EVALUATION OF WATER-USE IN TURFGRASS

Except where reference is made to the work of others, the work described in this dissertation is my own or was done in collaboration with my advisory committee. This dissertation does not include proprietary or classified information.

____

Leonard Jonah Mwai Githinji

Certificate of Approval:

Robert H. Walker Professor Agronomy and Soils	Jacob H. Dane, Chair Professor Agronomy and Soils
Joey N. Shaw Professor Agronomy and Soils	David Y. Han Associate Professor Agronomy and Soils

George T. Flowers
Interim Dean
Graduate School

EVALUATION OF WATER-USE IN TURFGRASS

Leonard Jonah Mwai Githinji

A Dissertation

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Doctor of Philosophy

Auburn, Alabama
December 17, 2007

EVALUATION OF WATER-USE IN TURFGRASS

Leonard Jonah Mwai Githinji

____
Signature of Author

____
Date of Graduation

VITA

Leonard Jonah Mwai Githinji was born and raised in Central Province, Kenya. He received his Bachelor of Science in Agriculture (Honors) from the University of Nairobi, Kenya. This was followed by several years of professional career as an Agronomist (Anicare Limited), Land and Water Management staff (University of Nairobi) and Agricultural Extension Specialist (Ministry of Agriculture). In May-July 1998, he received post-graduate training in Agricultural Meteorology (Bet Dagan Institute, Tel Aviv, Israel). In September 2001, he enrolled in Graduate School at Ghent University, Belgium for Master of Science in Physical Land Resources (Management of Physical Land Resources Option), where he graduated with Great Distinction. In January 2004, he enrolled in Ph.D. Agronomy and Soils program at Auburn University, Auburn, Alabama. Leonard is married to Eunice and has two children, Janet and Claire.

DISSERTATION ABSTRACT

EVALUATION OF WATER-USE IN TURFGRASS

Leonard Jonah Mwai Githinji

Doctor of Philosophy, December 17, 2007
(M.S., Ghent University, Belgium, 2003)
(B.S., University of Nairobi, Kenya, 1994)

170 Typed Pages

Directed by Jacob H. Dane and Robert H. Walker

This dissertation examined the response of four hybrid bluegrasses [Texas bluegrass (*Poa arachnifera* Torr.) × Kentucky bluegrass (*Poa pratensis* L.)], HB 129 (‘Thermal Blue’), HB 130, HB 328 and HB 329 (‘Dura Blue’) and two tall fescue cultivars (*Festuca arundinacea* Schreb.), ‘Green Keeper’ and ‘Kentucky 31’, to varying irrigation replenishments. Field experiments were conducted at the Turfgrass Research Facility, Auburn University, AL, from June through September 2005 and a similar period in 2006. Three irrigation treatments were applied based on potential evapotranspiration (ET), viz., 100 % ET, 80 % ET and 60 % ET replacements. The experimental design was a 6 by 6 Latin square with six replicates of each treatment combination within an irrigation block. Tensiometers were installed at 7.5-, 15- and 30-cm depths in the middle blocks of each plot, readings were recorded daily and the values were used to calculate the matric head, water content and water-use values. Turf color quality, root length density and root dry mass of hybrid bluegrasses and the tall fescue cultivars were evaluated. The research showed that the hybrid bluegrasses used less water compared to the tall fescue cultivars. The ranking based on root length density and turf color quality was: HB 329 (best) > HB 130 > HB 328 > HB 129 > Kentucky 31 > Green Keeper.

Physical and hydraulic properties of inorganic amendments used in turfgrass root zones were evaluated. The objectives of this study were i) to evaluate and compare the physical and hydraulic properties of un-amended sand (100% sand) and 7 commercially available inorganic amendments used in sand-based root zones, viz., zeolites (Clinolite and Ecolite), calcined diatomaceous earth (Isolite and Axis) and calcined clays (Moltan plus, Profile, and Pro’s Choice), and ii) to evaluate the physical and hydraulic properties of amendment-sand mixtures (15% amendment with 85% sand v/v). The properties analyzed were bulk density, particle density, porosity, particle size distribution, saturated hydraulic conductivity, water retention and available water. All the amendments and amendment-sand mixtures exhibited higher porosity, water retention and available water compared to 100% sand. The values were highest for the calcined diatomaceous earths.

A numerical model was applied to simulate soil water movement with root water uptake for a scenario with amendments (15% amendment plus 85% sand v/v), and without amendment incorporation (100% sand). The simulation results showed reduced surface dryness, higher volumetric water content and storage, and higher initial root water uptake rate for the root zones modified with amendments. The highest simulated water storage was observed for root zones modified with calcined diatomaceous earths, especially Axis amendment.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my research advisors, Dr. Jacob H. Dane and Dr. Robert H. Walker, for their guidance and support during my graduate program at Auburn University. I extend my thanks to the other committee members Dr. Joey N. Shaw and Dr. David Y. Han.

I wish to convey my appreciation to Mr. Jim Harris, the Turfgrass Research Facility superintendent who was invaluable during the irrigation experiment, Dr. Laurent Bahaminyakamwe for assisting during data collection, Mr. Jason Belcher in turf root samples collection, Mr. Bill Bryce who assisted during the root scanning, and Dr. Steve Prior for allowing me to use the root length scanner at the USDA.

Finally, I offer my deepest gratitude to my wife Eunice and our two daughters Janet and Claire for their unconditional love and support.

Style manual used: Handbook and Style Manual of the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America

Computer software used: Microsoft Word v. 2003; Microsoft Excel v. 2003; Hydrus 1-D; SigmaPlot v. 9.0; SigmaScan Pro v. 5.0; SAS System for Windows v. 9.13

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. LITERATURE REVIEW

INTRODUCTION

Plants and plant communities play an essential role in nature. They provide food which is derived mainly from three species of grasses, namely, rice, wheat, and corn (Gould, 1968). Plants contribute to the beauty or the aesthetic value of our living habitats (Ulrich, 1986). They have a very important medicinal value; they produce fibers which provide clothing; plants provide building materials such as wood; some fuel products are made from plants, such as ethanol made from corn and soy diesel made from soybeans (Gould, 1968). Plant communities form the basis for many important recreational activities, including hiking, fishing, hunting, and nature observation. It is not surprising that a nationwide poll published in Life magazine as quoted in Hooper (1970) showed that most Americans wish to be surrounded by green grass and trees. Most city dwellers attach considerable importance to urban parks and forests with views of grass, trees, and open space (Ulrich, 1986). Urban area would appear very unappealing without green turfgrasses in parks, beside boulevards, and surrounding homes, schools, businesses, and the workplace. This may in effect lead to a loss of productivity, more susceptibility to anxieties, and mental disease. Ulrich (1986) reported that an outdoor view contributed to more rapid recovery for hospital patients.

The grass family (*Poaceae*) is the most ubiquitous of the higher plant groups found on this earth (Gould, 1968). With an estimated 600 genera and more than 7,500 species of plants, *Poaceae* ranks third in the number of genera among families of flowering plants. In terms of coverage, it has the highest percentage of the world's vegetation (Beard and Green, 1994). Following disasters such as volcanic eruptions, floods, extended droughts, landslides, fires, explosions, and battle fields, grasses are one of the first vegetation to reestablish. Grasses have been utilized by humans for more than 10 centuries (Beard, 1973). Some historical perspectives include references in the early scriptures such as Genesis (1:11-12) which states "And God said, let the earth bring forth grass,…". Other biblical references have documented the existence of grass and probably some aspects of management (mowing) e.g. Psalm 72:6 which states: "He shall come down like rain upon the grass before mowing, like showers that water the earth", and Matthew 6:30 stating: "Now if God so clothes the grass of the field…..".Other literature dating back to the thirteen century contains references to gardens having turfs composed of grass monostands (Derrick, 2001). Turfgrass culture only started to aspire to its present level of sophistication when people had the security and leisure to start gardens and to take part in sports (Aldous, 1999). People have been willing to devote their time and resources for many centuries to enhance their quality of life and recreational opportunities through the use of turfgrasses (Beard, 1989).

Turfgrasses are defined as plants that form a dense ground cover that persists under regular mowing and traffic (Turgeon, 2002). When regularly mowed, they form a dense growth of leaf blades and roots. Turgeon (2002) differentiates turfgrass, which refers only to the plant community, with turf which encompasses the interconnection of turfgrass communities and the soil adhering to their roots and other below-ground organs. Only about 40 species of grasses are suited for turf use, out of which only 10 species are in common use in the southern region of the United States (Duble, 1996).

Benefits of Turfgrasses

Turfgrasses have played many and important roles throughout the centuries such as protection of our environment long before it became an issue of major importance to modern societies (Beard and Green, 1994). Turfgrass is important worldwide in enhancing and maintaining the function and beauty of contemporary landscapes. Uses of turfgrasses can be distinguished by their functional, ornamental, recreational and green-space purposes (Derrick, 2001; U.S. Department of Interior, 2003). A schematic (Fig. 1.1.) summarizes the benefits of turfgrasses.

Functional turfgrasses

The functional turfgrasses uses include the control of soil erosion by wind and water and elimination of pollution. Turfgrasses capture rainwater in their dense canopies, slowing runoff and enhancing water infiltration. Runoff from agriculture accounts for over 64% of the non-point source pollution affecting about 265,485 km of rivers in the USA (Beard and Green, 1994). Turfgrasses can serve to reduce contamination of water resources by minimizing runoff and sediment entry into lakes and streams. This ability to act as vegetative filter strips to remove sediments, especially when positioned down-slope of crop land, mines or animal feedlots has been documented by many scientist (Dillaha et al., 1988; Young, 1980). They also serve as a filtering system that removes nitrates and harmful chemicals prior to their reaching ground water sources. When used on roadsides turfgrasses absorb many toxic fumes from vehicles and thus provide an air cleansing effect (Turgeon, 2002). It is also essential for eliminating dust and mud problems on areas surrounding homes, schools, factories and businesses (Beard, 1973). Turfgrasses trap particulate matter, such as dust and pollen and are often used around airport runways to keep dust and particulate matter to a minimum, thus protecting jet engines from undue wear (Duble, 1996). Turfgrass canopies absorb light and reduce visual glare, making them less stressful on our eyes than pavement or other highly reflective materials. Turfgrasses significantly attenuate heat on urban sites which would otherwise be considerably hotter than they are during summer months. Turfgrasses are helpful in improving soil quality by their dense fibrous root system and dense canopy which contribute to soil organic matter. Large proportions of diverse soil micro-flora and micro-fauna are supported by the soil-turfgrass ecosystem (Beard and Green, 1994). Micro-flora constitutes the largest proportion of the decomposer biomass of most soils. The added organic matter improves soil structure, infiltration rate, moisture holding capacity, and nutrient retention. Over time the organic matter content of soils covered by turfgrasses increases due to the extensive production of root and shoot materials, and their subsequent recycling to the soil. A high proportion of the world's most fertile soil has been developed under vegetative cover of grass (Gould, 1968).

Ornamental Turfgrasses

The objective of using ornamental turfgrasses is to provide lawns with the highest visual quality (U.S. Department of Interior, 2003). Ornamental turfgrasses form attractive landscapes surrounding homes, parks, memorials and other significant sites and features. It is desirable for ornamental turfgrass to have color and textural uniformity, without noticeable weeds and disease patches. U.S. National Arboretum (2003) recommends that ornamental lawns should be exposed to minimal foot traffic and require the highest level of maintenance. Since these lawns require intensive maintenance to achieve high visual quality, managers should restrict the ornamental turfgrass to the minimum area. With increase in urbanization ornamental turfgrasses have gained popularity considering the aesthetic importance and their benefit to the mental health (Beard, 1973). The occurrence of green manicured lawns make the home landscapes an enjoyable place to live and work (Duble, 1996).

Recreational Turfgrasses

Turfgrasses are very important in recreational areas which provide the setting for both passive and active activities such as athletics. Recreational turfgrasses include small urban parks and some playing fields for organized sports, as well as turfgrass surrounding offices, parking lots, and other support facilities (U.S. Department of Interior, 2003). Sports and activities including baseball, cricket, field hockey, football, golf, hiking, lawn tennis, lacrosse, polo, racing, rugby, shooting and soccer all use turfgrass at their respective facilities (Beard, 1973). Although such areas may have ornamental significance, the visual quality and level of maintenance is less demanding than ornamental turfgrass, except at the very high levels such as NFL or FIFA (U.S. Department of Interior, 2003). Foot traffic is common and some weed infestation is tolerable while the uniformity in color and texture is not as critical as in ornamental areas (U.S. Department of Interior, 2003). Turfgrasses enhance the landscape by contributing to aesthetic and practical aspects. The end result of this contribution is that turfgrasses add significant economic value to properties. Turfgrasses contribute to our psychological and physical well-being. The contemporary rapid lifestyle, with the increase of urbanization has made the aesthetic values of green landscapes important to the psychological health of the modern man (Derrick, 2001).

Green-space Turfgrass

Green-space turfgrass include large areas that receive minimal maintenance other than mowing. The objective for green-space turfgrass is achieved simply by the presence of turf and not by its quality. Green-spaces would include large picnic and informal recreation areas, parkway medians, and roadsides (U.S. Department of Interior, 2003).

Economic Benefits of Turfgrasses

Turfgrass maintenance expenditure in the United States was estimated to be $4.3 billion in 1965 with more than 20 million acres of major turfgrass facilities (Aldous, 1999). This economic impact had increased tremendously to over $45 billion by 1993 (Beard and Green, 1994). Duble (1996) reported that turfgrass is maintained in more than 35 million areas, while the maintenance cost was been projected to increase to over $90 billion in the next decade. The turfgrass industry consists of many diverse groups including millions of homeowners, athletic field managers, lawn care operators, golf course superintendents, architects, developers, landscape designers and contractors, seed and sod producers, parks and grounds superintendents, roadside and vegetation managers and cemetery managers. Turfgrass beautifies tens of millions of home lawns, provides safe playing surfaces on over 700,000 athletic fields, outdoor recreation for nearly 26 million golfers on over 17,000 golf courses and economic opportunities for tens of thousands of seed and sod producers, lawn care operators and landscapers (National Turfgrass Federation, 2007).

Warm- and Cool -Season Turfgrasses

Turfgrasses can be divided into two groups: warm-season and cool-season turfgrasses. Cool-season turfgrasses are usually native to temperate areas and remain green all winter. Warm-season turfgrasses do well in hot weather and are usually native to tropical or sub-tropical environments. A comparison of the shoot growth patterns of cool- and warm-season grasses is shown (Figure 1.2).

Warm-season Turfgrasses

Warm-season turfgrasses are best adapted to temperatures between 27 and 35 ºC (Beard, 1973) and they go dormant in the winter and turn brown. They emerge from dormancy slowly and do not reach maximum growth rate until midsummer. Their growth rate slows in the fall, and they go into dormancy in regions where soil temperatures are below 10 ºC (Beard, 1973). Warm-season species lose their chlorophyll as they go dormant, and remain brown until spring (Christians, 2004). Most of the grasses used for turf in Alabama are warm-season grasses.

Cool-season Turfgrasses

Cool-season grasses are adapted to cooler times of the year and thrive in temperatures from 18 to 24 ºC (Christians, 2004). They optimally grow at soil temperature between 16 and 21 °C. The seeds of most cool-season grasses will germinate rapidly at air temperatures between 16 and 29 ºC (Duble, 1996). The emergence from dormancy is followed by rapid growth in spring and fall, with growth slowing in summer. Alternating temperature has been documented to be beneficial to the germination of grass seeds and may be a requirement in some species such as creeping bentgrass (*Agrostis palustris*), ryegrass (*Lolium* Spp.) and tall fescue (*Festuca arundinacea*), according to Duble (1996). More than 20 cool-season species are used for turf throughout the world (Duble, 1996).

Turfgrass Species Adaptation

The cool-season grasses are best adapted to the cooler regions of the northern latitudes and the warm-season grasses are best adapted to the warmer regions of the southern latitudes. Generally in the United States there are four separate climatic zones of grass adaptation (Figure 1.3). They include the cool-humid zone to the Northeast, Midwest, and much of the Pacific Northwest; the warm-humid zone, which includes the Southeast and extends into eastern Texas; the warm-arid zone, which extends from western Texas into southern California; and the cool-arid zone, which includes much of the dryer areas in the Midwest and West. There is also a transition zone, extending through the central part of the country that includes parts of each of the other four zones (Christians, 2004).

As temperatures drop and day lengths shorten in the southern U.S., the growth of warm-season turfgrasses slows to the point of total dormancy (if temperatures drop low enough). To provide a green, actively growing turfgrass cover during the winter season overseeding with cool-season turfgrasses is necessary (Christians, 2004).

