t$ ) and external ( $r_t - r_i$ ) resistances; and the calculated ratios of actual to potential evapotranspiration (E/Ep). ( $\Delta$  = slope of the saturation vapor pressure curve at the air temperature;  $\gamma$  = the psychrometric constant at the air temperature).

Mowing height cm	Temperature		$\Delta/\gamma$	$r_t$ sec/m	$r_i$ sec/m	$r_i/r_t$	$r_i/(r_t - r_i)$	E mg/(m <sup>2</sup> ·sec)	E/Ep
	Dewpoint	Air							
8.0	19.6	34.5	4.43	95	18	0.19	0.23	151	0.96
8.0	23.9	34.5	4.43	84	15	0.18	0.22	144	0.96
8.0	29.0	34.5	4.43	76	13	0.17	0.21	114	0.96
5.0	19.6	34.5	4.43	120	87	0.72	2.64	148	0.67
5.0	23.9	34.5	4.43	106	44	0.42	0.71	136	0.88
5.0	29.0	34.5	4.43	83	36	0.43	0.77	119	0.88
6.5	19.6	34.5	4.43	111	37	0.33	0.50	151	0.92
6.5	23.9	34.5	4.43	87	25	0.29	0.40	137	0.93
6.5	29.0	34.5	4.43	70	23	0.33	0.49	114	0.92
6.5	13.1	25.4	2.85	134	37	0.28	0.38	118	0.91
6.5	23.9	26.9	3.08	92	26	0.28	0.39	98	0.91

The  $r_i$  measured at 87 sec/m by a porometer in this set did not, however, agree well with the values for  $r_i$  determined by the other methods. Values in the other methods ranged from 33 to 62 sec/m. The ratios of  $r_i$  to  $r_t - r_i$  show that the magnitude of the external resistance were two to four times greater than the magnitudes of internal resistance in 10 of the 11 sets of conditions tested.

### DISCUSSION

Since internal resistance was substantially smaller than external resistance in these experiments, the hypothesis that stomata control the flux of water vapor from an adequately watered turfgrass canopy cannot be accepted. Instead, it is concluded that the rate of evapotranspiration was controlled to a greater extent by factors external to the plants rather than by physiological factors. Furthermore, actual evapotranspiration rates of adequately watered St. Augustinegrass turf were not "substantially" below potential evapotranspiration rates. These conclusions are in agreement with those of Van Bavel (1966, 1967) on alfalfa and Van Bavel and Ehrler (1968) on sorghum. It would be interesting to conduct similar studies with increased windspeeds and decreased soil moisture. These factors are known to significantly alter values of  $r_a$  and  $r_i$ .

The findings of these experiments imply that alteration of stomatal aperture, such as by a stomatal inhibitor, cannot be expected to result in a substantial decrease of evapotranspiration from an adequately watered turf. Nor would manipulation of stomatal size or frequency be a

propitious avenue of research in a breeding program designed to develop water-conserving turfgrasses.

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## DETERMINATION OF THE RESISTANCE TO SENSIBLE HEAT FLUX DENSITY FROM TURFGRASS FOR ESTIMATION OF ITS EVAPOTRANSPIRATION RATE\*

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### ABSTRACT

Johns, D., van Bavel, C.H.M. and Beard, J.B., 1981. Determination of the resistance to sensible heat flux density from turfgrass for estimation of its evapotranspiration rate. *Agric. Meteorol.*, 25: 15-25.

A method of determining the resistance to sensible heat flux density ( $r_h$ ) was tested on a turfgrass canopy in an environmental simulation chamber. The resistance was obtained by determining the rate of change (decay) of temperatures of an abruptly shaded canopy, and is equal to the volumetric heat capacity of air divided by the product of the rate of canopy temperature decay, the mass of leaf tissue per unit area of land surface, and the specific heat capacity of the leaves. Uncertainty analysis showed the mass of leaves per unit area of land surface to be the largest source of error in the determination of  $r_h$ . Values for  $r_h$  essentially equalled the values for resistance to latent heat flux density determined by three other methods. The application of this method of determining  $r_h$  to making rapid estimates of evapotranspiration rates was tested in the growth chamber. The estimated values agreed with the measured ones.

### INTRODUCTION

A simple and rapid method for determining the evapotranspiration rate, or latent heat flux density of a turf would be useful. Since the resistance to sensible heat flux density is approximately the same as the resistance to latent heat flux density outside of the foliage surface (Slatyer, 1967), the former can be substituted for the latter in equations, derived from the energy balance of the surface, for estimating the evapotranspiration rate. A method of determining the resistance to sensible heat flux density from a leaf by measuring the speed of temperature change (decay) of an abruptly shaded leaf has been described by Linacre (1964, 1967, 1972). The purpose of our study was the testing of Linacre's method when applied to a turfgrass canopy, rather than a single leaf. The sensible heat flux density can then be calculated and subtracted from the measured net radiant flux density to give the estimated latent heat flux density as a residual.

\* Contribution of the Texas Agricultural Experiment Station, Texas A&M University, College Station, Texas 77843 (U.S.A.) as TA 16486.

## THEORY

*Heat transfer resistance*

The technique employed is adapted from the one proposed by Linacre (1964) in which it was assumed, first, that the shading is essentially instantaneous and the duration of measurement is short enough so that the leaf stomata do not respond by a closing movement. Second, it was assumed that the sum of the net radiant flux and the latent heat flux densities remains constant during the brief shading period. Linacre showed that, under the conditions assumed, the sensible heat flux density between the air and an abruptly shaded canopy can be written in two equivalent expressions

$$H = \frac{-\rho c_p}{r_h} (T_s - T_a) = (M/A)h \frac{dT_s}{dt} \quad (1)$$

where  $H$  = sensible heat flux density ( $\text{W m}^{-2}$ ),  $\rho$  = density of air ( $\text{kg m}^{-3}$ ),  $c_p$  = heat capacity of air per unit mass at constant pressure ( $\text{J kg}^{-1} \text{ }^\circ\text{C}^{-1}$ ),  $T_s$  = temperature of the canopy ( $^\circ\text{C}$ ),  $T_a$  = ambient temperature above the canopy ( $^\circ\text{C}$ ),  $r_h$  = resistance to sensible heat flux ( $\text{s m}^{-1}$ ),  $M$  = mass of leaf blades (kg),  $A$  = area of land surface corresponding to  $M$  ( $\text{m}^2$ ),  $h$  = heat capacity of leaves per unit mass ( $\text{J kg}^{-1} \text{ }^\circ\text{C}^{-1}$ ), and  $t$  = time (s).