There are currently five cool-season turfgrasses that are routinely used for establishing and maintaining athletic fields. Kentucky bluegrass (*Poa pratensis* L.), perennial ryegrass (*Lolium perenne* L.), tall fescue (*Festuca arundinacea* L.) and to a lesser degree bentgrass (*Agrostis* spp) and the fine fescue (*Festuca* spp.), are the most predominant species (Duble, 1996).

In Alabama, most of the turfgrasses grown are warm-season grasses. However some cool-season species of fescue (especially tall fescue) are used for permanent lawns. Creeping Bentgrass (*Agrostis palustris*), is used on golf courses for putting greens in the northern half of the state. Ryegrass (*Lolium* Spp.) is used to overseed warm season grasses in the winter. This provides a green color when the warm-season grass is dormant (Derrick, 2001).

Tall Fescue (*Festuca arundinacae* Schreb.)

Tall fescue (*Festuca arundinacea* Schreb.) is a popular turfgrass grown in the northern, transitional, and upper to mid-southern climates of the U.S. It is particularly popular in the transition zone between the adaptative areas of cool-season and warm-season grasses (Sleper and West, 1996). Much of the popularity of tall fescue can be attributed to its adaptation to a wide range of soil, climatic, and management conditions (Asay et al., 2001). It is reported to have superior drought avoidance (Ervin and Koski, 1998; Huang and Gao, 2000; Qian and Fry, 1997; Sheffer et al., 1987), and to maintain growth and green color for longer periods between rainfall and irrigation events than other cool-season species (Carrow 1996a; Carrow and Duncan, 2003). Some tall fescue varieties have been reported to have better heat tolerance than many commonly used cool-season turfgrasses (Carrow 1996a; Carrow and Duncan, 2003). Some studies on drought resistance and avoidance characteristics including lower leaf firing i.e. the total percentage of chlorotic leaf area (Qian et al., 2004), greater rooting depth and higher root length density, were reported to be greater for ‘Rebel II’ and ‘Arid’ when compared with bluegrasses (Carrow, 1996a, b). Under low maintenance, Qian and Engelke (1999) reported that minimum irrigation quantity to prevent drought stress and maintain acceptable quality for tall fescue was 50 to 70% of evaporation from class-A pan. Meyer and Gibeault (1987) reported a similar amount of irrigation replenishment (60% of wind-modified pan evaporation) as sufficient to maintain turf quality. Under intensive management conditions Carrow (1995) reported that irrigation at 80% of pan-evaporation was required to maintain turf quality. Heat stress in combination with drought stress has been found to adversely impact photosynthesis, water relations, and root growth of tall fescue more than either of the stresses alone (Jiang and Huang, 2001a, b). While tall fescue has good drought resistance, it is not as fine textured as Kentucky bluegrass.

Forage-type tall fescue forms a coarse textured, low density, bunch-type turf. It does have rudimentary rhizomes, but is considered a weak sod-forming species. Its establishment rate is good, ranking better than Kentucky bluegrass, but slightly slower than perennial ryegrass (Fry and Huang, 2004). Recent developments have led to the introduction of darker green, finer textured tall fescue cultivars that are preferred for turfgrass use. These cultivars are generally referred to as turf-type as opposed to the older forage-type.

Tall fescue is considered a long-lived perennial when grown in the transitional region. In colder portions of the cool-humid and cool-arid regions, stands can be thinned due to direct low temperature injury, particularly in the seedling stage of development. As a turf in these areas, it tends to act like a short-lived perennial. Because of this susceptibility to low temperature kill, the stand can be thinned, leaving scattered coarse textured plants. Tall fescue is very heat and drought tolerant when compared to the other cool-season turfgrasses. It is also one of the most wear tolerant species. Its shade tolerance is intermediate. Tall fescue has a wide range of adaptation in terms of soil fertility, texture, and drainage. It prefers a pH of 5.5 to 6.5, but will tolerate a range of 4.7 to 8.5. It tolerates alkaline and saline soil conditions better than most cool-season turfgrasses. It also will tolerate periods of submersion and can be used in drainage areas.

Kentucky Bluegrass (*Poa pratensis* L.)

Kentucky bluegrass (*Poa pratensis* L.; KBG) is the most widely used cool-season grass in the United States (Ebdon and Petrovic, 1998) and is extensively used for lawns, athletic fields, and golf courses (Turgeon, 2002). KBG forms attractive turf when supplied with adequate water (Meyer and Funk, 1989). However, it has moderate to low drought tolerance (Beard, 1989), although there are cultivars within the species that have better drought tolerance (Murphy et al., 1995). KBG requires frequent irrigation to withstand hot, arid summers and usually goes dormant and loses color during periods of high temperature and drought. The lack of drought resistance restricts its use under water deficit conditions (Abraham et al., 2004). Meyer and Gibeault (1987) found that the quality of Kentucky bluegrass decreased significantly when irrigated at 60% of wind-modified pan evaporation. While tall fescue has good drought resistance, it is not as fine textured as Kentucky bluegrass. Furthermore, some turfgrass managers and home owners prefer the finer texture and recuperative capacity (i.e. the ability of turfgrasses to recover from damage, an important consideration when determining grass selection for high use areas such as sports fields) that Kentucky bluegrass offers (Bremer et al., 2006).

Kentucky bluegrass is recognized for its ability to create a high-quality turf (Fry and Huang, 2004). It forms a dense, medium-textured high quality turf when grown in open sunlight. Cultivars of Kentucky bluegrass are quite variable in texture, color, shoot density, growth habit, disease resistance, adaptation, and cultural requirements. It is this variability that most likely has led to the widespread acceptance and use of Kentucky bluegrass as a turfgrass species (Fry and Huang, 2004).

Kentucky bluegrass is adapted to a wide climatic region but periods of drought and high temperature substantially reduce shoot density and growth. Kentucky bluegrass is most suited to fertile, well-drained, medium-textured soils with a pH between 6.0 and 7.0. It prefers full sunlight, but can stand partial shade. Low temperature hardiness, fall color retention, and spring green-up rate are all good. Its wear tolerance is medium to good with good recuperative potential. Although Kentucky bluegrass is the most popular grass nationwide because of its great appearance, it does not have the heat resistance to stand up to Alabama summers. Therefore the lack of drought resistance restricts its use under water deficit conditions.

Texas Bluegrass (*Poa arachnifera* Torr.)

Texas bluegrass (*Poa arachnifera* Torr.; TBG) is tufted, cool-season perennial and a vigorous sod-forming native in the Southeastern and Southern Plains states. It is a rhizomatous, dioecious grass native to the southern U.S. (Gould, 1975), and used mainly as a forage grass. It persists under extended periods of high temperature (Gould, 1975) and summer drought (Abraham et al., 2004) without going dormant and is adapted to a range of soil conditions. TBG can maintain good color throughout the year and does not produce a lot of clippings. In warm season climates such as in the South, TBG may remain green all year long. Furthermore, TBG hybrids may use significantly less water than other cool-season species while maintaining their green color. Although Texas bluegrass is a more drought- and heat-tolerant relative to Kentucky bluegrass, it is characterized by low turf quality and poor seed production (Abraham et al., 2004). Texas Bluegrass is a tufted, cool season perennial. Dense clusters of stems and leaves rise from long, slender rhizomes. A broad, dense seed head, with tufts of silky-white hairs, tops the 30-45 cm long culms. Leaves are usually much shorter. Plants grow up to 60 cm on strong soil, with numerous leaves 15 to 30 cm long and 6 cm wide. This is a valuable species where native, but seeding is difficult because the species is dioecious, with male and female plants (Magness et al. 1971). Texas bluegrass is more drought- and heat-tolerant compared to Kentucky bluegrass.

Hybrid Bluegrasses

Hybrid bluegrasses are genetic crosses between Kentucky bluegrass and Texas bluegrass. They have the appearance of Kentucky bluegrass but maintain their green appearance during all but extreme conditions (Bremer et al., 2004). One hybrid of Texas bluegrass is "Reveille" (Read et al., 1999) which is an F1 hybrid between Texas bluegrass, *Poa arachnifera*, and Kentucky bluegrass, *Poa pratensis*. It has shade tolerance similar to tall fescue, and is a multi-use cool-season grass used for semi-arid regions of the U.S. According to Read et al. (1999), Reveille adapts well to golf courses, home lawns, commercial and industrial parks and makes an ideal home lawn. It needs less water, an important factor in cities where water restrictions are imposed. Low water use lawns become more important when drought occurs. The special properties of Reveille include its medium-texture, appealing green color and its resistance to powdery mildew and rust, fall armyworm and white grub (Read et al., 1999).

Turfgrass Water-use and Management

Water-stress (often used synonymously with drought-stress) affects practically every aspect of plant growth and metabolism. According to Beard (1973), drought-stress remains the most important environmental factor limiting growth of turfgrass. This is especially so in areas where water availability for landscape irrigation is increasingly limited. However, many recreational turfgrasses require appreciable amounts of water to maintain high quality and growth. One strategy to reduce irrigation requirement and water-stress is to use drought-resistant species and cultivars (Carrow, 1996 a, b). Drought-resistance is defined as the capability of an organism to survive extended dry periods with little or no injury. Variations in drought-resistance have been found among turfgrass species and cultivars (White et al., 1993). Huang et al. (1997), while investigating the root morphological and physiological characteristics in response to surface drying in seven warm-season turfgrasses found superior drought-resistance to surface soil drying in some *Paspalum* cultivars and centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.), which they attributed to the enhanced root growth and rapid root water uptake at deeper soil layers, maintenance of root viability at the surface drying soil, and rapid root regeneration after re-watering. Carrow (1991), using a combination rating for drought resistance and evapotranspiration, ranked some turfgrasses as follows:

Tifway bermudagrass (best) > common bermudagrass > Raleigh St. Augustinegrass > Rebel II tall fescue > common centipedegrass > Kentucky-31 tall fescue > Meyer zoysiagrass. Comparisons of shoot drought responses by six tall fescue cultivars have indicated that Rebel Jr. and Bonsai are relatively drought sensitive, Phoenix and Houndog V are intermediate, and Kentucky-31 and Falcon II are drought resistant (Huang and Gao, 2000). Cultivar variation in shoot responses to drought-stress appeared to be associated with the differences in root responses. Knowledge of variability in drought-resistance and its mechanisms can, therefore, be used as a tool for selection of grasses by growers, for improving management strategies, and for developing drought-resistant turfgrass species and cultivars (Carrow 1996b; Huang et al., 1997).

The mechanism for drought-resistance involves physiological and structural adaptations, which allow plants to survive extended periods of limited water availability (Anon., 2002). By selecting turfgrass species and varieties having superior drought-resistance adaptations, the turfgrass practitioner can delay or postpone drought-stress injury and the associated decline in turfgrass quality and function during extended periods of little or no water. Superior drought-resistance can lengthen the time between rainfall or irrigation events (Anon., 2002). Two major components of drought-resistance include drought-avoidance and drought-tolerance. According to Busey (1996), drought-tolerance is the ability to withstand a drying stress which penetrates plant tissue, while drought avoidance is the ability to avoid the drying stress (i.e., desiccation). During periods of drought both mechanisms are operating to ensure turfgrass survival. Drought avoidance adaptations, however, are most important to turfgrass managers because these allow for turfgrass survival (without dormancy) and provide for sustained growth and function, although at reduced levels, during drought stress periods (Anon, 2002). Avoidance mechanisms are short-term survival adaptations that allow plants to escape tissue injury during drought by postponing tissue dehydration through development of deep and extensive root systems to increase water uptake and modification of shoot morphology to reduce evapotranspiration rates. Cultural practices that promote extensive root development are important for enhancing drought avoidance. This maximization of the rooting depth ensures that turfgrass is able to draw moisture and nutrients from a greater portion of the soil profile (Beard, 1985; Anon., 2002). The other management factors that affect the ability of turfgrass to withstand drought include irrigation, plant nutrition or fertilization, aeration and mowing. Decreasing the mowing height of a turfgrass stand decreases the water use rate of the turfgrass because of the smaller leaf area which decreases transpiration. As nitrogen fertilization rate increases so does water use by the turfgrass because of increased growth stimulated by the fertilizer. Irrigation practices can influence water use rate. Frequent irrigations increase water use rate because of increased loss of water due to evaporation. Aeration increases water infiltration, root growth, deeper rooting and often turfgrass density. These factors can lead to increased water use because of an improved turfgrass stand (Anon., 2002).

As demand for water continues to increase, the allocation of water for irrigation has decreased (Hanks, 1983). Water availability for irrigation purposes, especially for non-food commodities is becoming increasingly scarce. Thus, water conservation strategies are needed for both economic and judicious reasons (Anon., 2002). In places where rainfall is inadequate and water resources are insufficient, the supplemental irrigation required to meet the water requirements for ornamental plantings such as turfgrass is the first casualty to suffer water rationing (Anon., 2002). There is a considerable amount of guesswork by turfgrass managers on the depth of water extraction and the amount of water available for turfgrass growth. Turfgrass managers know their turfgrass on the surface; however below the surface it is important that the turfgrass manager maximizes rooting depth so that turf is able to draw moisture and nutrients from a greater portion of the soil profile (Beard, 1985).

Some strategies have been suggested for minimizing water use, such as implementing water conserving management practices like precision irrigation through which turfgrass is allowed to deplete soil water to the point of incipient water stress within its rootzone before irrigation; incorporating water-use efficient turf grasses into the landscape; maximizing irrigation efficiency by controlling leaching, ponding and surface water runoff, and development of drought-resistant and drought avoidance turfgrasses (Carrow, 1996 a,b; Anon., 2002; Carrow and Duncan, 2003; Stewart et al., 2004). These efficient water use management practices and selection of turfgrasses that persist during drought stress are becoming increasingly important, not only in arid and semi-arid areas, but also in humid areas (Carrow, 1996b; Anon., 2002).

Sport Fields Management

Sport fields are an example of the many uses of recreational turfgrass and they are among the most difficult turf areas to manage. They receive intense traffic and may sustain much serious damage on a regular basis, yet expectations remain high (Christians, 2004). Sports including football, baseball and soccer are some of the major games played on sport fields. While players and coaches demand a safe and uniform playing surface all the time, the public wants an attractive, green turf that is creatively decorated with brightly colored team logos and other decorations (Christians, 2004). Differences in turfgrass species, soil type, precipitation, and use intensities all contribute to the wide range of conditions associated with sport fields (Rogers and Waddington, 1992).

Sport field construction has evolved over the years. During the 1970s and 1980s, synthetic turf including nylon was widely used on college and professional fields. With increased awareness on player safety and comfort, many of these fields have been converted to natural turf (Duble, 1996; Christians, 2004). In the late 1980s and 1990s, many of these fields were converted to natural turf with sand-based root zones (Christians, 2004).

Greens Construction

Golf courses have received more management attention than that of athletic fields over the years. In the early days, the greens were formed by simply shaping the soil on the site to the desired contours. These greens are known as push-up greens and this method of construction is still widely used on low budget courses. A problem with the push up greens was found to occur when play increased in the early years where heavy soils would be compacted to a point where they became unsuitable for plant growth (Christians, 2004). It was realized by the 1950s that the best way to alleviate compaction was to remove the existing soil profile and replace it with sand. This is the basis of the USGA recommendation. For more than 40 years the USGA sand-based root zones have been the most widely used method of green construction throughout the United States and in other parts of the world. Sand provides good drainage and low to moderate turf growth, both conducive to playing the game of golf. When built and maintained properly, USGA greens have provided consistently good results for golf courses over a period of many years. The USGA Green Section first published guidelines on root zone construction in 1960, with the most recent update being completed in 2004. These guidelines primarily describe the physical parameters for constructing a root zone that will create a well-drained playing surface. Research has demonstrated that the range of properties described in the guidelines is large enough to provide a notable range in the behavior of the root zone (that is, requirements for water and nutrient management). Thus, particular combinations of sand and amendment(s) can be selected to produce a specific influence on the vigor of the turf, which, as previously mentioned, is often intended to be low to moderate for good playing conditions.

RESEARCH JUSTIFICATION

In the Southeast, turfgrass represents a $1 billion a year industry (Auburn University Newsletter, 1997) due largely to a booming interest in golf and the growing number of golf courses. A lot of water is used to meet the turf water requirement. It is presently estimated that 9 percent of the total annual water consumption in the United States is used on turf and ornamentals in urban areas. Therefore, as water becomes more costly and/or supplies decrease, it will become more important to conserve water or use it efficiently for turfgrass. The adoption of best management practices related to irrigation hardware, scheduling and plant material selection and maintenance has lagged behind many other more successful water conservation efforts.