If  $T_a$  is constant, eq. 1 is recognized as Newton's law of cooling. Integration of eq. 1 yields the equation

$$\ln |T_s - T_a| = \frac{-\rho c_p}{r_h(M/A)h} t + T_i \quad (2)$$

in which  $T_i$  is the constant of integration. For any given canopy, a constant  $\phi$  can be defined such that

$$\phi = \frac{-\rho c_p}{(M/A)h} \quad (3)$$

so that

$$\ln |T_s - T_a| = \frac{\phi}{r_h} t + k \quad (4)$$

and

$$r_h = \phi/a \quad (5)$$

where  $a$  is the slope of eq. 4. The value of  $a$  is obtained by fitting eq. 4 to successive measurements of the temperature of the shaded canopy. The value of  $\phi$  can be calculated from reported values of  $h$ , measured values of  $M/A$ , and standard values of  $\rho$  and  $c_p$ . Then  $r_h$  is obtained from eq. 5.

The second assumption leading to eq. 1 is clearly an approximation, as the temperature of the leaf changes during the shading period and, hence,

the effect on the radiative and latent heat transfer can only fortuitously be equal and opposite. Linacre has investigated this assumption further in later work (1967, 1972). For our purposes, the question is how well these ideas are adapted when applied to a turf canopy, and we propose to adopt the simple model of eq. 1 and determine how the results compare with independent estimates of the parameter  $r_h$ .

It should be noted, however, that a somewhat similar study for single leaves made by Linacre (1967) showed that the simple eq. 1 was adequate.

#### *Other resistances*

Total resistance,  $r_t$ , to latent heat flux density is defined by the equation

$$\lambda E = -\lambda(\chi_s - \chi_a)/r_t \quad (6)$$

in which  $\lambda$  = latent heat of vaporization ( $\text{J kg}^{-1}$ ),  $E$  = evapotranspiration rate ( $\text{kg m}^{-2} \text{s}^{-1}$ ),  $\chi_s$  = vapor density inside the leaves of the canopy ( $\text{kg m}^{-3}$ ),  $\chi_a$  = vapor density of the air above the canopy ( $\text{kg m}^{-3}$ ), and  $r_t$  = total resistance ( $\text{s m}^{-1}$ ). The components of  $r_t$  are defined by the equation

$$r_t = r_a + r_c + r_s \quad (7)$$

in which  $r_a$  = aerodynamic resistance above the canopy ( $\text{s m}^{-1}$ ),  $r_c$  = resistance to air mass exchange between canopy layers ( $\text{s m}^{-1}$ ), excluding the molecular boundary layer, which is included in  $r_s$  = epidermal (stomatal) diffusive resistance of the leaves, or 'surface resistance' ( $\text{s m}^{-1}$ ). It is assumed, in agreement with the general literature (Tanner, 1963; Slatyer, 1967), that a valid comparison can be made between  $r_h$  and  $r_a + r_c$  since both are transport resistances across the same effective boundary layer.

Several methods can be used to obtain values for  $r_a + r_c$ , but only three are discussed here. The first method is expressed by rearranging eq. 7

$$r_a + r_c = r_t - r_s \quad (8)$$

Thus,  $r_a + r_c$  is the residual of total resistance minus surface resistance.

A second method of determining  $r_a + r_c$  consists of determining the resistance to evapotranspiration from a canopy wetted by a fine mist. Under these conditions, the surface resistance is zero (Linacre, 1972). Therefore

$$r_a + r_c = (\chi_s^0 - \chi_a)/E \quad (9)$$

in which  $\chi_s^0$  = saturation vapor density of the measured temperature of the wetted canopy ( $\text{kg m}^{-3}$ ).

The third method of determining  $r_a + r_c$  consists of finding the resistance to enthalpy loss from a wetted canopy. Ignoring soil heat flux density, an energy balance equation for the wetted canopy can be written

$$RN + H + \lambda E = 0 \quad (10)$$

in which  $RN$  = flux density of net radiation over the canopy ( $W m^{-2}$ ). Substituting eqs. 1 and 9 into eq. 10 gives

$$RN - \frac{\rho c_p (T_s - T_a)}{r_h} - \frac{\lambda (\chi_s^0 - \chi_a)}{r_a + r_c} = 0 \quad (11)$$

Assuming  $r_h$  and  $r_a + r_c$  are equal, eq. 11 can be rearranged to solve for  $r_a + r_c$

$$r_a + r_c = [\rho c_p (T_s - T_a) + \lambda (\chi_s^0 - \chi_a)] / RN \quad (12)$$

The numerator in eq. 12 equals the enthalpy difference between the air inside the leaf and that of the air above the canopy. This method does not require a measurement of the rate of water loss.

#### MATERIALS AND METHODS

All experiments were conducted in an environmental simulation chamber. The chamber was 1.0 m long, 0.37 m wide, and 0.57 m high with a root zone 0.2 m deep. Air flowed horizontally along the chamber at an average speed of  $0.6 m s^{-1}$ , measured at 0.15 m above the canopy with a hot-wire anemometer (Hastings, Model B-22). Air temperature and humidity were controlled by a conditioning module (Scientific Systems, Inc. Model THC-300) which was a modification of the unit described by Shearman and Beard (1973). Light was supplied by three 1-kW metal-halide lamps suspended 0.33 m above the chamber. The short-wave irradiance was  $300 W m^{-2}$  and the day-length was 15 h.

Turfgrass (*Stenotaphrum secundatum* (Walt.) Kuntze) covered the floor of the chamber. The root-zone medium was fritted clay (van Bavel et al., 1978). Three removable pots of turf, 0.22 m in diameter and 0.20 m deep, were embedded in the floor and were level with the sward. The pots could be removed and weighed to determine water loss.

The environmental conditions for the eleven series of experiments are shown in Table I. At the beginning of each series, the turf canopy was clipped at 9 p.m. to the desired height, then irrigated to saturation with a nutrient solution described by Moore (1974). Thirty-six hours elapsed between irrigation and the first measurements to allow drainage to cease. Approximately 10 mm of nutrient solution was added to the turf each night during a series to maintain unlimited soil-moisture conditions. Each series lasted 5 days.

The following were measured during 4 days of each series: rate of evapotranspiration, air temperature, dewpoint temperature, canopy temperature, and epidermal diffusive resistance. The evapotranspiration rate was measured 3 times per day by weighing the pots at 3-hour intervals with a Mettler balance (Model P10N). Air temperature was measured hourly with shielded thermocouples positioned 0.2 m above the center of the canopy. The dewpoint was measured hourly with an EG&G dewpoint hygrometer (Model 660), using air pumped from the downstream end of the chamber at 0.25 m

TABLE I

Time sequences and environmental conditions for heat transfer studies from St. Augustinegrass turf

Time sequence of events			
Day 0	Day 1	Day 2	Day 5
9:00 p.m. Mow Irrigate Set Conditions	Allow drainage	Take measurements	Take measurements Begin Day 0 of next sequence at 9:00 p.m.
Series No.	Environmental conditions		
	Mowing height (cm)	Dewpoint (°C)	Air temperature (°C)
1	8.0	19.6	34.5
2	8.0	23.9	34.5
3	8.0	29.0	34.5
4	5.0	19.6	34.5
5	5.0	23.9	34.5
6	5.0	29.0	34.5
7	6.5	19.6	34.5
8	6.5	23.9	34.5
9	6.5	29.0	34.5
10	6.5	13.1	25.4
11	6.5	23.9	26.9

above the canopy. The canopy temperature of each of the 3 pots in the chamber was measured with a Barnes infrared thermometer (model IRT-3) calibrated in the manner described by Holman (1978).

Epidermal diffusive resistance was measured twice daily on leaves from 2 pots with a LI-COR diffusive resistance meter (LI-60) and a porometer with a 3.5 × 20 mm aperture (LI-205A). The porometer was calibrated in the manner described by McCree and van Bavel (1977). Measurements were taken on a minimum of 7 leaves from each pot. Wide leaves were selected to facilitate the use of the narrow-aperture porometer. The resistance of the adaxial side of a leaf was measured first, then the abaxial side. Leaf temperature was then measured by pressing a Cu-Constantan thermocouple (36 gauge) to the shaded side of the leaf. The following equation was used to calculate  $r_s$ ,

$$r_s = n / \left[ L \sum_{i=1}^n \left( \frac{1}{r_{ab}} + \frac{1}{r_{ad}} \right)_i \right] \quad (13)$$

where  $i$  = number of an individual leaf blade,  $n$  = total number of leaves sampled,  $r_{ab}$  = abaxial epidermal resistance ( $s\ m^{-1}$ ),  $r_{ad}$  = adaxial epidermal resistance ( $s\ m^{-1}$ ), and  $L$  = leaf area index.

To measure the changing temperatures of an abruptly shaded canopy, the infrared thermometer was positioned quickly over an abruptly shaded pot and the temperatures were recorded with a strip-chart recorder (Soltec, Model 252). The canopy was shaded by placing a large cardboard sheet over the roof of the chamber. When the shaded canopy reached a constant temperature, usually requiring 90 to 150 s, the cardboard and thermometer were removed. Within a few minutes, the canopy temperature had returned to its former value. The entire procedure was repeated three times for each of the 2 pots from which epidermal resistances were obtained. Least squares fitting was used to find  $a$ , the slope of eq. 4.

To determine the resistance to evapotranspiration and the resistance to enthalpy loss from a wetted canopy, the turf was thoroughly wetted with a water-surfactant mist applied with a small hand-squeezed spray gun. The surfactant (Big Blue) was mixed with distilled water in a 1:100 ratio. The pots were weighed and repositioned carefully in the chamber. Air temperature, canopy temperature, and dewpoint were measured 5 times in the next 30 minutes. At the end of 30 min, the pots were removed and re-weighed. The entire procedure then was repeated. These procedures were conducted each day after 9 h of evapotranspiration measurements.

Chamber roof temperatures ( $T_r$ ) were measured with thermocouples. An Eppley pyranometer was used to measure the short-wave radiation ( $RS$ ) above the canopy and the albedo ( $\alpha$ ) of the canopy. Net radiant flux density was then calculated from

$$RN = RS(1 - \alpha) + \sigma(T_r^4 - T_s^4)$$

where  $\sigma$  = Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ ). The emissivities of the chamber roof and turf canopy were assumed to be 1.0, implying that the transmission of longwave radiation from the lamps by the chamber roof was 0.0.

Leaf area indices were obtained in parallel sequences of experiments conducted at the end of each series of experiments. As before, the turf was mowed and irrigated at the beginning of each series. On each afternoon of days 2 through 5 of a series, a 0.01 m sample of turf canopy was extracted from a pot. The green, living leaf blades were separated from the sheaths at the collar, weighed, and then measured for total area (one side only) with a LI-COR area meter (Model LI-3000). Leaf area index was calculated from the ratio of total leaf area to 0.01 m. These values were used in the calculation of  $r_s$  (eq. 13). Mass of leaves per unit area of land surface was calculated and used in eq. 3.

The uncertainty of  $r_h$  was determined with the method described by Kline and McClintock (1953) in which

$$Wr_h = \left[ \left( \frac{\partial r_h}{\partial \phi} W\phi \right)^2 + \left( \frac{\partial r_h}{\partial a} W_a \right)^2 \right]^{1/2} \quad (14)$$

where  $W_{r_h}$  = uncertainty of  $r_h$ ,  $W_\phi$  = uncertainty of  $\phi$ , and  $W_a$  = uncertainty of  $a$ . The uncertainty of  $\phi$  was calculated from

$$W_\phi = \left[ \left( \frac{\partial \phi}{\partial \rho} W_\rho \right)^2 + \left( \frac{\partial \phi}{\partial c_p} W_{c_p} \right)^2 + \left( \frac{\partial \phi}{\partial (M/A)} W_{(M/A)} \right)^2 + \left( \frac{\partial \phi}{\partial h} W_h \right)^2 \right]^{1/2} \quad (15)$$

where  $W_\rho$  = error estimate of  $\rho$ ,  $W_{c_p}$  = error estimate of  $c_p$ ,  $W_{(M/A)}$  = error estimate of  $M/A$ , and  $W_h$  = error estimate of  $h$ .