GENERAL OBJECTIVES

The general research objectives were:

i) Evaluation of water-use patterns of tall fescue and hybrid bluegrass cultivars;

ii) Evaluation of turf color quality, root length density and root mass of hybrid bluegrass and tall fescue under irrigation scheduling;

iii) Evaluation of physical and hydraulic properties of inorganic amendments used in turfgrass root zones; and

iv) Modeling turfgrass root water uptake for an USGA root zone design modified with inorganic amendments.

REFERENCES

Abraham, E.M., B. Huang, S.A. Bonos, and W.A. Meyer. 2004. Evaluation of drought resistance for Texas bluegrass, Kentucky bluegrass, and their hybrids. Crop Sci. 44:1746–1753.

Aldous, D.E. 1999. International turf management handbook. Dep. of Env. Hort. and Res. Manage., Univ. of Melbourne, VIC, Australia, and CRC Press, Boca Raton, FL.

Anonymous, 2002. Turfgrass culture and management: Turfgrass irrigation and water conservation. Univ. of Massachusetts Ext.

Asay, K.H., K.B. Jensen, and B.L. Waldron. 2001. Responses of tall fescue cultivars to an irrigation gradient. Crop Sci. 41:350–357.

Auburn University Newsletter.2007. (Accessed July 10, 2006) www.auburn.edu/administration/univrel/news/archive/2_97news/2_97turf.html

Beard, J.B. 1973. Turfgrass: Science and Culture. Prentice-Hall, Englewood Cliffs, N.J.

Beard, J.B. 1985. An assessment of water use by turfgrasses. *In* Gibeault V.A., Cockerham S.T. (eds.): Turfgrass water conservation. Univ. of California, Oakland.

Beard, J.B. 1989. Turfgrass water stress: Drought resistance components, physiological mechanisms, and species-genotype diversity. p. 23–28. *In* Takatoh, H. (ed.) Proc. Japanese Soc. Turfgrass Sci., Tokyo.

Beard, J.B., and R.L. Green. 1994. The role of turfgrasses in environmental protection and their benefits to humans. J. Environ. Qual. 23:452–468.

Bremer, D. J., K. Su, S. J. Keeley, and J. D. Fry. 2006. Performance in the transition zone of two hybrid bluegrasses compared with Kentucky bluegrass and tall fescue. Online. Applied Turfgrass Science doi:10.1094/ATS-2006-0808-02-RS.

Busey, P. 1996. Wilt avoidance in St. Augustinegrass germplasm. HortScience 31:1135-1138.

Carrow, R.N. 1991.Turfgrass water-use, drought resistance and rooting patterns in the Southeast. ERC-01-91. Env. Res. Center. Georgia Institute of Tech., Atlanta, GA. and the College of Agric. and Env. Sci., Univ. of Georgia, Athens, GA.

Carrow, R.N. 1995. Drought resistance aspects of turfgrasses in the southeast: ET and crop coefficients. Crop Sci. 35:1685–1690.

Carrow, R.N. 1996 a. Drought avoidance characteristics of diverse tall fescue cultivars. Crop Sci. 36:371–377.

Carrow, R.N. 1996 b. Drought resistance aspects of turfgrasses in the Southeast: Root-shoot responses. Crop Sci. 36:687–694.

Carrow, R.N., and R.R. Duncan. 2003. Improving drought resistance and persistence in turf-type tall fescue. Crop Sci. 43:978-984.

Christians, N., 2004. Fundamentals of turfgrass management. 2nd ed. John Wiley & Sons.

Derrick, C.L. 2001. Deep-tine aerification and topdressing effects on compacted athletic fields. MSc. Thesis, dep. of Agron. and Soils, Auburn University.

Dillaha, T.A., J.H. Sherrard, D. Lee, S. Mostaghimi, and V.O. Shanholtz. 1988. Evaluation of vegetative filter strips as a best management practice for feed lots. J. Water Pollut. Control Fed. 60:1231-1238.

Duble, R.L. 1996. Turfgrasses: Their management and use in the southern zone. 2nd ed. Texas A&M Univ. Press, College Station, TX.

Ebdon, J.S., and A.M. Petrovic. 1998. Morphological and growth characteristics of low- and high-water use Kentucky bluegrass cultivars. Crop Sci. 38:143-152.

Ervin E. H. and A. J. Koski. 1998. Drought avoidance aspects and crop coefficients of Kentucky bluegrass and tall fescue turfs in the semiarid west. Crop Sci. 38:788-795.

Fry, J. and B. Huang. 2004. Applied turfgrass science and physiology. Chapter 4: Temperature stresses. Wiley and Sons, Inc., Hoboken, NJ.

Gould, F.W. 1968. Grass systematics. McGraw-Hill Book Company, NY.

Gould, F.W. 1975. The grasses of Texas. Texas A&M Univ. Press. College Station, TX.

Hanks, R.J. 1983. Yield and water-use relationships. p. 393-410. *In* Taylor, H.M., W.J. Jordan and T.R. Sinclair (eds) Limitations to efficient water-use in crop productions. ASA Madison, WI.

Hooper, B. 1970. The real change has just begun. Life. 68 (1):102-106.

Huang, B. and H. Gao. 2000. Root physiological characteristics associated with drought resistance in tall fescue cultivars. Crop Sci. 40:196-203.

Huang, B., R.R. Duncan and R.N. Carrow. 1997. Drought resistance mechanisms of seven warm-season turfgrass under surface soil drying: I. Shoot response. Crop Sci. 37:1858-1863.

Jiang, Y., and B. Huang. 2001a. Drought and heat stress injury to two cool-season turfgrasses in relation to antioxidant metabolism and lipid peroxidation. Crop Sci. 41:436-442.

Jiang, Y., and B. Huang. 2001 b. Physiological responses to heat stress alone or in combination with drought: A comparison between tall fescue and perennial ryegrass. HortSci. 36:682–686.

Magness, J.R., G.M. Markle, C.C. Compton. 1971. Food and feed crops of the U.S. Interregional Research Project Bul. 828. Agr. Expt. Sta., NJ.

Meyer, W.A. and C.R. Funk. 1989. Progress and benefits to humanity from breeding cool-season grasses for turf. p.31-48. *In* Sleper, D.A., K.H. Asay, and J.F. Pedersen (eds.). Contributions from breeding forage and turf grasses. Crop Sci. Special Pub. 15. Crop Sci. Soc. Amer. Madison, WI.

Meyer, J.L., and V.A. Gibeault. 1987. Turfgrass performance when under irrigated. Appl. Agric. Res. 2:117–119.

Murphy, J.A., R.F. Bara, W.K. Dickson, D.A. Smith, and C.R. Funk. 1995. Performance of Kentucky bluegrass cultivars and selections in New Jersey turf trials. Rutgers Turfgrass Proc. 27:69–116.

National Turfgrass Federation, Advancing Turfgrass science for society. http://www.turfresearch.org (Accessed July 2, 2007).

Qian, Y.L. and J.D. Fry. 1997. Water relations and drought-tolerance of four turfgrasses. J. Am. Soc. HortSci. 122:129-133.

Qian, Y.L., and M.C. Engelke. 1999. Performance of five turfgrasses under linear gradient irrigation. HortSci. 34:893–896.

Qian, Y. L., R. F. Follett, S. Wilhelm, A. J. Koski, and M. A. Shahba. 2004. Carbon isotope discrimination of three Kentucky bluegrass cultivars with contrasting salinity tolerance. Agron J. 96: 571-575.

Read, J.C., J.A. Reinert, P.F. Colbaugh, and W.E. Knoop. 1999. Registration of `Reveille' hybrid bluegrass. Crop Sci. 39:590.

Rogers, J. N. III, and D.V. Waddington. 1992. Impact absorption characteristics on turf and soil surfaces. Agron. J. 84:203-209.

Sheffer, K.M., J.H. Dunn, and D.D. Minner. 1987. Summer drought response and rooting depth of three cool-season turfgrasses. HortScience 22:296–297.

Sleper, D.A., and C.P. West. 1996. Tall fescue. p. 471–502. *In* Moser, L.E., D.R. Buxton, and M.D. Casler (eds.) Cool-season forage grasses. Agron. Monogr. 34. ASA, CSSA, SSSA, Madison, WI. Turgeon, A.J. 2002. Turfgrass management. 6th ed. Prentice Hall, Englewood Cliffs, NJ.

Stewart R.S., R. Kjelgren and P.G. Johnson and M.R. Kuhns. 2004. Soil Water-use Charactersitsics of Precision-irrigated Buffalograss and Kentucky Bluegrass. Online. Applied Turfgrass Science doi: 10.1094/ATS-2004-1118-01-RS.

Turgeon, A. J. 2002. Turfgrass Management. 6^{th} ed. Prentice Hall, Upper Saddle Brook, N.J. 400 p.

Ulrich, R.S. 1986. Human responses to vegetation and landscapes. Landscape urban planning 13:29-44.

U.S. Department of the Interior. National Parks Services. 2003. http://www.nature.nps.gov/biology/ipm/manual/turfweed.cfm (Accessed June 30, 2007).

U.S. National Arboretum. Turfgrass questions and answers. 2006. http://www.usna.usda.gov/Gardens/faqs/turfgrassfaq2.html (Accessed June 30, 2007).

White, R.H., A.H. Bruneau and T.J. Cowett. 1993. Drought resistance of diverse tall fescue cultivars. Int. Turfgrass Soc. Res. 7: 607–613.

Young, R. A., T. Huntrods, and W. Anderson. 1980. Effectiveness of vegetated buffer strips in controlling pollution from feedlot runoff. J. Environ. Qual. 9:483–487.

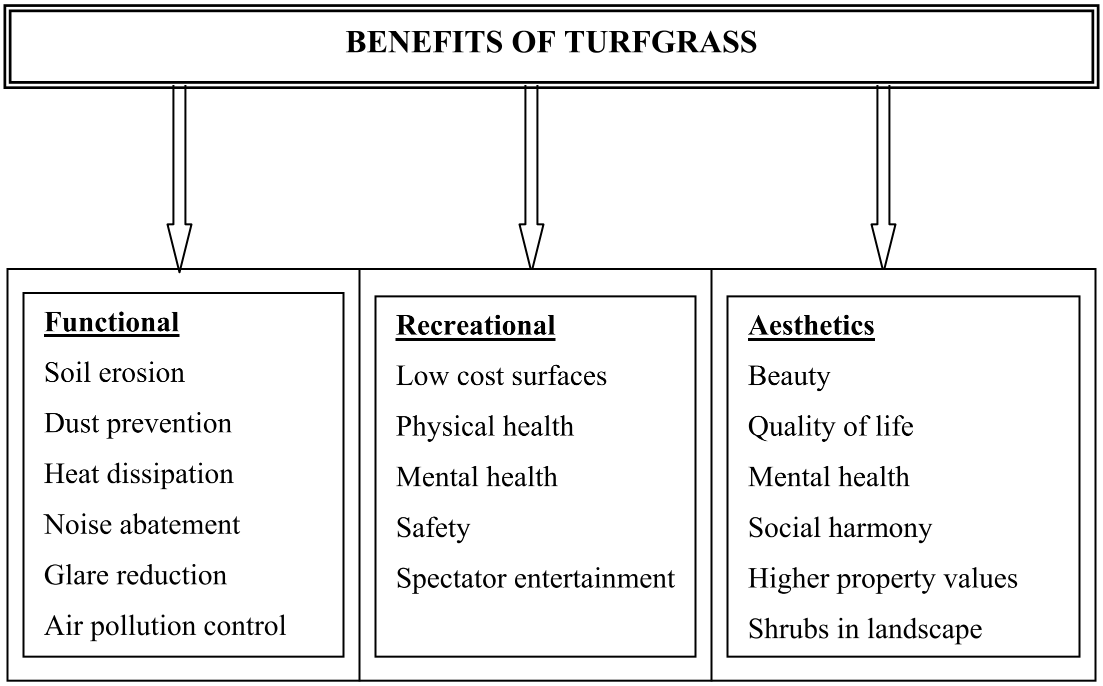


Fig. 1.1. Schematic summary of benefits of turfgrasses (Beard and Green, 1994)

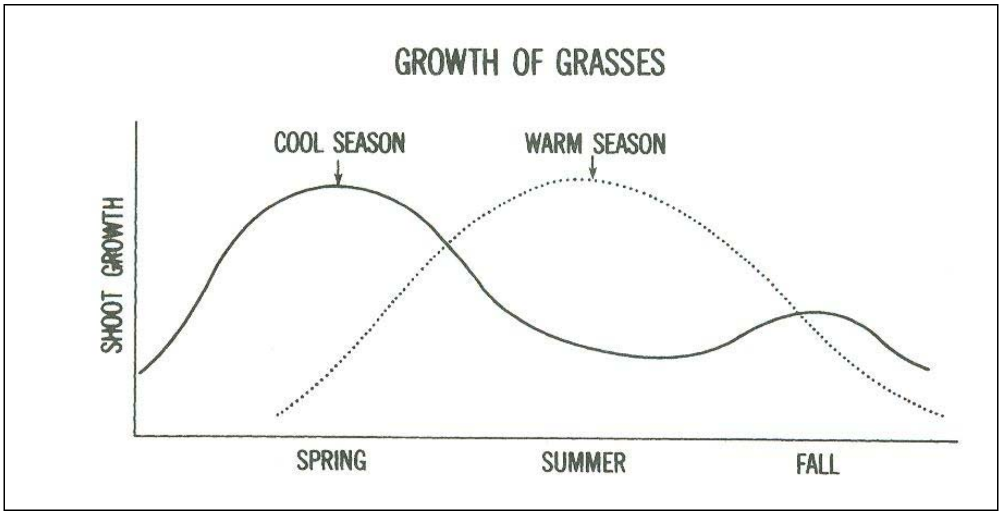


Fig. 1.2. Shoot growth patterns of cool-season and warm-season grasses (Christians, 2004)

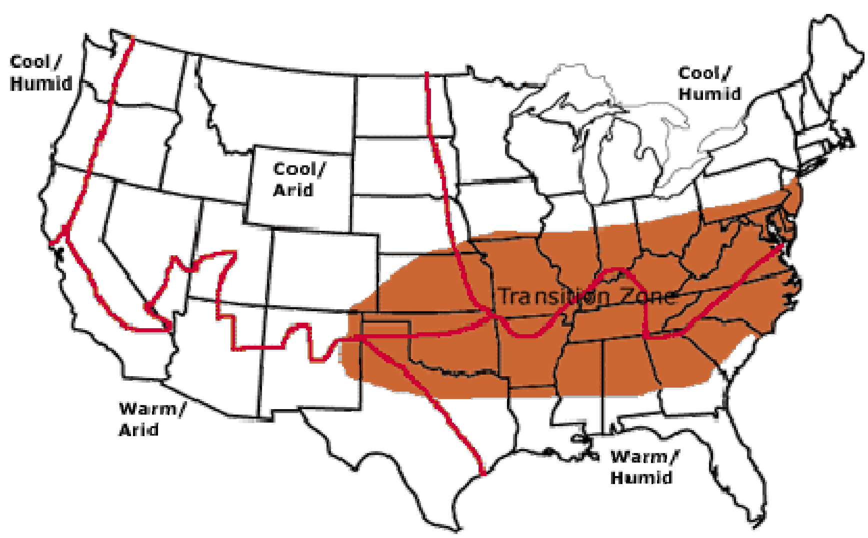


Fig. 1.3. Distribution of turfgrass growing area in the U.S. (Christians, 2004)

II. EVALUATION OF WATER-USE PATTERNS OF TALL FESCUE AND HYBRID BLUEGRASS CULTIVARS

ABSTRACT

Knowledge of water-use patterns is important in the turf industry for selecting turfgrasses that minimize water-use and for developing efficient irrigation management practices. This study was designed to assess the response of tall fescue (*Festuca arundinacea* Schreb.) and hybrid bluegrass cultivars to varying irrigation replenishments. The hybrid bluegrasses are genetic crosses between Kentucky bluegrass (*Poa pratensis* L.) and Texas bluegrass (*Poa arachnifera* Torr.). Field experiments were conducted at the Turfgrass Research Facility, Auburn University, AL, from June through September, 2005 and for a similar period in 2006. Four hybrid bluegrasses, viz., HB 129 ['Thermal Blue'], HB 130 (Experimental line), HB 328 (Experimental line) and HB 329 ['Dura Blue'] and two tall fescue cultivars ('Kentucky 31' and 'Green Keeper') were included in this study. Three irrigation treatments were applied based on potential evapotranspiration (ET), viz., 100% ET, 80% ET and 60% ET replacements. A set of three tensiometers were installed at 7.5, 15 and 30 cm depths in the middle blocks of each of the plots, readings were recorded daily, and the values were used to calculate the matric head, water content and water-use values. Results demonstrated that hybrid bluegrasses used less water compared to tall fescue cultivars. Ranking based on water-use was: HB 130 (least water-use) > HB 129 > HB 328 > HB 329 > Kentucky 31 > Green Keeper.