Analysis of variance was used to determine the significance of difference among resistance values.

In order to evaluate the usefulness of an estimate of  $r_h$  for estimating evapotranspiration rates, estimates of latent heat flux density in the environmental simulation chamber were made using calculated values of  $RN$  and  $H$  in eq. 10.  $H$  was determined from eq. 1 using temperature measurements of the shaded canopy made with the infrared thermometer: the initial temperature was  $T_s$ , the final temperature, for the purpose of this calculation, was assumed to be  $T_a$ , and  $r_h$  was determined with Linacre's method. These estimates of latent heat flux density were compared with steady-state measurements of evapotranspiration rate (times latent heat of vaporization) made in the chamber, and the relative errors were calculated.

## RESULTS

An example of the calculation of  $r_h$  and its uncertainty is presented first. Table II contains the changing temperatures of an abruptly shaded canopy and values for the resistance parameters  $\rho$ ,  $c_p$ ,  $M/A$ ,  $h$ , and  $a$ . The value for  $h$  and its estimated error was based on values reported by Shull (1930) and

TABLE II

Decay of temperatures of an abruptly shaded St. Augustinegrass canopy and resistance variables

Time (s)	Canopy temperature ( $^{\circ}\text{C}$ )	Temperature difference between canopy and air ( $^{\circ}\text{C}$ )
7.1	32.0	1.7
8.3	31.8	1.5
12.1	31.5	1.2
15.1	31.4	1.1
18.0	31.3	1.0
21.0	31.1	0.8
35.2	30.7	0.4
43.8	30.5	0.2
70.4	30.4	0.1
83.7	30.3*	—

Example:  $a = -0.046 \pm 0.003 \text{ s}^{-1}$ ,  $\rho = 1.20 \pm 0.06 \text{ kg m}^{-3}$ ,  $c_p = 1.004 \pm 0.002 \text{ kJ kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$ ,  $M/A = 0.20 \pm 0.03 \text{ kg m}^{-2}$ ,  $h = 3.7 \pm \text{kJ kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$ .

\*Final temperature.



Watson (1934). For the example in Table II,  $a$  was  $-0.046 \text{ s}^{-1}$  with a standard error of  $\pm 0.003 \text{ s}^{-1}$  and a coefficient of determination of 0.977. The value of  $\phi$  was  $-1.63 \text{ m}^{-1}$  with an uncertainty of  $\pm 0.2 \text{ m}^{-1}$ . The largest source of error in the determination of  $\phi$  was  $M/A$ . From eq. 5.

$$r_h = \frac{-1.63}{-0.046} = 35 \text{ s m}^{-1}$$

with an uncertainty of  $\pm 6 \text{ s m}^{-1}$ .

The results of all resistance measurements obtained following the schedule of Table I are given in Table III. Although some significant differences were found among resistances, the magnitudes of the differences were small. Under conditions of high humidity in particular, resistances to sensible heat flux density were virtually indistinguishable from resistances to latent heat flux density.

Comparisons of estimated and measured latent heat flux densities are shown in Table IV. The average error ranged from 5–18%. Not shown are estimates of latent heat flux density during periods of advective heating. During these periods, latent heat flux density exceeded net radiant flux density, thus the direction of sensible heat flux density was from the warm air to the cooler canopy. Linacre's method cannot be applied during conditions of advective heating.

TABLE III

Resistances to sensible heat flux ( $r_h$ ) compared with external resistances ( $r_a + r_c$ ) to evapotranspiration obtained by three methods: (1) the differences between total and surface resistances to evapotranspiration (eq. 8); (2) evapotranspiration from a wetted canopy (eq. 9); and (3) enthalpy loss from a wetted canopy (eq. 12), for 11 series of experiments (Table I)

Series number	$r_h$	$r_a + r_c$		
		eq. 8	eq. 9	eq. 12
1	44* b	75* a	76* a	79* a
2	47 b	64 a	67 a	71 a
3	50 a	59 a	55 a	51 a
4	59 b	35 c	87 a	62 b
5	44 c	60 b	74 a	69 a
6	53 a	48 a	55 a	51 a
7	56 c	72 b	93 a	94 a
8	53 c	58 bc	69 a	62 ab
9	51 ab	42 c	53 a	46 bc
10	50 c	92 b	106 a	102 a
11	52 c	61 b	74 a	65 b

\* Means followed by the same letter within a row are not significantly different ( $P = 0.05$ ).

TABLE IV

Comparisons of estimated and actual latent heat fluxes from a turfgrass canopy in an environmental simulation chamber

Set	Number of observations	Latent heat flux ( $W m^{-2}$ )		Average error (%)
		Estimated	Actual	
1	7	313	350	11
2	12	306	332	8
3	24	287	275	8
4	12	293	316	11
5	18	306	321	8
6	24	292	290	10
7	6	299	323	8
8	16	305	317	7
9	24	294	275	10
10	24	295	289	5
11	24	280	238	18

#### DISCUSSION

The values for resistance to sensible heat flux density obtained with the original Linacre (1964) method were close to the values for resistances obtained by the three other methods in spite of the simplifying assumptions and approximations. When applied to a canopy, an additional complication is that the resistance to sensible heat flux density equals the sum of aerodynamic and canopy mass exchange resistances to latent heat flux density only if the sources and sinks of the two forms of heat are the same (Tanner, 1963; Philip, 1966). Also, the canopy temperature as measured with an infrared thermometer is not an average temperature, nor an accurate measure of the average vapor pressure of the air inside the leaves. Further, the mass of leaves per unit area of land surface, being a critical variable in eq. 1, must be accurately measured. In a low density turf, it may be necessary to include the mass of the stems in determining  $M/A$ , which we did not. It is nevertheless concluded that, in practice, useful values for resistance to sensible heat transfer from a turf canopy can be determined by Linacre's method.

There are two distinct applications of a measurement of the resistance to sensible heat flux density. Both can be used to estimate the evapotranspiration rate of turf. The first application can be used on a turf in any condition, and was demonstrated by the procedure used to obtain the estimates of latent heat flux density shown in Table IV. This method requires the use of an infrared thermometer and a net radiometer. Since  $E$  is obtained as a residual using eq. 10, the values reflect the errors in both  $RN$  and  $H$ . In our trials, good agreement between estimated and actual latent heat flux density was obtained in all but one set of conditions.

The second application of Linacre's method is valid only for a sufficiently watered turf. The surface resistance of well-watered St. Augustinegrass turf is negligible (Johns, 1980). Therefore, the actual evapotranspiration rate equals its potential value (see van Bavel, 1966) as given by

$$E_p = \frac{(\Delta/\gamma)(RN/\lambda) - (\chi'_a/r_a)}{(\Delta/\gamma) + 1} \quad (16)$$

where  $E_p$  = potential evapotranspiration rate ( $\text{kg m}^{-2} \text{s}^{-1}$ ),  $\Delta$  = slope of the saturation vapor density curve ( $\text{kg m}^{-3} \text{ }^\circ\text{C}^{-1}$ ),  $\gamma$  = the volumetric heat capacity of air divided by the latent heat of vaporization ( $\text{kg m}^{-3} \text{ }^\circ\text{C}^{-1}$ ),  $RN$  = flux density of net radiation ( $\text{W m}^{-2}$ ),  $\lambda$  = latent heat of vaporization ( $\text{J kg}^{-1}$ ),  $\chi'_a$  = vapor density deficit of the air ( $\text{kg m}^{-3}$ ), and  $r_a$  = aerodynamic resistance ( $\text{s m}^{-1}$ ). Values for  $r_h$  can be substituted for  $r_a$  in eq. 16, thereby eliminating the wind profile measurements required for determining  $r_a$ . In addition to the measurements required for the first application of Linacre's method, however, air humidity must be measured.

Equation 16 is more of an approximation than eq. 10. Since an infrared thermometer is required in either case, and since the second application is restricted, the first method appears preferable. A detailed field comparison with an independent standard is needed before a final preference can be established.

The proposed technique would be particularly useful for evaluating relative evapotranspiration among various treatments or cultivars involving a number of small plots. Since a single measurement requires no more than five minutes, a scan of several plots of turf could be made during a period in which  $RN$  would not vary much. Comparisons of  $E$  for the different plots could then be made.

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Chapter | **Spring root decline (SRD) :  
discovery, description  
and causes <sup>(1)</sup>**

73 | S.I. SIFERS, J.B. BEARD and J.M. DI PAOLA

**ABSTRACT**

Seasonal rooting investigations utilizing a rhizotron containing a subterranean chamber with 24 glass-faced root observation boxes positioned on each side resulted in the discovery of the spring root decline (SRD) phenomenon. Subsequently, SRD was documented to occur on eight major C-4 warm season turfgrass species utilized for turfgrass purposes.

SRD occurred in 4 of the 8 years of observation at College Station, Texas, when soil temperatures at 10 cm depth rose to 17°C. In those years when SRD was not observed, shoot growth during the initial one to two spring months was extremely slow due to cool soil temperatures. Subsequently, the SRD phenomenon was duplicated utilizing cold stress simulation chambers for the respective chilling and spring greenup phases. These experiments were conducted in replicated, portable, glass-faced root observation boxes placed in growth chambers at 24°C and 32°C. Spring root decline only occurred at the higher temperature, indicating that the rate of temperature rise subsequent to spring greenup is an important factor in determining whether SRD actually occurs.

Additional key words : Rhizotron, Warm season turfgrass, Shoot growth

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## INTRODUCTION

Rooting studies had been conducted on C-3 perennial cool season turfgrasses by means of periodic evaluation methods (Sprague, 1933; Stuckey, 1941; Weaver and Zink, 1946; Beard, 1966; and Boeker, 1974). Rooting studies using destructive techniques also had been conducted on C-4 perennial warm season turfgrass species (Burton, 1942; Burton, et al, 1954). The discontinuity and difficulty of observations with these techniques has limited their usefulness. Traditionally, researchers have relied on responses of the grass shoot as the basis for the development of turfgrass cultural practices. Consequently, responses such as the seasonal behavior of root systems have not been adequately explored. Continuous, nondestructive root investigations were made possible in 1976 with the establishment of the first turfgrass rhizotron at Texas A&M University in College Station, Texas (DiPaola and Beard, 1976). This facility allowed nondestructive, daily evaluations of root systems year around. Thus, the seasonal rooting characteristics of the major C-4 warm season perennial turfgrasses and selected cool season turfgrasses have been studied in the Texas A&M Turfgrass Rhizotron since 1976.

## MATERIALS AND METHODS

The Texas A&M Turfgrass Rhizotron consists of a 48 compartment subterranean observation chamber with 2 rows of 24 glass-faced root observation boxes (Figure 1) separated by a work space. Each of the 25 cm wide by 75 cm deep boxes had a slanted glass face, 0.64 cm thick, through which root observations were made. The glass face was kept dark and insulated with 2.5 cm thick polyurethane pads during nonobservation periods. Root extension lengths were recorded daily by tracing new root growth on clear acetate sheets which were pressed against the glass plate. Soil temperatures were continuously monitored within four randomly selected boxes at 10 and 30 cm depths (DiPaola et al, 1982). Soil temperatures within the boxes were found to be the same as those in an adjacent undisturbed turf area.

### Discovery

Initially two warm season perennial turfgrasses were selected for detailed daily study over an entire year. Mature, soil-less Tifgreen bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Davy] and Floratam St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] turfs were transplanted onto the soil surface of the root observation boxes in August of 1976. The root zone utilized was a washed sand with 90% of the particles between 0.2 and 0.5 mm. Phosphorus was applied annually at 148 kg actual P ha<sup>-1</sup> as superphosphate; nitrogen was applied weekly as KNO<sub>3</sub> and (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> at a rate of 49 kg actual N ha<sup>-1</sup> per growing month; and potassium as KNO<sub>3</sub> at a rate of 49 kg actual K ha<sup>-1</sup> per growing month. Mowing was accomplished weekly at 2.5 cm for the bermudagrass and at 5 cm for the St. Augustinegrass, with clippings removed. The turfs were irrigated as necessary to prevent visual wilt. No pest injury was visually evident, and no pesticides were applied. Treatments were replicated four times. Observations included: the continuous monitoring of soil temperatures at 10 and 30 cm depths by means of a 2-point Foxboro temperature recorder, daily extension of each root visible on the glass face, daily visual turfgrass quality ratings, daily observations of new root initiation on the glass face, and daily root color ratings after the spring root decline was initially observed.