INTRODUCTION

The demand for fresh water to meet agricultural, municipal, and industrial needs has increased more than 35 fold during the last three centuries (Kirda and Kanber, 1999). As demand for this finite supply of water continues to increase, the allocation of water for irrigation has decreased, especially for non-food commodities (Hanks, 1983). In places where rainfall is inadequate and water resources are insufficient, supplemental irrigation to meet the water requirements for ornamental plantings such as turfgrass is the first casualty to suffer water rationing leading to drought stress, which according to Beard (1973), is the most important environmental factor limiting growth of turfgrass. Thus, water conservation on turfgrass sites should be accorded high priority (Carrow and Duncan, 2000a; Kenna and Horst, 1993; Kirda and Kanber, 1999). Turfgrass scientists and managers desire to develop strategies for maintaining a certain level of quality in turf while considerably reducing irrigation input (Ervin and Koski, 1998).

Much of the previous research on cultivar selection for drought tolerance has laid emphasis on warm-season turfgrasses [common and hybrid bermudagrass (*Cynodon dactylon* L. Pers , *C. dactylon* L. Pers × *C. transvaalensis* Burtt-Davy), buffalograss (*Bouteloua dactyloides* (Nutt.) Columbus), St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze), and zoysiagrass (*Zoysia japonica* Steud. and *Z. matrella* (L.) Merr.] due to their widespread use. Similar research is needed for cool-season turfgrasses, especially hybrid bluegrasses [Texas bluegrass (*P. arachnifera* Torr.) × Kentucky bluegrass (*Poa pratensis* L.)], which are new in the market. Carrow (1991) using a combination rating for drought resistance and evapotranspiration, ranked some warm and cool season turfgrasses as follows: Tifway bermudagrass (best) > common bermudagrass > Raleigh St. Augustine grass > 'Rebel II' tall fescue > common centipedegrass [(*Eremochloa ophiuroides* (Munro) Hack.)] > Kentucky 31. Comparisons of shoot drought responses by six tall fescue cultivars indicated that 'Rebel Jr.' and 'Bonsai' were relatively drought sensitive, 'Phoenix' and 'Houndog V' were intermediate, and Kentucky 31 and 'Falcon II' were drought resistant (Huang and Gao, 2000). Cultivar variation in shoot responses to drought stress was associated with the differences in root responses. Knowledge of variability in drought-resistance and its mechanisms can therefore be used as a tool for selection of grasses by growers, for improving management strategies, and for developing drought resistant turfgrass species and cultivars (Carrow 1996 b; Huang et al., 1997). The mechanism for drought resistance involves physiological and structural adaptations, which allow plants to survive extended periods of limited water availability. By selecting turfgrass species and varieties having superior drought resistance adaptations, the turfgrass practitioner can delay or postpone drought stress injury and the associated decline in turfgrass quality and function during extended periods of little or no water. Superior drought resistance can lengthen the time between rainfall or irrigation events. Two major components of drought resistance are drought avoidance and drought tolerance (Busey, 1996). During periods of drought both mechanisms operate to ensure turfgrass survival. Drought-avoidance adaptations, however, are more important to turfgrass managers because they ensure turfgrass survival (without dormancy) and enhance sustained growth and function. Avoidance mechanisms are short-term survival adaptations that allow plants to escape tissue injury during drought by postponing tissue dehydration through development of deep and extensive root systems to increase water uptake and modification of shoot morphology to reduce evapotranspiration rates. Cultural practices that promote extensive root development are important for enhancing drought avoidance. Maximization of rooting depth ensures that turfgrass is able to draw moisture and nutrients from a greater portion of the soil profile (Beard, 1989). Other management factors that affect the ability of turfgrasses to withstand drought include irrigation, plant nutrition or fertilization, aeration and mowing. Increasing mowing height of a turfgrass stand may increase water use rate as a larger leaf area index leads to increased transpiration. As nitrogen fertilization rate increases so does water use by turfgrass due to increased growth stimulated by the fertilizer. Irrigation practices can influence water-use rate, and frequent irrigations increase water use rate because of increased loss of water due to evapotranspiration. Aeration increases water infiltration, root growth, deeper rooting and often increased turfgrass density and this can lead to increased water use because of an improved turfgrass stand (Carrow and Duncan, 2003).

Water Saving Strategies

Some suggested strategies to minimize water-use include precision irrigation through which turfgrass is allowed to deplete soil water to the point of incipient water stress within its root zone before irrigation (Stewart et al., 2004); incorporating water-use efficient turfgrasses into the landscape (Wade et al., 1992); maximizing irrigation efficiency by controlling leaching, ponding and surface water runoff (Olson, 1985; Wade et al.,1992); development and selection of drought resistant and drought avoidance turfgrasses (Carrow, 1996 a, b; Carrow and Duncan, 2003; Kenna and Horst, 1993); and use of wastewater and seawater for turfgrasses (Carrow and Duncan, 2000 a, b). These water-use management practices, especially selection of turfgrasses that persist during drought stress, and development of grasses that use less water are becoming increasingly important, not only in arid and semi-arid areas, but also in humid areas (Carrow, 1996 b). Water-use varies among turfgrass species (Carrow, 1991) and also among cultivars of the same species (Carrow, 1996a). It also varies with environmental factors including solar radiation, wind speed, temperature and soil moisture (Cary and Wright, 1971). Some researchers have reported a higher water-use associated with higher water availability (Beard, 1973; Biran et al., 1981). Minimization of water supply may enhance water-use efficiency in turfgrass (DaCosta and Huang, 2005). Knowledge of water-use in turfgrasses would improve management strategies and facilitate turfgrass breeding for drought resistance and/or development of low water-use species and cultivars (Huang et al., 1997).

Irrigation Scheduling

Irrigation scheduling is aimed at establishing the timing and the amount of water to apply to a field. The objective is to attain optimal water supply for crop production, while maintaining soil water content close to field capacity (Jones, 2004). Irrigation scheduling maximizes irrigation efficiency by applying precise amounts of water needed to replace soil moisture to a desired level as needed to obtain optimum yield and quality of a desired plant constituent (Dane et al., 2006). Irrigation scheduling saves water, energy and has additional environmental benefits (minimizing the risks of salinization and nutrient leaching). Taylor (1965) suggested that irrigation should be initiated when soil water potential is high enough so that the soil can supply water fast enough to meet the crop evapotranspiration, hence avoiding drought stress that would reduce yield or quality of the crop. Other researchers suggest the practice of irrigating crops below maximum potential water demand, which has been found to increase water savings and water-use efficiency (Feldhake et al., 1984; Kirda, 2002). Between 20 and 40% water savings have been reported when water is replenished at 60 to 80% of crop evapotranspiration (Meyer et al., 1985). Less frequent irrigation scheduling has been suggested to enhance deep rooting and subsequently drought avoidance (Youngner, 1985). Chalmers et al. (1981) reported that a slight plant water deficit could improve the distribution of carbohydrate to the reproductive structures and also control excessive vegetative growth.

All irrigation-scheduling procedures consist of monitoring parameters that determine the need for irrigation. The direct objectives are to determine the amount of irrigation water to supply the crop and the timing of this irrigation. Several irrigation scheduling methods have been suggested, and they can be categorized as soil-, plant- and atmosphere-based approaches. The suggested methods include measuring the soil matric potential by means of tensiometers (Cassel and Klute, 1986; Young and Sisson, 2002; Dane et al., 2006), time domain reflectometry (Topp and Davis, 1985), electrical resistance and heat dissipation soil-water sensors (Campbell and Gee, 1986; Bristow et al., 1993), neutron water meters (Evett and Steiner, 1995; Gardner, 1986), and frequency domain reflectometry (Laboski et al., 2001). Irrigation scheduling can also be determined by monitoring atmospheric conditions followed by potential evapotranspiration (ET) calculation (Doorenbos and Pruitt, 1992). There are several methods proposed for computation of the potential ET, viz., the pan evaporation method, the Blaney-Criddle method, the Penman method and the Penman-Monteith method (Allen et al., 1998). Of these, the Penman-Monteith method appears to be the most promising due to its inclusion of the climatic variables that affect crop evapotranspiration.

The Penman-Monteith equation has the following form:

$$ET = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma\left(1 + 0.34 u_2\right)} \qquad [2.1]$$

where:

ET is the grass reference evapotranspiration (mm d^{-1}), R_n is net radiation (MJ m^{-2} d^{-1}), G is soil heat flux (MJ m^{-2} d^{-1}), γ is the psychrometric constant (kPa °C^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), and Δ is the slope of the saturation vapor pressure-temperature curve (kPa °C^{-1}), T is the average daily air temperature (°C), and u_2 is the mean daily wind speed at 2 m (m s^{-1}). On a daily scale, the nature of the climate system allows for the soil heat flux term, G, to be ignored as soil heat flux on a daily scale is essentially zero although the term cannot be ignored for longer time scales, such as monthly data (Allen et al., 1998).

Tensiometers and Water Retention Curves

Tensiometers are instruments that are used to measure the soil water tension, or the matric head, h_m, which can be related to the soil water content, θ. This θ-h_m relationship is referred to as the water release curve (WRC), moisture characteristic curve (MCC), or water retention curve (WRC), and various models have been used to describe the relationship. The most commonly used models are the van Genuchten (van Genuchten, 1980) and the Brooks and Corey (1964) expressions. The van Genuchten relation is:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha\left|h_m\right|)^n}\right]^m$$

$$m = 1 - 1/n \; ; \; n > 1 \qquad [2.2]$$

where S_e is the effective water saturation, θ is the volumetric water content, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, h_m is the matric head (cm) and α, m, and n are curve fitting parameters. The Brooks-Corey relation is:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{h_d}{h_m}\right]^{\lambda} \quad for\ h_m < h_d$$

$$S_e = 1 \quad for\ h_m > h_d \qquad [2.3]$$

where h_d is the displacement pressure, i.e., the matric head value at which water is being displaced by air, and λ is the pore size distribution index. Unlike the Brooks-Corey relationship, the van Genuchten has a single θ-h_m relationship representing the total range of data points, and this has an advantage of model simplicity. The Brooks–Corey recognizes the displacement pressure, h_d, which is the matric head value below which the biggest pores will start to drain when the matric head decreases during drying of the soil. When the soil is maintained above this matric head value, the soil remains saturated, and this situation is undesirable in turfgrass where drainage is of paramount importance as turfgrass will die if prolonged periods of saturation exist. The residual water content, θ_r, is the water content below which water cannot be extracted from the soil except through the evaporation process. For practical purpose, θ_r represents the permanent wilting point for sandy soils, although the exact value of the permanent wilting point depends on the physiological parameters (rooting depth, leaf area index and above ground biomass) of the plant in question. To determine the available water capacity of the soil, it is important to consider the water content at field capacity, θ_{FC}. This refers to the water content of the soil after excess water has drained out of the root zone up to the point where the rate of downward movement has essentially stopped. This takes place within 2–3 days after a rainfall or irrigation event on a porous medium (soil) of uniform structure and texture. It is usually expressed in terms of the matric head value, and conventionally the matric head value of −1/3 bar (≈−330 cm of water pressure) is considered to represent field capacity. Several researchers (Dane et al., 1983, and Cassel, 1985), however, have found this value to be often greater than −100 cm of water pressure. For this study, we assumed the θ_{FC} to be the *in situ* measured matric head values after 2 days of drainage of a thoroughly wetted soil.

The matric head values can be used to determine the timing of irrigation, while the amount of water to be applied to the profile can be calculated from the ET values. For grass plants, Visser (1959) suggested the matric head values be maintained between -300 and -1000 cm of water pressure to sustain optimum growth.

The objective of this study was to evaluate the soil water-use patterns of four hybrid bluegrasses (HB 129, HB 130, HB 328, and HB 329) and two tall fescue cultivars (Kentucky 31 and Green Keeper) irrigated at a rate of 100% ET, 80% ET and 60% of ET replacements. Information on water-use patterns will be used to infer the ability of a cultivar to use less water, an important parameter of drought avoidance.

MATERIALS AND METHODS

Experimental Set-up

This study was conducted from June through September 2005 and during a similar period in 2006, at the Auburn University Turfgrass Research Facility. The soil at the research site is Marvyn soil series (Fine-loamy, kaolinitic, thermic Typic Kanhapludult), having a considerably deep profile without a root-limiting layer. Particle size analyses (Gee and Or, 2002), water release characteristics (Dane and Hopmans, 2002), organic matter and pH of this soil are presented for two depths (Table 2.1). The USDA textural class is loamy sand with high bulk density values. The sand content decreases with depth while the clay content increases. At any matric head value, the upper part of the 30-cm profile has more water than the lower part, which is attributed to a higher organic matter content in the upper part of the profile.

The study area is equipped with an automated irrigation system and weather station (Campbell Scientific, Logan, UT). Four hybrid bluegrasses, viz., HB 129, HB 130 (experimental line), HB 328 (experimental line) and HB 329, and two tall fescues, viz., Kentucky 31 and Green Keeper, were seeded in the fall of 2004. Fumigation with methyl bromide was done prior to seeding to eliminate weeds and soil pathogens. The seeding rate was 10 g m^{-2} for the hybrid bluegrasses and 30 g m^{-2} for the tall fescue cultivars. The grasses were allowed to properly establish before imposing the irrigation treatments, set to meet 100% ET, 80% ET and 60% ET replacements. The ET values were calculated using the Penman-Monteith formula (Allen et al., 1998). A rotary deck mower set to a height of 5 cm was used to mow and collect the clippings three times per week. The areas around the tensiometers were trimmed with a battery-operated hand clipper. Fungicides were applied occasionally to control rust (*Puccinia graminis*, *Uromyces*) and dollar spot (*Sclerotinia homeocarpa*). Starting in the fall of 2005, NPK (0-0-30) granular fertilizer was applied uniformly across all plots at a rate of 2.5 g m^{-2} month^{-1} and K fertilizer at a rate of 1.2 g m^{-2} month^{-1} in the spring to maintain high soil test K.

A set of three tensiometers were installed at 7.5, 15 and 30 cm depths at the middle blocks for each of the plots (Fig. 2.1). Before installation, tensiometers were tested for leaks using the method proposed by Puckett and Dane (1981), after soaking the porous ceramic cups in water overnight to saturate them. During installation a soil corer tube was used to create holes in the soil to accept the tensiometers. The steel tube was driven to the soil to depths of 10, 17.5 and 32.5 cm to make the middle of the ceramic porous cups correspond to 7.5, 15 and 30 cm depth. Previously de-aerated water, with a trace amount of cupric sulfate to prevent algae growth, was used to fill the tensiometers up to the transparent plastic tube of the tensiometer. Trapped air was removed using a hand-operated suction pump, and finally, the tensiometers were closed off by inserting a rubber septum. The readings were obtained with a tensimeter (Soil Measuring System, Tucson, AZ), with a measuring range of 0-1000 cm of H_2O and accuracy > 98% accuracy. During the measurement, a hypodermic needle was inserted through the rubber septum and a reading was recorded on a daily basis. Each turfgrass cultivar had 2 locations with similar irrigation replenishment. Using the tensimeter readings and the known depth of the porous ceramic cup, matric head values were calculated by adding the distance from the soil surface to the middle of the ceramic porous cup (depth).

Volumetric water content was calculated from the matric head values and the corresponding water retention curves. Water flow in the root zone was calculated based on hydraulic head values and hydraulic properties of the soil. Available water in the 30-cm deep soil profile was determined from the volumetric water content values, while water-use was determined using the water balance approach. Since the graphical presentation of the matric head, volumetric water content, hydraulic head and available water as a function of time are similar for all cultivars, we will only show the data for one turfgrass cultivar, viz., HB 129. Water-use are shown in tabular form for comparison of all cultivars.

The matric head values for 7.5 and 15 cm depth were used to calculate the hydraulic head gradient and the water content, while the values for the 30 cm depth were used in the water balance equation to calculate water-use.