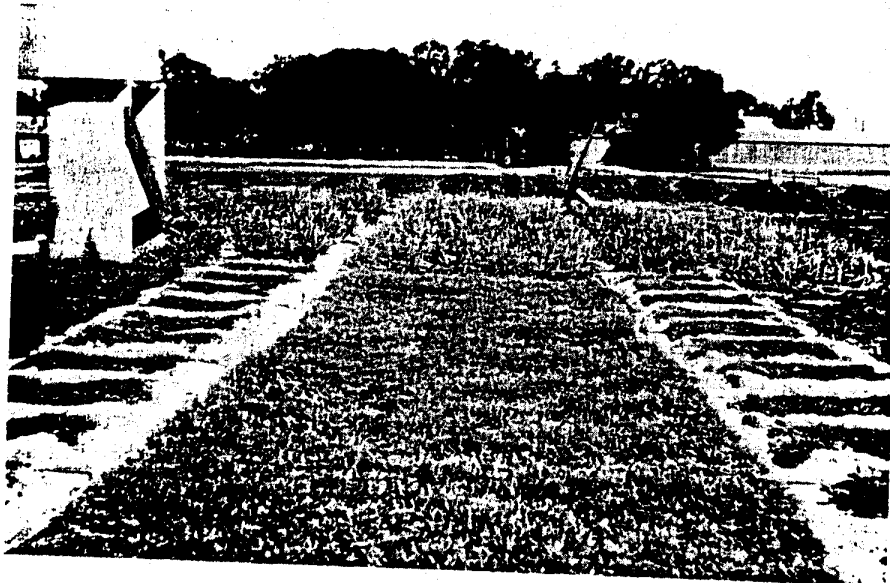


Figure 1. Top and end views of the Texas A&M Turfgrass Rhizotron.

Root growth observations in the rhizotron were continued for six consecutive years on both Tifgreen and Floratam (Beard and Kim, 1982).

### Interspecies Study

The study was expanded to a total of ten warm season perennial grasses in July 1981. Three replications of mature, soil-less sods of Common, Tifgreen, and Tifway bermudagrasses [*Cynodon* spp. (L.) Pers.], Floratam and Texas Common St. Augustinegrasses [*Stenotaphrum secundatum* (Walt.) Kuntze], Meyer zoysiagrass [*Zoysia japonica* Steud.], common centipedegrass [*Eremochloa ophiuroides* (Munro.) Hack.], Pensacola bahiagrass [*Paspalum notatum* Flugge.], Adalayd seashore paspalum [*Paspalum vaginatum* Sav.], and Texoka buffalograss [*Buchloe dactyloides* (Nutt.) Engelm.] were utilized. The mowing and nutritional regimes selected were representative of the optimal turf culture for each species (Table 1). The other cultural practices were the same as previously described. No pest injury was visually evident and no pesticides were applied during the course of this experiment.

### Induction Study

The objective of this study was to determine the environmental parameter(s) that induce spring root decline. Mechanistic studies were begun in September of 1982 utilizing controlled environmental stress simulation chambers and portable, glass-faced root observation boxes. The controlled environment growth chambers utilized were modified with high intensity lighting to provide  $300 \text{ W m}^{-2}$  of PAR. These chambers allowed control of day/night temperatures and day length. Mature, soil-less Tifgreen bermudagrass and Floratam St. Augustinegrass sods were transplanted onto the glass-faced root observation boxes (61 cm high by 30 cm square) that had been filled with the washed sand previously described (Figure 2). The mowing, nutrient, and irrigation regimes were the same as those described for the rhizotron study.

After two months of rooting and acclimation in a greenhouse, the replicated glass-faced root observation boxes containing each species were placed in a controlled environment growth chamber at a temperature of  $5^{\circ}\text{C}$  and day length of 14 hours. After low temperature discoloration and dormancy of the shoots were observed, the turfs were transferred into split treatments. Two replications of each species were placed in separate chambers at  $32^{\circ}\text{C}$  and  $24^{\circ}\text{C}$  for a period of 21 days. This experimental procedure was repeated three times during the year, in January, March, and June. No pest injury problems were visually evident during the course of these experiments.

## RESULTS

### Discovery

The daily observations of Tifgreen bermudagrass and Floratam St. Augustinegrass roots for three consecutive years (1976 - 1979) showed that root growth was sustained at much lower temperatures than expected (Beard, et al 1981). Although root extension occurred at a decreased rate when temperatures at a 10 cm soil depth were below  $10^{\circ}\text{C}$ , root growth at these temperatures had not been reported previously for these warm season species. Root growth continued after shoot growth had ceased

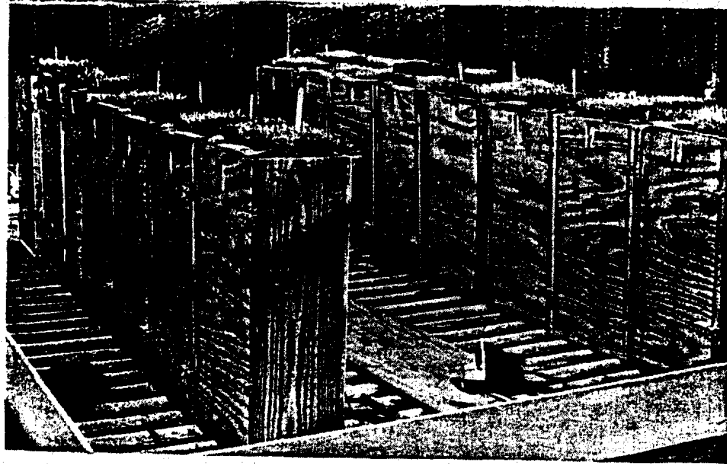


Table 1. Cutting height and nitrogen fertilization rate utilized for each turfgrass species during the spring root decline study conducted under non-limiting soil moisture conditions.

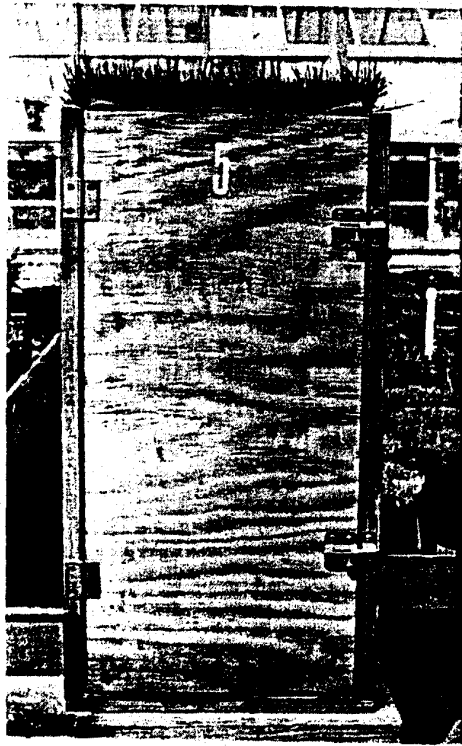
Turfgrass Species	Cutting Height (cm)	Nitrogen Fertilization Rate (g are <sup>-1</sup> growing month <sup>-1</sup> )
Common bermudagrass	2.5	500
Tifgreen bermudagrass	2.5	500
Tifway bermudagrass	2.5	500
Adalayd seashore paspalum	2.5	500
Pensacola bahiagrass	5.0	500
Florata St. Augustinegrass	5.0	250
Texas Common St. Augustinegrass	5.0	250
Texoka buffalograss	5.0	125
Common centipedegrass	5.0	125
Meyer zoysiagrass	5.0	125

Table 2. Eight year summary of observations of spring root decline and the associated environmental conditions at College Station, Texas.

Spring	Spring Root Decline Occurrence	Winter Temperatures Extremes	Spring Greenup	Spring Shoot Growth
1977	Yes	Cold	Early	Rapid
1978	Yes	Cold	Normal	Rapid
1979	Yes	Cold	Normal	Normal
1980	No	Mild	Late	Very slow
1981	No	Mild	Late	Slow
1982	Yes	Very cold	Early	Normal
1983	No	Mild	Late	Slow
1984	No	Very cold	Late	Slow



2a. Portable, glass-faced root observation boxes planted with Tifway bermudagrass. College Station, Texas.



2b. Closeup of portable, glass-faced root observation box with door in normal closed position.



2c. Closeup of portable, glass-faced root observation box with door opened for root observation.

and after low temperature shoot discoloration and conditional winter dormancy had occurred. There were distinctly different root and shoot dormancy phases.

The most significant finding from this study was the occurrence of a severe browning of the entire root system of both grasses just after spring shoot greenup. The root decline occurred rapidly, usually within a 24 to 48 hour period. Initiation of new roots only occurred from meristematic regions of the crown and the nodes of lateral stems. There was a one day delay in new root appearance for Tifgreen bermudagrass, while Floratam St. Augustinegrass had a 14 day delay before new roots were initiated. The time required for effective root replacement was actually longer, as it took approximately 20 days for the new roots to reach a 30 cm depth. Thus, there was a 2 to 3 week period when the functional capabilities of the grass root system were severely restricted (Figure 3).

The occurrence of spring root decline and the associated post-greenup environmental conditions are summarized in Table 2 for the period from 1977 through 1984. A pattern emerged in terms of the specific winter-spring temperature conditions associated with the occurrence of spring root decline.

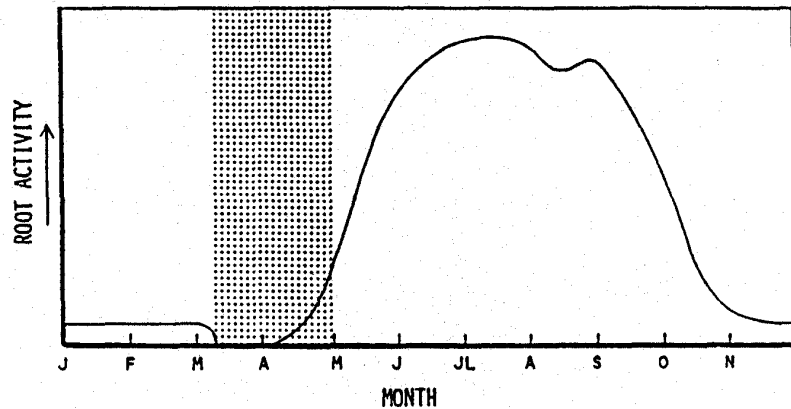


Figure 3. Typical seasonal root growth cycle of bermudagrass and St. Augustinegrass illustrating the spring root decline phenomenon.

The spring root decline phenomenon occurred each spring for the first three years of observation and again in the spring of 1982. In these years, shoot greenup occurred early or at the normal time in the spring following a cold winter. However, spring root decline was not observed in 1980, 1981, 1983, or 1984. During these springs, shoot growth was slow due to very cool temperatures, especially nocturnal temperatures, which maintained an atypically low soil temperature well into mid-May. Thus, rapid spring shoot growth did not occur nor was spring root decline observed.

#### Interspecies Study

Observations during the winter of 1981-1982 revealed that the root growth responses for all ten warm season perennial grasses were the same as those previously observed for Tifgreen and Floratam during the first three years. Specifically, roots continued to grow at a slow rate for 2 to 4 weeks after low temperature discoloration and conditional winter dormancy of the shoots had occurred. Subsequently, the root systems of all ten species remained white and appeared healthy throughout the entire winter period. In early spring when soil temperatures at a 10 cm depth exceeded 17°C and shoot greenup had occurred, spring root decline was observed on seven species. The severe low temperatures during the winter of 1982 resulted in direct low temperature kill of Floratam and Texas Common St. Augustinegrass and Pensacola bahiagrass. Fortunately, the spring root decline response had been observed in three previous years on St. Augustinegrass. Therefore, these observations indicate that spring root decline is common to most of the warm season perennial grasses used for turfgrass purposes.

#### Induction Study

Roots from the sods established in the portable glass-faced root observation boxes maintained a white healthy condition throughout the low temperature shoot discoloration and dormancy phases, even though there was a total loss of chlorophyll in the shoots. Some green color could be

observed in the nodes, especially on lateral stems. After subjecting the plants to the higher temperature treatment, new shoot initiation occurred within four days at both 24 and 32°C. However, the rooting responses were very distinct and contrasting. At 32°C, the existing roots ceased growth and turned brown four days after shoot greenup began. New root initiation occurred six to seven days after shoot greenup and appeared exclusively from meristematic regions in the crowns and nodes of lateral stems. In contrast, at 24°C, only slight root discoloration was observed, and after eight days, root growth extension was reinitiated from the tips of existing roots.