Determination of the Water Scheduling

Hydraulic properties of the soil in the study area were determined prior to the start of the experiment. Six undisturbed soil samples (height = 6.0 cm and internal diameter = 5.35 cm) were obtained from a depth between 3 and 9 cm and a similar number between 17 and 23 cm. The water retention properties determined for the 3-9 cm depth samples were assumed to apply to the upper 15 cm (7.5 cm deep tensiometers), while those determined for the 17-23 cm depth samples were assumed to apply to the lower 15 cm of the 30-cm deep profile (15 and 30-cm deep tensiometers). Water retention curves were determined using Tempe pressure cells (Dane and Hopmans, 2002). Combining the soil sample data by depth and fitting the van Genuchten equation through the data points resulted in $\theta_r = 0.150$, $\theta_s = 0.327$, $\alpha = 0.03227$, and $n = 2.34473$ ($r^2 = 0.93$) for the 3 - 9 cm depth, and $\theta_r = 0.109$, $\theta_s = 0.270$, $\alpha = 0.04127$, and $n = 2.51037$ ($r^2 = 0.96$) for the 17 - 23 cm depth, respectively. The Brooks-Corey parameter values were $\theta_r = 0.157$, $\theta_s = 0.318$, $\lambda = 1.207$ and $h_d = -23.5$ cm for the 3 to 9 cm depth, and $\theta_r = 0.106$, $\theta_s = 0.264$, $\lambda = 1.019$ and $h_d = -16.3$ cm for the 17 to 23 cm depth, respectively. Matric head values for the 100% ET replacement block (see Fig. 2.1) were used to adjust the ET-based irrigation treatments. This was achieved by using the tensiometer readings and setting a lower matric head limit of approximately -300 cm of H_2O, which equals the upper limit of the range suggested by Visser (1959) for sustaining grass plants without stress. This corresponds to $\theta = 0.158$, while the field capacity was defined as the water content at a matric head of approximately- 40 cm water ($\theta = 0.248$). Irrigation was triggered when ≥ 50% of the tensiometers at the 15 cm depth of the 100% ET-replacement plots reached a matric head (h_m) value of -300 cm of H_2O or lower. However, the amount of water replaced was calculated based on cumulative ET. To determine the amount of water (cm) needed to initially (start of experiment) replenish the soil profile for the 100% ET, we used the upper 15 cm depth and calculated the difference between the average soil water content determined with a 12 cm depth TDR probe ($\theta = 0.16$) and field capacity ($\theta = 0.25$). The amount irrigation was calculated as: (0.25 – 0.16) × 15 cm = 1.35 cm or 13.5 mm of water. Thus, the initial water supplied was 13.5, 10.8 and 8.1 mm, respectively, for the 100% ET, 80% ET and 60% ET replacements. The ET values were computed daily from the weather data using the Penman-Monteith equation (Allen et al., 1998).

Water-use Calculation

Water-use (WU) was determined by a water balance equation:

$$WU = P + I - \left[\Delta S\right]_z^0 - q_z \Delta t - R \qquad [2.4]$$

where P is precipitation (cm), I is irrigation amount (cm), $\left[\Delta S\right]_z^0$ is change in root zone soil water storage from the surface to z (30 cm for this study), $q_z\ \Delta t$ (cm) is the drainage components and is the product of drainage flux density ($cm^3\ cm^{-2}\ h^{-1}$) and time (h), and R

is water loss due to lateral surface water flow, i.e. runoff (cm). Soil moisture deficit occurs when the amount of water withdrawn exceeds the amount of water added. Runoff was assumed to be negligible as the ground was rather level and well vegetated during the experimental period. Furthermore, there were no intense rainfall events and no rills or washing of debris were observed following each rainfall event. The drainage flux density was determined from the hydraulic head gradient as stated in the Darcy equation:

$$q_z = -\left[K(\theta) \frac{\partial H}{\partial z} \right]_z \qquad [2.5]$$

where q is the flux density (cm^3 cm^{-2} s^{-1}), K is the hydraulic conductivity (cm s^{-1}), H is the hydraulic head (cm), and z is the vertical distance (cm) (negative downwards). The hydraulic head was calculated from:

$$H = h + z = h_a + h_m + z \qquad [2.6]$$

where h (cm) is the pressure head, h_a (cm) is the air pressure head, h_m (cm) is the matric head, and z (cm) is the gravitational head. We assumed the air pressure in the soil profile to be atmospheric (h_a=0), hence:

$$H = h_m + z \qquad [2.7]$$

We selected the reference level for the gravitational head to be the soil surface. Using the tensiometers located at 7.5 and 15 cm depth, the z-values were -7.5 and -15 cm, respectively. Hydraulic conductivity (K) values were calculated from the values determined at saturation (K_s), using the Mualem expression (Mualem, 1976):

$$K(h) = K_s S_e^{\,l} \left[1 - (1 - S_e^{\,1/m})^m \right]^2 \qquad [2.8]$$

where S_e is the effective water content, *K(h)* is the hydraulic conductivity as a function of pressure head (cm h^{-1}), K_s is the hydraulic conductivity at saturation (cm h^{-1}), *m* is a van Genuchten curve fitting parameter, and *L* is the pore connectivity parameter estimated by Mualem (1976) to be on average about 0.5. Eq. 2.8 was solved using a hydraulic conductivity at saturation value (2.22 cm h^{-1}) estimated from the soil texture information (Table 2.1) as provided in HYDRUS-1D code (Simunek et al., 1998) .

Precipitation was measured daily at the weather station. Irrigation water was supplied by sprinklers that uniformly delivered 2.54 cm of water per hour, with the duration of each block regulated by a timer. Water content was monitored daily from tensiometer (7.5, 15 and 30 cm depths) readings, and the previously determined water retention parameters.

RESULTS AND DISCUSSIONS

The Physical Environment

The total monthly precipitation, potential evapotranspiration (ET), mean solar radiation and air temperature for the period June through September are shown in Fig. 2.2. The total monthly precipitation was higher for 2005 than for 2006, except in September. The mean solar radiation was higher for each month in 2006 than in corresponding months of 2005. A similar trend was observed for the average air temperature, except for the month of September, suggesting that solar radiation was related to the mean air temperatures. The calculated potential evapotranspiration (ET) was higher in 2006 compared to 2005. The environmental conditions at the experimental site were considered to be warmer and drier during the summer of 2006.

Irrigation treatments were initiated in June 2005 after full establishment of the turf. A higher irrigation amount was applied in 2006 following a higher ET and lower precipitation for that year compared to that observed in 2005. In 2006, the amounts of water irrigated to achieve the desired replenishments were applied in increments of 2 or 3 times, a practice not adhered to in 2005. This practice may have had an effect on root development for the 2 years under consideration.

Matric Head Trends

The matric head values (h_m, cm) for the HB 129 are plotted for the experimental periods 6 June, through 30 September 2005 (Fig. 2.3, 2.4, and 2.5) and 8 June through 30 September 2006 (Fig. 2.6, 2.7, and 2.8), for the 7.5-, 15-, and 30-cm depths, respectively. We used a similar scale ($0 > h_m > -800$ cm water) for all plots to enhance visual comparison. The matric head show peaks and dips which correspond with the wetting (irrigation and rainfall) and drying (evaporation, transpiration and drainage) cycles, respectively. There are 15 pronounced dips at the 15-cm depth in 2005 (Fig. 2.3a) and 17 in 2006 (Fig. 2.6a) for the HB 129 plots, which correspond to the days wit $h_m \leq -300$ cm of H_2O for at least 50% of the plots. We irrigated during those days to prevent the h_m values from getting more negative. For each year, the matric head patterns for the 7.5- and 15-cm depths are very similar (Fig. 2.3 and 2.4; Fig. 2.6 and 2.7), but the patterns for the 30-cm depth (Fig. 2.5 and Fig. 2.8) show less h_m variation with time. These results suggest active root activity (root water uptake) between 7.5- and 15-cm depth, and little root influence at 30-cm depth. The data for the 30-cm depth was, however, useful for calculating the downward flux, a process leading to water loss from the root-zone. Since the plots were well covered by grass during the experimental period, the evaporation component of the water balance was considered to be minimal. During the first year of the experiment (2005), the average h_m value for the HB 129 cultivar was -75 cm of H_2O at 7.5-cm depth for 100% ET replacement (Fig. 2.3a), and -115 and -168 cm of H_2O, respectively, for 80% and 60% ET replacements (Fig. 2.3b-c). At 15-cm depth the average h_m values were -64, -94 and -166 cm of H_2O, respectively, for 100%, 80% and 60% ET replacements (Fig. 2.4a-c). At 30-cm depth the average h_m values were -33, -54, and -64 cm of H_2O respectively, for 100%, 80% and 60% ET replacements (Fig. 2.5a-c). For 2006, the average h_m values were -64, -130, and -160 cm of H_2O, respectively, for 100%, 80% and 60% replacements at 7.5-cm depth (Fig. 2.6a-c). At 15-cm depth, the values were -93, -120, -150 cm of H_2O, respectively, for 100%, 80% and 60% ET replacements at (Fig. 2.7a-c). At 30-cm depth the h_m values were -43, -50, and -53 cm of H_2O, respectively, for 100%, 80% and 60% ET replacements (Fig. 2.8a-c). These results show that plots receiving higher irrigation replacements show higher (less negative) h_m values compared to those receiving lower replacements. The h_m values increased with depth, suggesting that root activity decreased with increasing depth. Lower h_m values were observed for the tall fescue cultivars (Kentucky 31 and Green Keeper) than for the hybrid bluegrasses. This suggests greater water depletion by the tall fescue compared to the hybrid bluegrasses.

Volumetric Water Content in the Root Zone

Water content is easier to follow as indication of drying and wetting process than is matric head. We calculated water content from the matric head values using the van Genuchten relation (Eq. [2.2]) and knowledge of the parameter values. We used the main drying curves for these calculations and ignored any occurrence of hysteresis. Our previous results on matric head versus time suggested minimal root activity at the 30-cm depth. Therefore, we calculated the water content only for the 7.5- and 15-cm depths. The results for HB 129 are presented for 2005 (Fig. 2.9) and 2006 (Fig. 2.10). The average water content was higher for the 7.5-cm depth (0.235 for 100% ET, 0.217 for 80% ET, and 0.195 for 60% ET replacements) compared to 15-cm depth (0.176 for 100% ET, 0.165 for 80% ET, and 0.148 for 60% ET) in 2005. Similar patterns were observed in 2006, with values at 7.5-cm depth (0.209 for 100% ET, 0.202 for 80% ET, and 0.201 for 60% ET replacements) being higher than values at 15-cm depth (0.160 for100% ET, 0.160 for 80% ET, and 0.156 for 60% ET replacements). The average water content was higher in 2005 compared to 2006, which was likely due to 2005 being a wetter year compared to 2006 (Fig. 2.2). Variation in water content was also observed between irrigation treatments with 100% ET replacement generally showing the highest water content. Among the cultivars, HB 130 had on average the highest average water content while Green Keeper had the lowest for both years (data not shown).

Although the matric head values calculated earlier increased with depth, the calculated volumetric water content values actually decreased with depth. This was attributed to a higher residual water content at 7.5-cm depth (θ_r = 0.150) compared to the value at 15-cm depth (θ_r = 0.109). The higher residual water content at 7.5-cm depth is likely to have been due to a higher organic matter content at 7.5-cm depth (1.6%) compared to the amount at 15-cm depth (1.2%).

Dane et al. (2006) suggested that irrigation management should be controlled by matric head rather than by water content values since absorption of water by roots is more governed by the former than the latter. Also, it should be noted that the calculated values for the volumetric water content may differ due to hysteresis, which depends on whether one uses the main drying curve (MDC), the main wetting curve (MWC) or combining both the wetting and drying curves (i.e., using scanning curves).

Hydraulic Gradient and Water-flow

The results for the matric head and volumetric water content suggested wetter plots for higher ET replacement. To determine if these plots received inadequate, adequate, or more than adequate replenishment, we determined the direction of water flow in the root zone from the hydraulic head gradient ($\partial H / \partial z$). If a plot is too wet, water is likely to flow downward, leaching out of the root zone. The values for $\partial H / \partial z$ were calculated from knowledge of the matric head, (h_m, cm) and gravitational head (z, cm) between 7.5- and 15-cm and between 15- and 30-cm depth. It is clear from the Darcy's equation (Eq. 2.7) that for the flux density to be upwards (positive), $\partial H / \partial z$ must be negative. The hydraulic head gradients in 2005 and 2006 (Fig. 2.11 and 2.12, respectively), show some days with downward flow for each of the ET replacements. This suggests that the rate of water supply was usually higher than the rate of uptake by roots. The number of days with downward flow was greater for higher ET replacements. For the 100% ET replacement, we counted 39 days of downward flow, out of 115 days in 2005. These were 28 and 27, respectively, for 80% ET and 60 % ET replacements. The days with downward flow in 2006 were 30, 26, and 23, respectively, for 100% ET, 80% ET and 60% ET replacements, out of 116 days. The conspicuous hydraulic head gradient peaks between days 8-15, 25-35, 60-65 and 85-100 for the100% ET replacement (Fig. 2.12a) and days 8-15, and 25-35 for the 80% ET replacement (Fig. 2.12b) in 2006 suggest excess water supply in those plots. During the same period it is clear that the plot receiving 60% ET replacement (Fig. 2.12c) shows excess water supply. It could be that during that period, inadequate water was supplied to the 60% ET replacement plots.

The plots receiving 80% ET replacement showed stronger upward gradients (valleys), suggesting a healthier root system, compared to the 60% ET replacement. With non-distinct upward gradient peaks, the 100% ET replacement plots may have been kept too wet to diminish root water uptake.

Available Water

The available water for plant growth was calculated from the daily measurements of volumetric water content for the depths 0-10 cm, 10-20 cm, and 20-30 cm, and adding the three values. This was achieved by calculating $(\theta\text{-}\theta_r)$ ×10 cm on a daily basis, with θ_r values of 0.109, 0.150, and 0.150, respectively, for depths 0-10 cm, 10-20 cm, and 20-30 cm as determined from the water retention curves. It should be noted that these calculations present the available water at the time of measurement. The graphical results of available water for HB 129 are presented for 2005 (Fig. 2.13) and 2006 (Fig. 2.14).The graphs show similar trends to those of the matric head, which is explained by the use of θ_r values determined from the water retention curve, which are constant values for each depth. These graphs demonstrate the effect of irrigation treatments whereby lower available water values persist longer for lower ET compared to higher ET replacements. The average summation of available water (∑AW) at 0-30 cm depth root zone across the cultivars, was 287.9 cm for 100% ET, 265.4 cm for 80% ET, and 245.8 cm ET replacements in 2005 (Table 2.2). These values were 246.4, 221.2 and 204.3 cm, respectively, for 100% ET, 80% ET and 60% ET replacements in 2006 (Table 2.3). Summation of the available water during the experimental period shows that hybrid bluegrass HB 130 had the highest ∑AW values at the 0-30-cm root zone (343.5, 300.7 and 267.0 cm, respectively, for 100% ET, 80% ET and 60% ET replacements in 2005 and 267.1, 240.0, and 222.9 cm in 2006) as compared to the rest of the cultivars. The hybrid bluegrasses showed higher ∑AW values compared to tall fescue cultivars during the experimental period.

Water-use

The results show higher water-use for higher ET replacements, viz., 63.6 cm for 100% ET, 59.7 for 80% ET and 56.1 cm for 60% ET replacements in 2005 (Table 2.4). The water-use values were 51.7 cm for100% ET, 44.3 cm for 80% ET, and 39.0 cm for 60% ET replacements in 2006 (Table 2.5). These results are in line with the plant physiological principle where plants conserve water during periods of inadequacy and transpire at a maximum rate when water is not limiting. Tall fescue cultivars showed higher water-use values compared to the hybrid bluegrasses. For all the irrigation replenishments, two hybrid bluegrass cultivars, HB 129 and HB 130 show lower water-use than the average value across the cultivars. For HB 129, the water-use values were 61.1, 57.8 and 53.8 cm, respectively, for 100% ET, 80% ET, and 60% ET replacements in 2005, and 50.4, 43.7, and 38.6 cm, respectively, for 100% ET, 80% ET, and 60% ET replacements in 2006. For HB 130, the water-use values were 59.1, 55.2 and 51.8 cm, respectively, for 100% ET, 80% ET, and 60% ET replacements in 2005, and 47.5, 41.5, and 36.0 cm, respectively, for 100% ET, 80% ET, and 60% ET replacements in 2006. One of the tall fescue cultivars, Kentucky 31 had the highest water-use values (66.1 cm for 100% ET, 61.8 cm for 80% ET, and 58.0 cm for 60% ET replacements in 2005; and

54.0 cm for100% ET, 46.2 cm for 80% ET, and 41.4 cm for 60% ET replacements in 2006).

Cultivar Performance Evaluation

It is desirable to have a cultivar that minimizes water-use even when water supply exceeds water requirements. Hence, the amount of water not used by the plant can be saved in the soil root zone for subsequent use during dry periods. Based on matric head, volumetric water content, summation of available water (∑AW) and water-use data, it is clear that hybrid bluegrass cultivars use less water compared to tall fescue cultivars. Of the hybrid bluegrass cultivars, HB 130 showed relatively lower matric head values compared to other cultivars and had the least water-use. Also the plots with HB 130 showed the highest ∑AW in the profile. The HB 129 cultivar was very close to HB 130 in terms of water-use. The ranking of turf water-use could be summarized as follows: HB 130 (least water-use)> HB 129 > HB 328 > HB 329 > Kentucky 31 > Green Keeper.