#### DISCUSSION

The characterization of two distinctly different dormancy phases for the root and shoot systems of warm season perennial grasses is important to note. That is, the roots continue to grow for 3 to 4 weeks after shoot low temperature discoloration and conditional dormancy. Furthermore, the roots retain a white, healthy appearance throughout the winter period. These observations suggest that although the shoots are metabolically inactive, the roots remain capable of absorbing water and nutrients longer into the winter period and may perhaps be able to sustain physiological activities throughout the winter whenever temperatures are favorable. This may be an important consideration from the standpoint of strategies in the timing of fall fertilizations.

The first published report of the spring root decline (SRD) phenomenon was not initiated until after two full years of observations had been completed. This allowed us to reaffirm its occurrence in the rhizotron for a second year, and also to confirm that SRD was occurring in surrounding turf areas. The latter positive assessment established that SRD was not just an artifact of the rhizotron environment.

The spring root decline phenomenon has now been observed to occur in eight C-4 warm season perennial grass species utilized for turfgrass purposes. Furthermore, the species studied represented a broad array of genera which suggests that SRD could be a temperature-induced physiological event common to a broad range of C-4 perennial grasses. It should be pointed out that these studies have been conducted under mowed conditions representative of the optimum cutting height for each respective species. However, observations by G. Burton (personal communication) suggest that the SRD phenomenon also occurs on some species such as *Cynodon* when not under frequent close mowing.

The occurrence of direct low temperature kill of three turfgrasses during the interspecies study brought out another dimension in terms of the proper diagnosis of spring root decline. That is, SRD is distinctly different from direct low temperature kill where the roots die at the time when freeze stress occurs with the visual symptoms of discoloration and cell degradation appearing as temperatures rise above 0°C. In contrast, the SRD phenomenon is triggered when the soil temperature at a 10 cm depth rises to 17°C. Thus, when attempting to distinguish between direct low temperature kill and spring root decline in the field, it should be recognized that these events occur at distinctly different temperatures, especially their expression in terms of the resultant visual root degradation and associated discoloration.

The growth chamber simulation studies were critical in demonstrating that the spring root decline phenomenon is unique in its own right. In

other words, it confirms that SRD exists as a separate phenomenon rather than being the result of low temperature kill, low temperature fungi, or some other external stress. This, however, does not mean that one of these latter three stresses cannot, in some situations, accentuate the severity of root death associated with SRD.

Induction studies indicate that a canopy temperature greater than 24°C subsequent to shoot greenup is required to induce spring root decline, whereas temperatures below this range do not induce SRD. One interpretation of this temperature differential in the induction of SRD is that higher temperatures stimulate rapid shoot growth and the associated demand for carbohydrates. As a result of the high carbohydrate demand in the above ground portion of the plant, a deficit in carbohydrates to support root maintenance may occur or there may even be a hormonal control that redirects the available carbohydrates in support of shoot growth. This internal carbohydrate partitioning may create a deficiency in the roots, and therefore, produce spring root decline, with root regrowth not occurring until the shoot demand is satisfied. These latter mechanistic aspects are yet to be elucidated experimentally. However, eight years of field characterizations of spring root decline, the associated spring temperature cycles, and the shoot growth response, or lack thereof, all support this hypothesis.

#### Significance

The occurrence of spring root decline may increase the susceptibility of turfs to injury from low temperature stress, desiccating winds, traffic, diseases, and insect pests. Furthermore, pesticide applications at normal rates, which result in no observable injury when applied during the growing season, have caused phytotoxicity problems if applied during the spring root decline period. Vegetative establishment of these grasses is also much more difficult during this period. Thus, the inability of these warm season perennial grasses to root during spring greenup due to SRD can be a major factor contributing to such spring observed problems as winterkill, desiccation, pesticide toxicity, and establishment failures. From a turfgrass cultural standpoint, spring root decline may be a critical determining factor in the timing and intensity of mowing, fertilization, irrigation, vertical cutting, and herbicide applications.

The discovery of spring root decline may change the total cultural strategy of turfs during the spring period. Lack of a significant root system for 2 to 3 weeks emphasizes the importance of maintaining an adequate soil moisture regime. Previously, the importance of spring irrigation had not been adequately recognized. Due to the critical nature of carbohydrate partitioning during spring root decline, a higher cutting height would be beneficial. In the past, close mowing had been practiced in early spring. In addition, minimal nitrogen fertilization during the 2 to 3 week period of spring root decline must be considered. It is important to not force shoot growth to the extent that it causes the root carbohydrate deficit to exist for an even longer time period, thus delaying root replacement. Finally, there are such spring phenomenon as iron chlorosis, herbicide phytotoxicity, winter injury, and certain serious disease and insect attacks that may be accentuated, or in some cases, induced on turfs that have been weakened by spring root decline. Further studies are continuing at Texas A&M University concerning the basic physiological mechanism controlling spring root decline as well as the effects of various cultural practices on the incidence of spring root decline and subsequent rate of root replacement.

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## SUMMARY IN FRENCH

Déclin printanier des racines : découverte, description et cause.

Des observations saisonnières sur les racines à l'aide d'un rhizotron souterrain comprenant 24 cellules d'observation à parois en verre, ont permis de découvrir un déclin printanier des racines (DPR). Nous avons constaté que ce phénomène existait chez huit des principales espèces de gazon de saison chaude, du type C-4 employées pour la réalisation des gazons.

Le déclin printanier des racines est apparu dans quatre des huit années d'observation à College Station, quand les températures du sol à 10 cm de profondeur atteignaient 17°C. Dans les années où le phénomène n'a pas été observé, la croissance de la plante depuis le début du premier jusqu'au second mois de printemps était extrêmement lente à cause des basses températures du sol. Ensuite, nous avons reproduit le DPR pendant l'été en utilisant des chambres de stress au froid où les phases d'hibernation et de reverdissement printanier de la plante avaient lieu. Ces essais sont faits dans des cellules d'observation en verre, dans des chambres climatisées à 24°C et à 33°C. Le DPR n'apparait qu'à la température plus haute, indiquant l'augmentation de la température, après le reverdissement printanier, est un facteur important dans l'apparition du déclin printanier des racines.