SUMMARY AND CONCLUSIONS

Field experiments were conducted at the Auburn Turfgrass Research Facility from June to September in 2005 and 2006, to evaluate performance of hybrid bluegrasses and tall fescue cultivars. Four hybrid bluegrass (HB 129, HB 130, HB 328 and HB 329) and two tall fescue cultivars (Kentucky 31 and Green Keeper) were evaluated in this study. Three irrigation treatments were applied to replenish water at a rate of 100% ET, 80% ET and 60% ET. The ET value were calculated from the weather data and employing the Penman-Monteith formula. Tensiometers were installed at 7.5-, 15- and 30-cm depths to monitor the soil water matric head. Water retention curves determined for the soil at the study area were used to convert matric head values to volumetric water content values, while water-use values were calculated using a water balance approach.

Results demonstrated that hybrid bluegrasses were able to conserve soil moisture in the root zone better than tall fescue cultivars.

REFERENCES

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrig. and Drain. Paper 56. FAO, Rome.

Beard, J.B. 1973. Turfgrass: Science and culture. p. 1-658. Prentice-Hall, Englewood Cliffs, N.J.

Beard, J.B. 1989. Turfgrass water stress: Drought resistance components, physiological mechanisms, and species-genotype diversity. p. 23–28. *In* Takatoh, H. (ed.) Proc. 6th Int. Turf. Res. Conf., Tokyo, Japan.

Biran, I., B. Bravdo, I. Bushkin-Harav, and E. Rawitz. 1981. Water consumption and growth rate of 11 turfgrasses as affected by mowing height, irrigation frequency, and soil moisture. Agron. J. 73:85–90.

Bristow, K.L. G.S. Campbell, and K. Calissendorff. 1993. Test of a heat-pulse probe for measuring changes in soil water content. Soil Sci. Soc. Am. J. 57 930-934.

Brooks, R.H., A.T. Corey. 1964. Hydraulic properties of porous media. Hydrology paper 3. Colorado State Univ., Fort Collins, CO.

Busey, P. 1996. Wilt avoidance in St. Augustinegrass germplasm. HortSci. 31:1135-1138.

Campbell, G.S., and G.W. Gee. 1986. Water potential: Miscellaneous methods. p. 619–633. *In* Klute, A. (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Carrow, R.N. 1991.Turfgrass water use, drought resistance and rooting patterns in the Southeast. ERC-01-91. Envir. Res. Center. Georgia Inst. of Tech., Atlanta, GA. and the College of Agric. and Env. Sci., Univ. of Georgia, Athens, GA.

Carrow, R.N. 1996 a. Drought avoidance characteristics of diverse tall fescue cultivars. Crop Sci. 36:371–377.

Carrow, R.N. 1996 b. Drought resistance aspects of turfgrasses in the Southeast: Root-shoot responses. Crop Sci. 36:687–694.

Carrow R.N. and R.R. Duncan 2000 a. Strategies for water conservation in turfgrass situations. Proc. Irr. Assoc. Melbourne, Australia.

Carrow R. and R.R. Duncan 2000 b. Wastewater and seawater use for turfgrasses: Potential problems and solutions. Proc. Irr. Assoc. Melbourne, Australia.

Carrow, R.N., and R.R. Duncan. 2003. Improving drought-resistance and persistence in turf-type tall fescue. Crop Sci. 43:978-984.

Cary, J.W., and J.L. Wright. 1971. Responses of plant water potential to the irrigated environment of Southern Idaho. Agron. J. 63:691-695.

Cassel, D.K., 1985. Physical Characteristics of soils of the southern region-summary of in situ unsaturated hydraulic conductivity. Southern co-op. series bulletin 303. NC Agric. Exp. St., Raleigh, NC.

Cassel, D.K., and A. Klute. 1986. Water potential: Tensiometry. p. 563–596. *In* Klute, A. (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Mon. 9 ASA, and SSSA, Madison, WI.

Chalmers, D.J., P.D. Mitchell, and L. Vanheek. 1981. Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. HortSci. 111:904-907.

DaCosta, M., and B. Huang. 2005. Deficit irrigation effects on water use characteristics of Bentgrass species. Crop Sci. 46:1779-1786.

Dane, J.H., D.K. Cassel, J.M. Davidson, W.L. Pollans, V.L. Quisenberry. 1983. Physical characteristics of soils of the southern region-Troup and Lakeland series. Southern Cooperative Series Bulletin 262. Alabama Agric. Exp. St., Auburn Univ., Alabama.

Dane, J.H. and Jan W. Hopmans. 2002. Water retention and storage. Introduction. p.671-673. *In* Dane, J.H. and G.C. Topp (eds.) Methods of soil analysis. Part 4. Physical methods. SSSA Book Ser. 5. SSSA, Madison, WI.

Dane, J.H., R.H. Walker, L. Bahaminyakamwe and J.L. Belcher. 2006. Tall fescue and hybrid bluegrass response to soil water matric head limits. Agricultural Water Management. 86:177-186.

Doorenbos, J. and W.O. Pruitt. 1992. Crop water requirements. FAO irrigation and drainage paper No. 24. FAO, Rome, Italy.

Ervin E. H. and A. J. Koski. 1998. Drought avoidance aspects and crop coefficients of Kentucky bluegrass and tall fescue turfs in the semi-arid West. Crop Sci. 38:788–795.

Evett, S.R., and J.L. Steiner. 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. Soil Sci. Soc. Am. J. 59:961-968.

Feldhake, C.M., R.E. Danielson, and J.D. Butler. 1984. Turfgrass evapotranspiration. II. Responses to deficit irrigation. Agron. J. 76:85–89.

Gardner, W.H. 1986. Water content. p. 493-544. *In* Klute, A. (ed.). Methods of soil analysis, Part 1: Physical and mineralogical methods. Am. Soc. Agron. Book Ser. 9. Madison, WI.

Gee, G.W., and D. Or. 2002. 2.4. Particle-size analysis. p. 255–293. *In* Dane, J.H., Topp, G.C. (eds.). Methods of soil analysis. Part 4. Physical methods. Soil Sci. Soc. Am. Book Ser. 5. Madison, WI.

Hanks, R.J. 1983. Yield and water-use relationships. p. 393-410. *In* Taylor, H.M., W.J. Jordan and T.R. Siclair (eds). Limitations to efficient water-use in crop productions. ASA, Madison, WI.

Huang, B. and H. Gao. 2000. Root physiological characteristics associated with drought resistance in tall fescue cultivars. Crop Sci. 40:196-203.

Huang, B., R. R. Duncan, and R.N. Carrow. 1997. Drought-resistance mechanisms of seven warm-season turfgrasses under surface soil drying: I. Shoot response. Crop Sci. 37(6):1858-1863.

Jones, H.G. 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods J. Exp. Bot. 55:2427-2436.

Kenna, M. R., and G.L. Horst. 1993. Turfgrass water conservation and quality. Int. Turf. Soc. Res. J. 7: 99-113.

Kirda, C. 2002. Deficit irrigation scheduling based on plant growth stages showing water stress tolerance. *In* Water reports. FAO. United Nations. Rome.

Kirda C. and R. Kanber. 1999. Water, no longer a plentiful resource, should be used sparingly in irrigated agriculture. p. 1-18. *In* Kirda, C., P. Mountonnet, C. Hera and D.R. Nielsen (eds). Crop yield response to deficit irrigation.

Laboski, C.A.M., J.A. Lamb, R.H. Dowdy, J.M. Baker, and J. Wright. 2001. Irrigation scheduling for a sandy soil using mobile frequency domain reflectometry with a checkbook method. J. Soil Water Cons. 56(2):97-100.

Meyer, J.L., V.A. Gibeault, and V.B. Youngner. 1985. Irrigation of turfgrass below replacement of evapotranspiration as a means of water conservation. p. 357–364. *In* Lemaire, F. (ed.). Determining crop coefficient of turfgrasses. Proc. Int. Turfgrass Res. conf., Avignon, France.

Mualem, Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res.12 (3): 513–522.

Olson, C.O. 1985. Site design for water conservation. *In* Gibeault, V.A. and S.T. Cockerham (eds.). Turfgrass water conservation. Pub. No. 21405. Co-op. Ext. Service. Univ. of California, Oakland, CA.

Puckett, W.E. and J.H. Dane. 1981. Testing tensiometers by a vacuum method. Soil Sci. 132:444–445.

Šimunek, J., M. Sejna, and M. Th. van Genuchten.1998. The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. v. 2.0. Colorado School of Mines. Golden, CO.

Stewart R.S., R. Kjelgren and P.G. Johnson and M.R. Kuhns. 2004. Soil water-use characteristics of precision-irrigated buffalograss and Kentucky bluegrass. App. Turfgrass Sci. 10:1094-1118.

Topp, G.C., and J.L. Davis. 1985. Time-domain reflectometry (TDR) and its application to irrigation scheduling. p. 107-127. *In* Hillel, D. (ed.). Advances in irrigation, Vol. 3, Academic Press, Inc., New York, NY.

Taylor, S.A. 1965. Managing irrigation water on the farm. Am. Soc. Agric. Eng. Trans. 8:433-436.

van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898.

Visser, W.C. 1959. Crop growth and availability of moisture. Inst. Land Water Manage. Res. Tech. Bul 6. Wageningen, Netherlands.

Wade, G.L., J.T. Midcap, K.D. Coder, G. Landry, A.W. Tyson, and N. Weatherby, Jr. 1992. Xeriscape- A Guide to developing a water-wise landscape. Cooperative ext. service bulletin 1073. Univ. of Georgia, Athens, GA.

Young, M.H., and J.B. Sisson. 2002. Tensiometry. p. 575–608. *In* Dane, J.H. and G.C. Topp (eds.) Methods of soil analysis. Part 4. Physical methods. S.S.S.A. Book Ser. 5. SSSA, Madison, WI.

Youngner, V.B. 1985. Physiology of water use and water-stress. p. 37–43. *In* Gibeault, V.A. and S.T. Cockerham (eds.) Turfgrass water conservation. Publ. 21405. Univ. of California, Div. Agric. and Nat. Resources, Oakland, CA.

Table 2.1. Physical and chemical properties of soil at the research site

Soil depth	Soil texture			Organic matter	K_s	Bulk density	pH	Soil water content at applied pressure, cmH_2O						
	Sand	Silt	Clay					0	-5	-10	-50	-100	-250	-500
cm	%				cm h^{-1}	g cm^{-3}		cm^3 cm^{-3}						
3-9	86.0	13.0	1.0	1.6	6.23	1.69	6.2	0.33	0.33	0.32	0.22	0.19	0.16	0.15
17-23	83.0	11.0	6.0	1.2	2.22	1.79	6.2	0.27	0.27	0.26	0.16	0.13	0.11	0.10
Average	84.5	12.0	3.5	1.4	4.23	1.74	6.2	0.30	0.30	0.29	0.19	0.16	0.14	0.12

Table 2.2. Summation of available water as measured on a daily basis and the number of days with water flow in the profile during the first year (2005) of the experiment.

		∑ Available Water at each depth (cm)				No. of days with flow	
Cultivar	**Treatment**	**0-10**	**10-20**	**20-30**	**0-30**	**Upward**	**Downward**
G. Keeper	100ET	*86.4*	*78.4*	*99.0*	*263.8*	*76*	*25*
HB 129	100ET	*94.2*	*86.7*	*108.9*	*289.8*	*69*	*39*
HB 130	100ET	*117.3*	*105.7*	*120.4*	*343.5*	*60*	*41*
HB 328	100ET	*95.5*	*81.4*	*107.8*	*284.7*	*59*	*39*
HB 329	100ET	*92.1*	*80.7*	*104.3*	*277.1*	*70*	*30*
KY 31	100ET	*92.5*	*85.0*	*91.2*	*268.7*	*66*	*29*
	average:	***96.3***	***86.3***	***105.3***	***287.9***	***66.7***	***33.5***
G. Keeper	80ET	*79.6*	*69.5*	*86.0*	*235.1*	*85*	*22*
HB 129	80ET	*93.0*	*85.8*	*107.2*	*286.0*	*72*	*28*
HB 130	80ET	*100.4*	*93.0*	*107.4*	*300.7*	*57*	*39*
HB 328	80ET	*85.4*	*76.0*	*90.5*	*251.9*	*68*	*31*
HB 329	80ET	*89.9*	*80.4*	*99.5*	*269.8*	*81*	*22*
KY 31	80ET	*82.9*	*73.2*	*93.0*	*249.1*	*72*	*28*
	average:	***88.5***	***79.7***	***97.3***	***265.4***	***72.5***	***28.3***
G. Keeper	60ET	*71.4*	*66.1*	*85.4*	*222.9*	*75*	*15*
HB 129	60ET	*92.3*	*79.9*	*96.8*	*269.0*	*65*	*27*
HB 130	60ET	*90.2*	*81.6*	*95.1*	*267.0*	*60*	*38*
HB 328	60ET	*83.7*	*74.6*	*92.4*	*250.6*	*58*	*26*
HB 329	60ET	*83.9*	*68.5*	*87.6*	*240.0*	*65*	*19*
KY 31	60ET	*78.8*	*66.3*	*80.0*	*225.1*	*66*	*27*
	average:	***83.4***	***72.8***	***89.5***	***245.8***	***64.8***	***25.7***

Table 2.3. Summation of available water as measured on a daily basis and the number of days with water flow in the profile for the second year (2006) of the experiment.

		∑ Available Water at each depth (cm)				No. of days with flow	
Cultivar	**Treatment**	**0-10**	**10-20**	**20-30**	**0-30**	**Upward**	**Downward**
G. Keeper	100ET	*97.1*	*64.7*	*64.0*	*225.8*	*76*	*22*
HB 129	100ET	*119.3*	*82.8*	*71.0*	*273.2*	*79*	*30*
HB 130	100ET	*113.8*	*78.0*	*75.3*	*267.1*	*60*	*39*
HB 328	100ET	*96.0*	*71.4*	*69.7*	*237.1*	*59*	*39*
HB 329	100ET	*94.3*	*70.0*	*63.3*	*227.5*	*70*	*30*
KY 31	100ET	*91.7*	*69.1*	*66.4*	*227.2*	*86*	*27*
	average:	***103.0***	***74.2***	***69.1***	***246.4***	***71.7***	***31.2***
G. Keeper	80ET	*88.1*	*62.3*	*54.4*	*204.8*	*85*	*24*
HB 129	80ET	*105.5*	*68.0*	*69.7*	*243.2*	*72*	*26*
HB 130	80ET	*98.8*	*77.0*	*64.2*	*240.0*	*57*	*37*
HB 328	80ET	*95.0*	*63.3*	*60.3*	*218.6*	*68*	*31*
HB 329	80ET	*88.0*	*57.3*	*60.5*	*205.7*	*82*	*22*
KY 31	80ET	*89.8*	*61.0*	*64.0*	*214.8*	*72*	*25*
	average:	***94.2***	***64.8***	***62.2***	***221.2***	***72.7***	***27.5***
G. Keeper	60ET	*81.7*	*60.5*	*52.2*	*194.4*	*75*	*25*
HB 129	60ET	*83.5*	*64.0*	*65.6*	*213.1*	*45*	*23*
HB 130	60ET	*92.0*	*74.0*	*56.9*	*222.9*	*60*	*33*
HB 328	60ET	*81.7*	*54.4*	*62.2*	*198.2*	*55*	*26*
HB 329	60ET	*73.7*	*55.6*	*58.1*	*187.4*	*79*	*22*
KY 31	60ET	*80.2*	*58.0*	*61.7*	*199.9*	*56*	*22*
	average:	***82.2***	***61.2***	***60.9***	***204.3***	***61.7***	***25.2***

Table 2.4. Water-use by hybrid bluegrass and tall fescue cultivars (June-September 2005)

Cultivar	**Precipitation**	**Irrigation**	**Change in Storage**	**Drainage**	**Water-use**
	P (cm)	**I (cm)**	**$[\Delta S]^0_z$ (cm)**	**$q_z\Delta t$ (cm)**	**WU (cm)**
G. Keeper	*54.0*	*21.7*	*1.6*	*7.5*	*66.6*
HB 129	*54.0*	*21.7*	*2.0*	*12.6*	*61.1*
HB 130	*54.0*	*21.7*	*2.1*	*14.5*	*59.1*
HB 328	*54.0*	*21.7*	*1.7*	*9.4*	*64.6*
HB 329	*54.0*	*21.7*	*1.5*	*9.8*	*64.4*
KY 31	*54.0*	*21.7*	*1.7*	*7.9*	*66.1*
average:					***63.6***
G. Keeper	*54.0*	*17.4*	*1.8*	*7.2*	*62.4*
HB 129	*54.0*	*17.4*	*1.6*	*12.0*	*57.8*
HB 130	*54.0*	*17.4*	*1.8*	*14.3*	*55.2*
HB 328	*54.0*	*17.4*	*1.7*	*8.8*	*60.9*
HB 329	*54.0*	*17.4*	*1.9*	*9.2*	*60.2*
KY 31	*54.0*	*17.4*	*2.1*	*7.4*	*61.8*
average:					***59.7***
G. Keeper	*54.0*	*13.0*	*1.6*	*7.0*	*58.4*
HB 129	*54.0*	*13.0*	*1.8*	*11.4*	*53.8*
HB 130	*54.0*	*13.0*	*1.6*	*13.6*	*51.8*
HB 328	*54.0*	*13.0*	*1.7*	*6.7*	*58.6*
HB 329	*54.0*	*13.0*	*1.9*	*9.0*	*56.1*
KY 31	*54.0*	*13.0*	*1.6*	*7.4*	*58.0*
average:					***56.1***

Table 2.5. Water-use by hybrid bluegrass and tall fescue cultivars (June-September 2006)

Cultivar	**Precipitation P (cm)**	**Irrigation I (cm)**	**Change in Storage $[\Delta S]^0_z$ (cm)**	**Drainage $q_z\Delta t$ (cm)**	**Water-use WU (cm)**
G. Keeper	*29.4*	*31.6*	*1.6*	*4.9*	*54.5*
HB 129	*29.4*	*31.6*	*1.9*	*8.7*	*50.4*
HB 130	*29.4*	*31.6*	*2.0*	*11.5*	*47.5*
HB 328	*29.4*	*31.6*	*1.4*	*8.6*	*51.0*
HB 329	*29.4*	*31.6*	*1.8*	*6.2*	*53.0*
KY 31	*29.4*	*31.6*	*1.0*	*6.0*	*54.0*
average:					***51.7***
G. Keeper	*29.4*	*25.3*	*1.7*	*4.5*	*48.5*
HB 129	*29.4*	*25.3*	*1.7*	*9.3*	*43.7*
HB 130	*29.4*	*25.3*	*2.0*	*11.2*	*41.5*
HB 328	*29.4*	*25.3*	*1.6*	*8.2*	*44.9*
HB 329	*29.4*	*25.3*	*1.6*	*8.5*	*44.6*
KY 31	*29.4*	*25.3*	*2.3*	*6.2*	*46.2*
average:					***44.3***
G. Keeper	*29.4*	*19.0*	*1.7*	*3.8*	*42.9*
HB 129	*29.4*	*19.0*	*1.6*	*8.2*	*38.6*
HB 130	*29.4*	*19.0*	*1.7*	*10.7*	*36.0*
HB 328	*29.4*	*19.0*	*2.9*	*7.4*	*38.1*
HB 329	*29.4*	*19.0*	*3.0*	*4.1*	*41.3*
KY 31	*29.4*	*19.0*	*2.4*	*4.6*	*41.4*
average:					***39.0***

1	2	6 †	4 †	5	3	
4	5	1 †	6 †	3	2	
6	3	4 †	1 †	2	5	
5	6	2 †	3 †	1	4	I
2	4	3 †	5 †	6	1	
3	1	5 †	2 †	4	6	

3	4	5 †	2 †	6	1	
2	6	3 †	5 †	1	4	
5	1	2 †	3 †	4	6	
6	5	4 †	1 †	3	2	II
4	2	1 †	6 †	5	3	
1	3	6 †	4 †	2	5	

1	3	5 †	4 †	5	2	
4	2	3 †	6 †	1	5	
6	5	2 †	1 †	4	3	
5	4	1 †	3 †	2	6	III
2	1	6 †	5 †	3	4	
3	6	4 †	2 †	5	1	

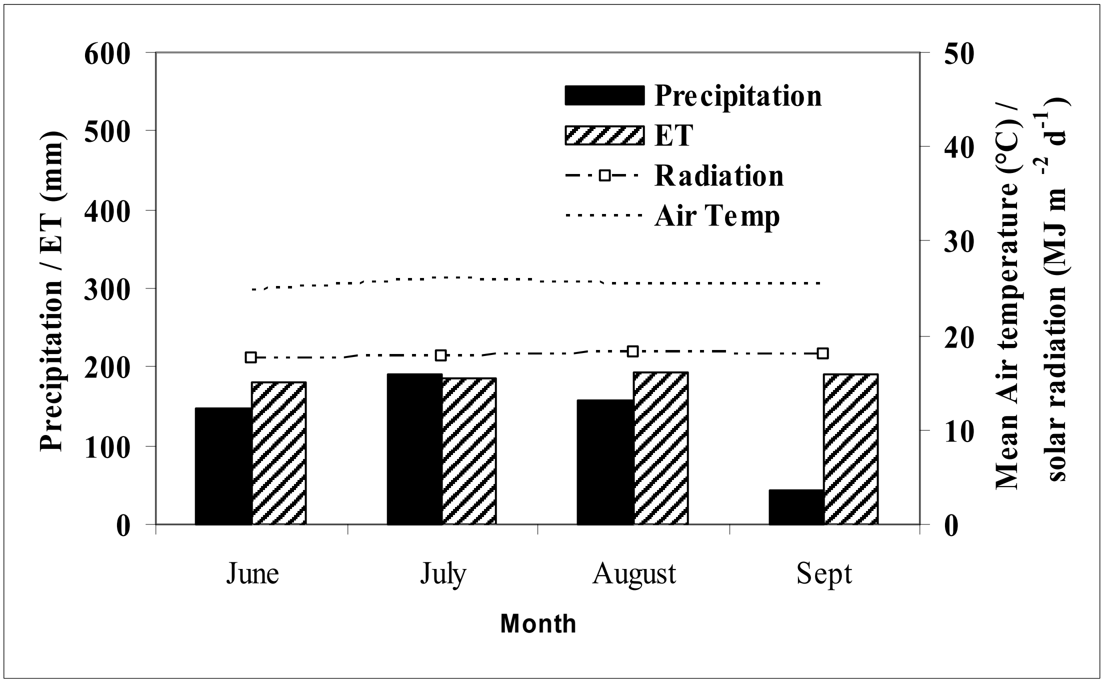
1 = HB 129 (Thermal Blue), 2 = HB 130 (Experimental line), 3 = HB 328 (Experimental line), 4 = HB 329 (Dura Blue), 5 = Green Keeper tall fescue, 6 = Kentucky 31 tall fescue

Treatments: I = 100 % ET replacement, II = 80% ET replacement, III = 60% ET replacement.

† = Tensiometers sets. The plots with tensiometers sets were sampled for turf color.

Fig. 2.1. Layout for bluegrass and tall fescue irrigation experiment.

(a)



(b)

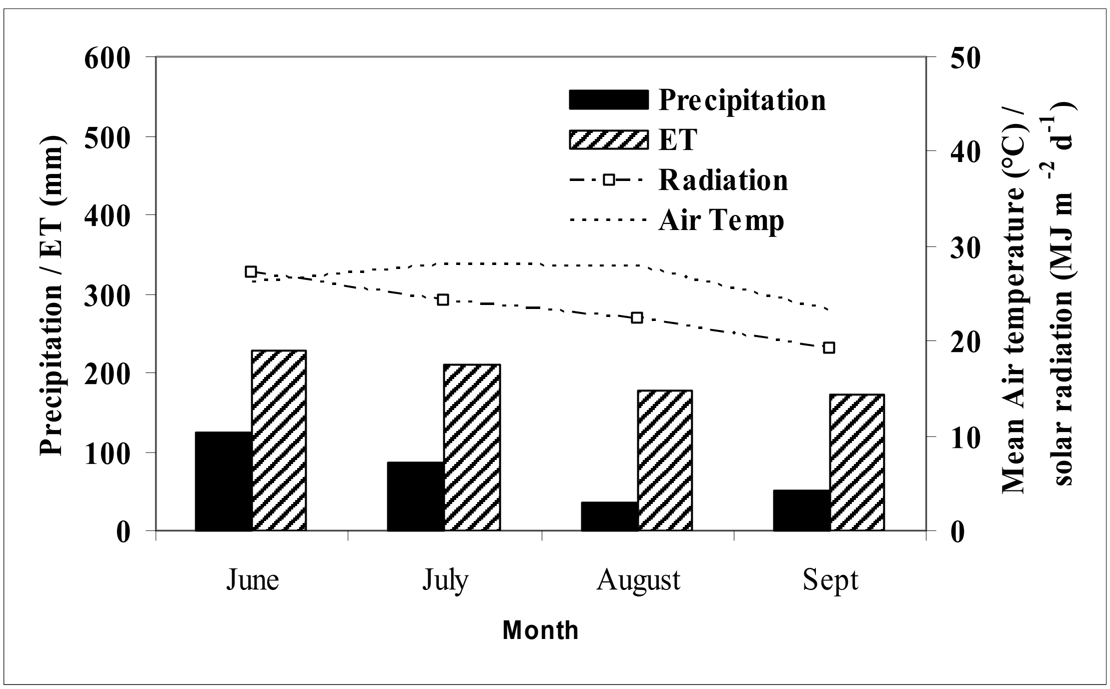


Fig. 2.2. Monthly total precipitation, potential evapotranspiration (ET), mean solar radiation and air temperature for the period June-September (A) 2005 and (B) 2006.

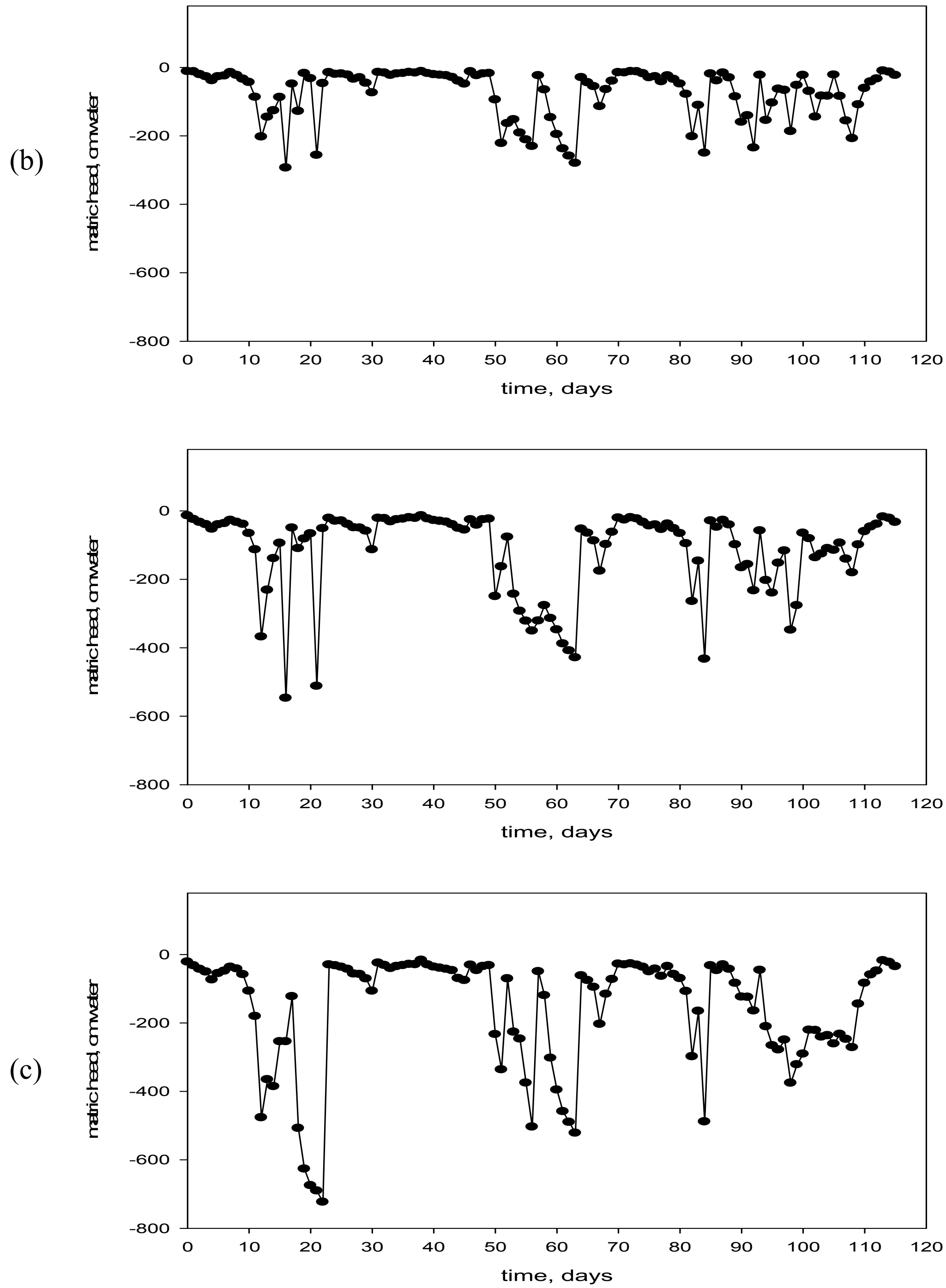


Fig. 2.3. Matric head values as a function of time for 100% ET (a), 80% ET (b) and 60% ET (c) replacement at 7.5 cm depth for HB 129 (Thermal Blue) in 2005.

(a)

(b)

(c)

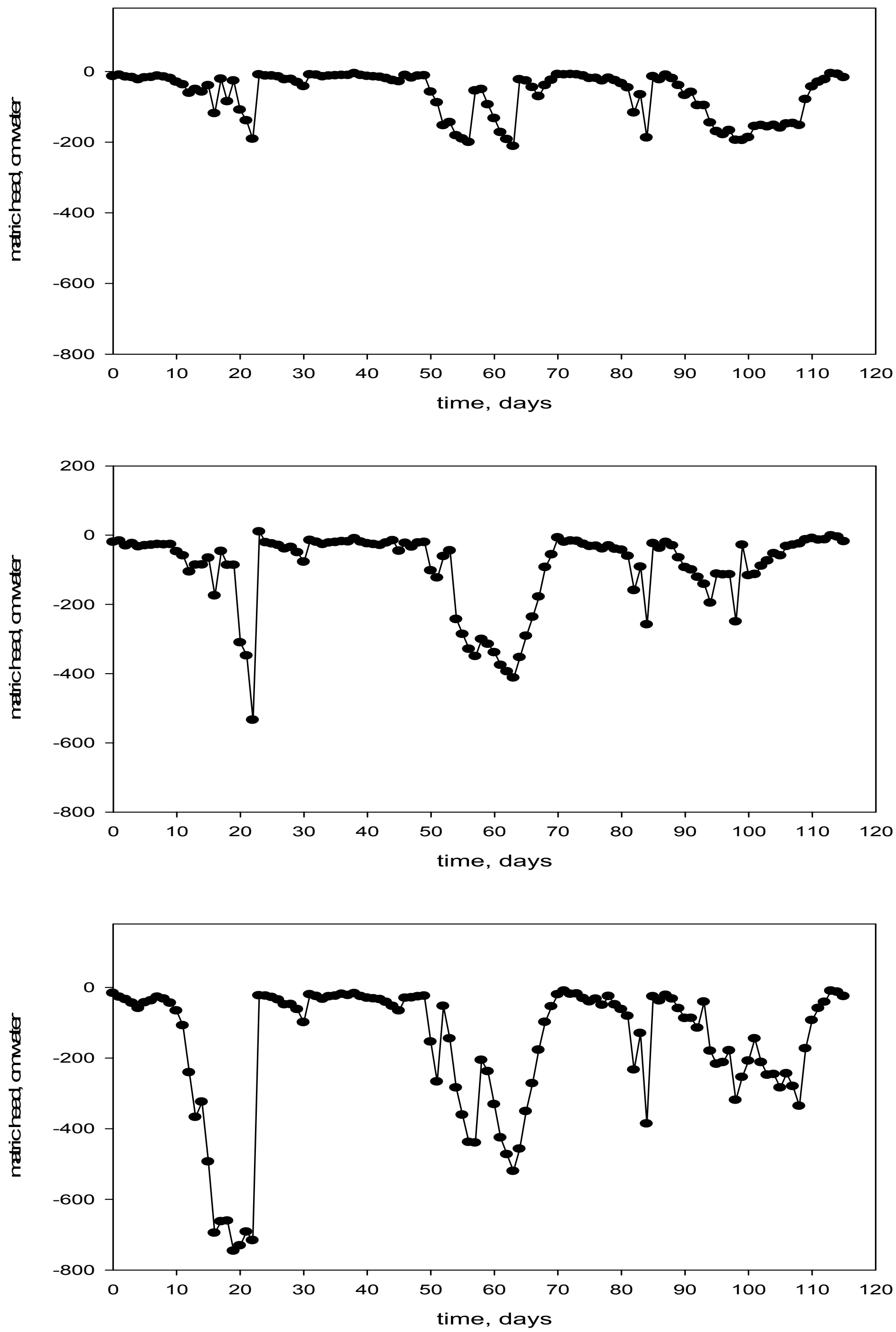


Fig. 2.4. Matric head values as a function of time for 100% ET (a), 80% ET (b) and 60% ET (c) replacement at 15 cm depth for HB 129 (Thermal Blue) in 2005.

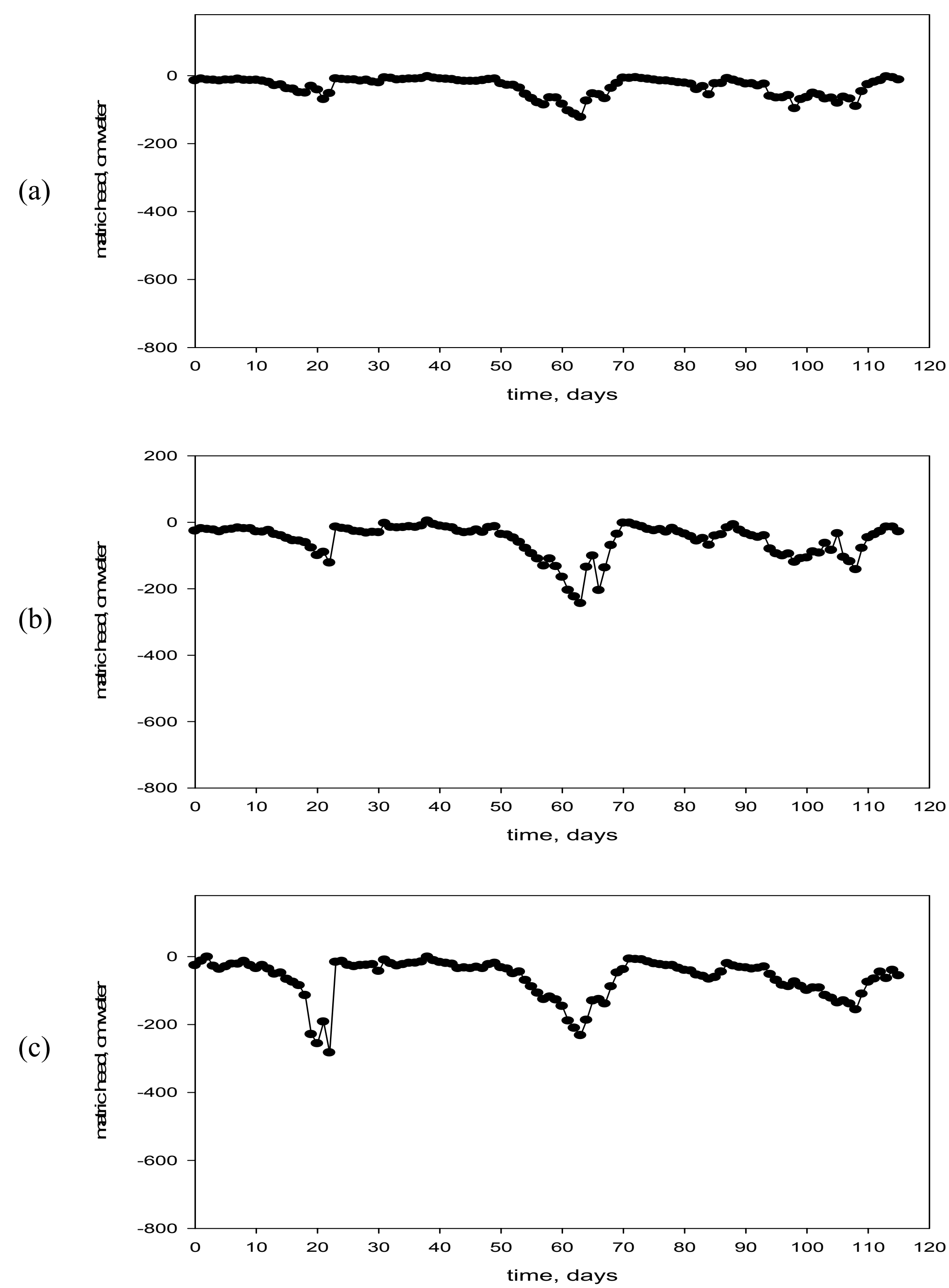
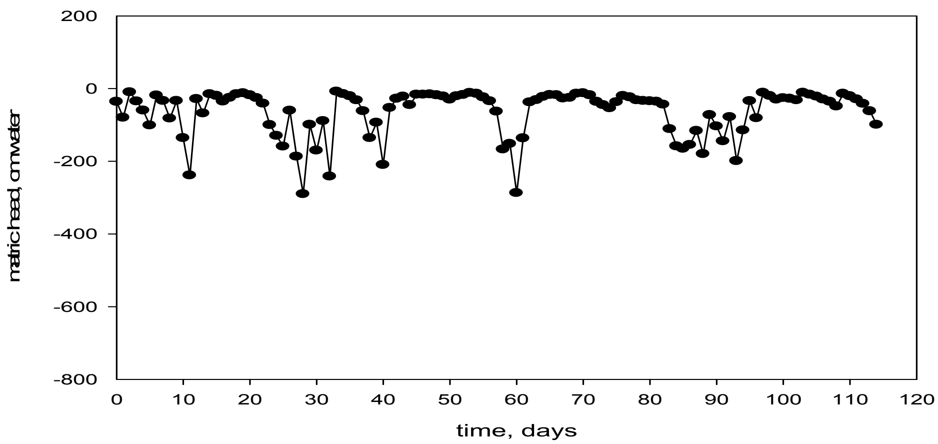
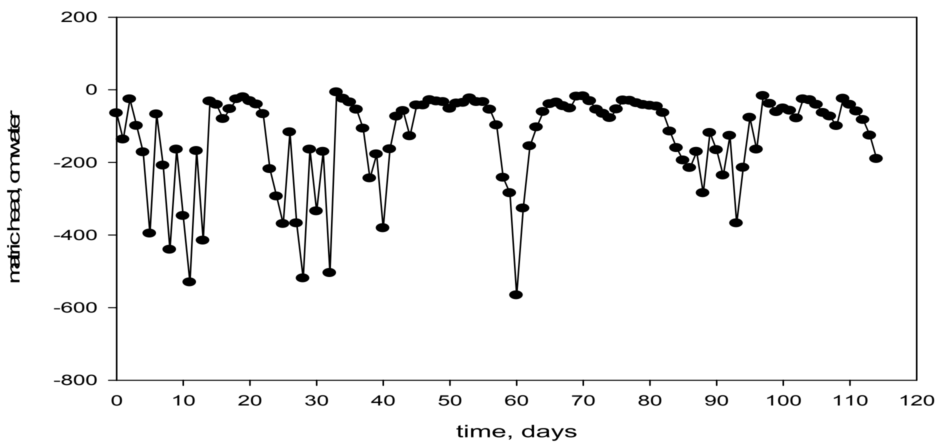


Fig. 2.5. Matric head values as a function of time for 100% ET (a), 80% ET (b) and 60% ET (c) replacement at 30 cm depth for HB 129 (Thermal Blue) in 2005.

(a)



(b)



(c)

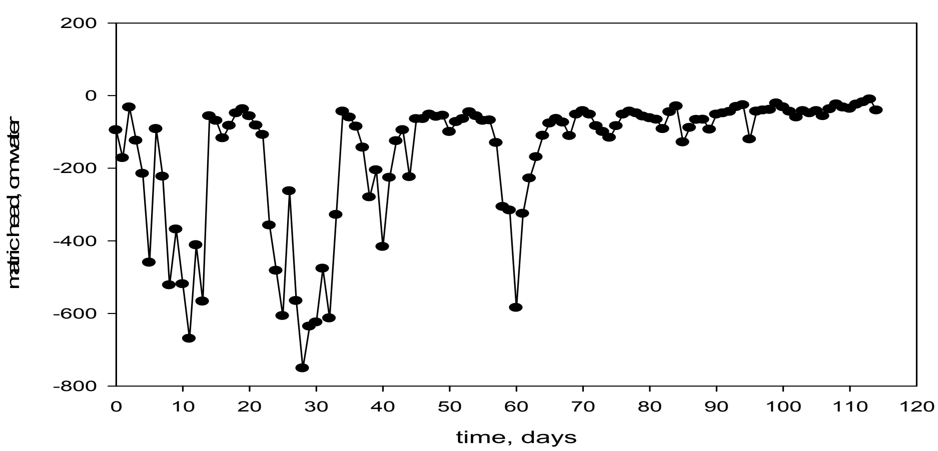


Fig. 2.6. Matric head values as a function of time for 100% ET (a), 80% ET (b) and 60% ET (c) replacement at 7.5 cm depth for HB 129 (Thermal Blue) in 2006.

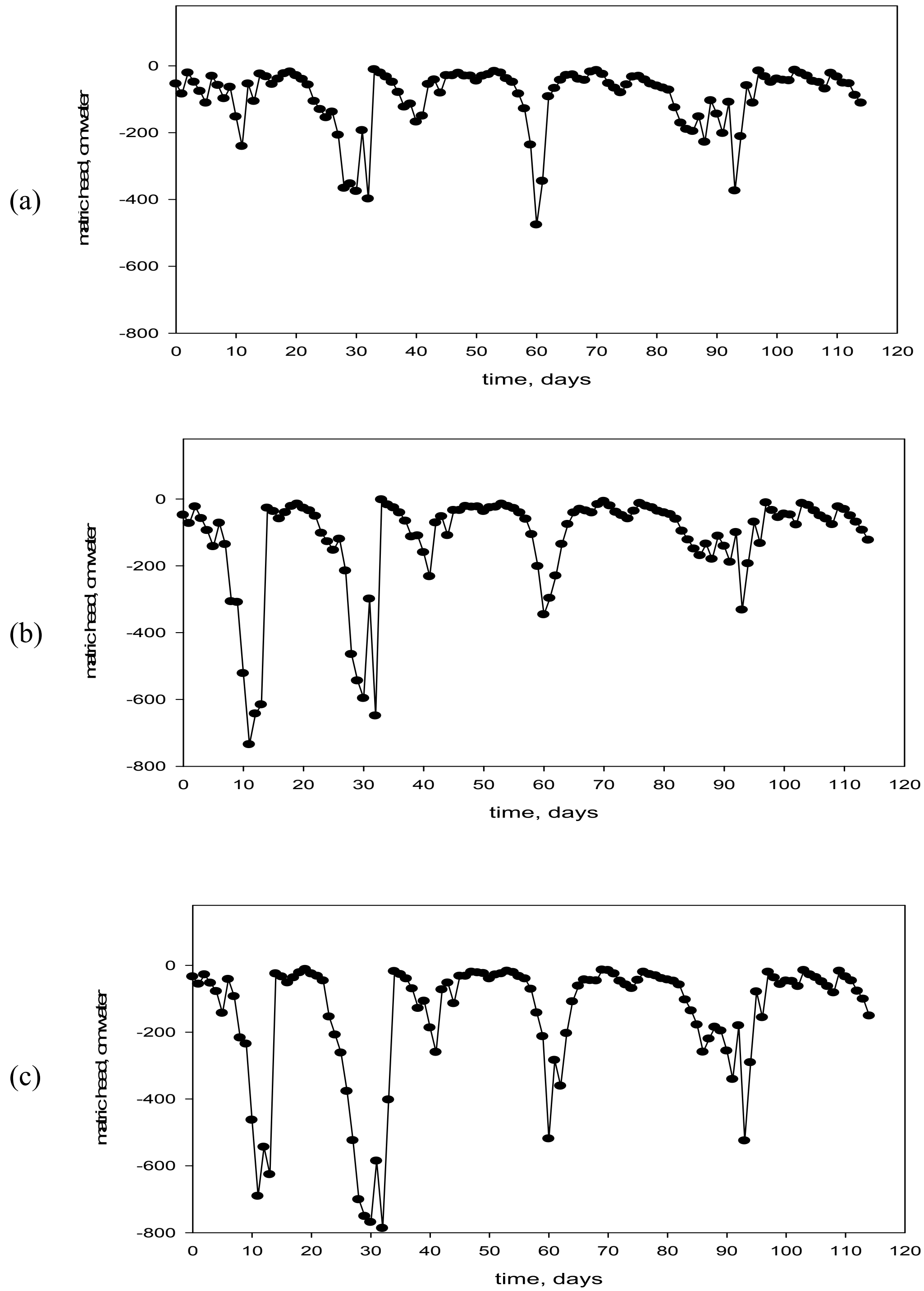


Fig. 2.7. Matric head values as a function of time for 100% ET (a), 80% ET (b) and 60% ET (c) replacement at 15 cm depth for HB 129 (Thermal Blue) in 2006.

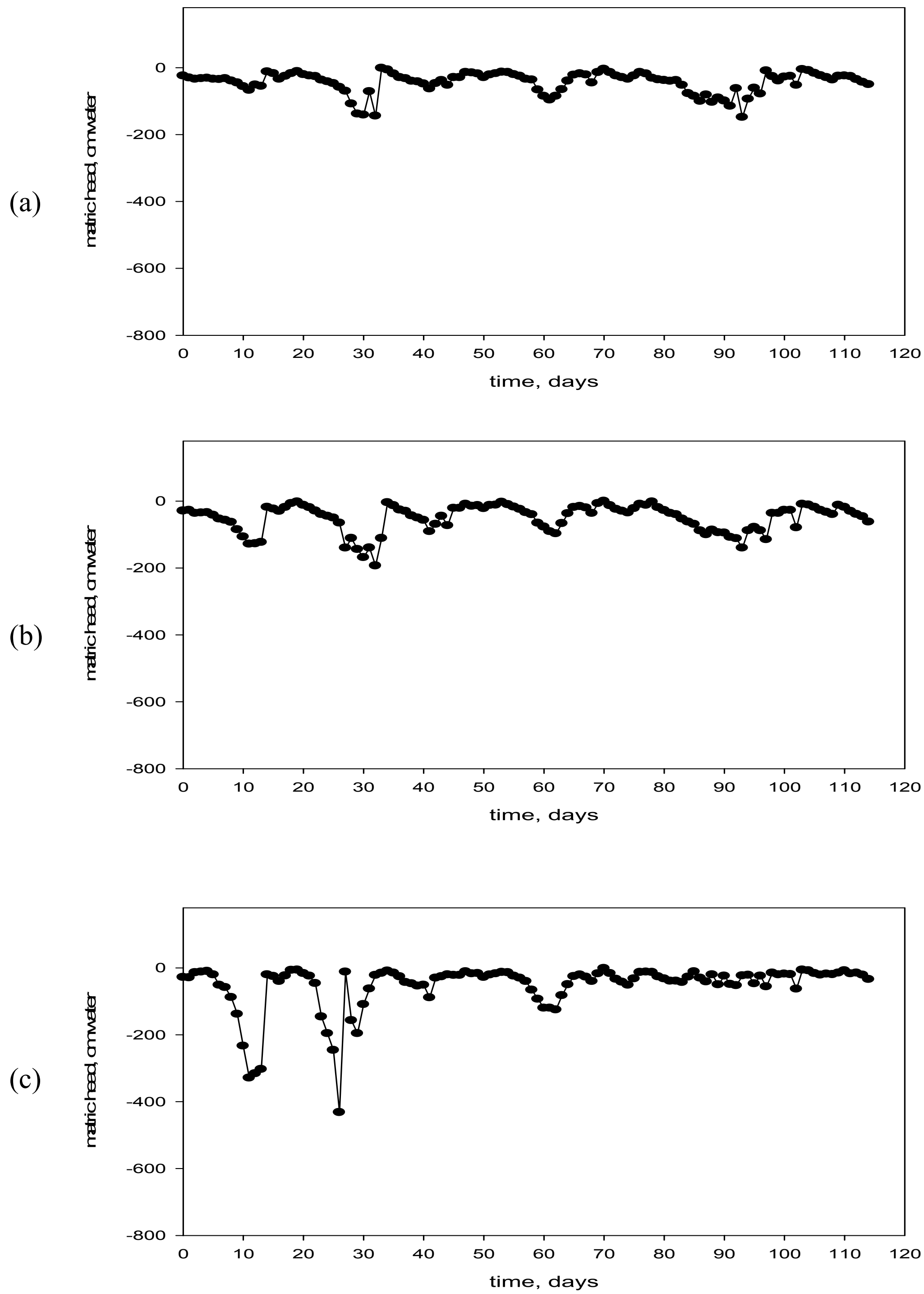


Fig. 2.8. Matric head values as a function of time for 100% ET (a), 80% ET (b) and 60% ET (c) replacement at 30 cm depth for HB 129 (Thermal Blue) in 2006.

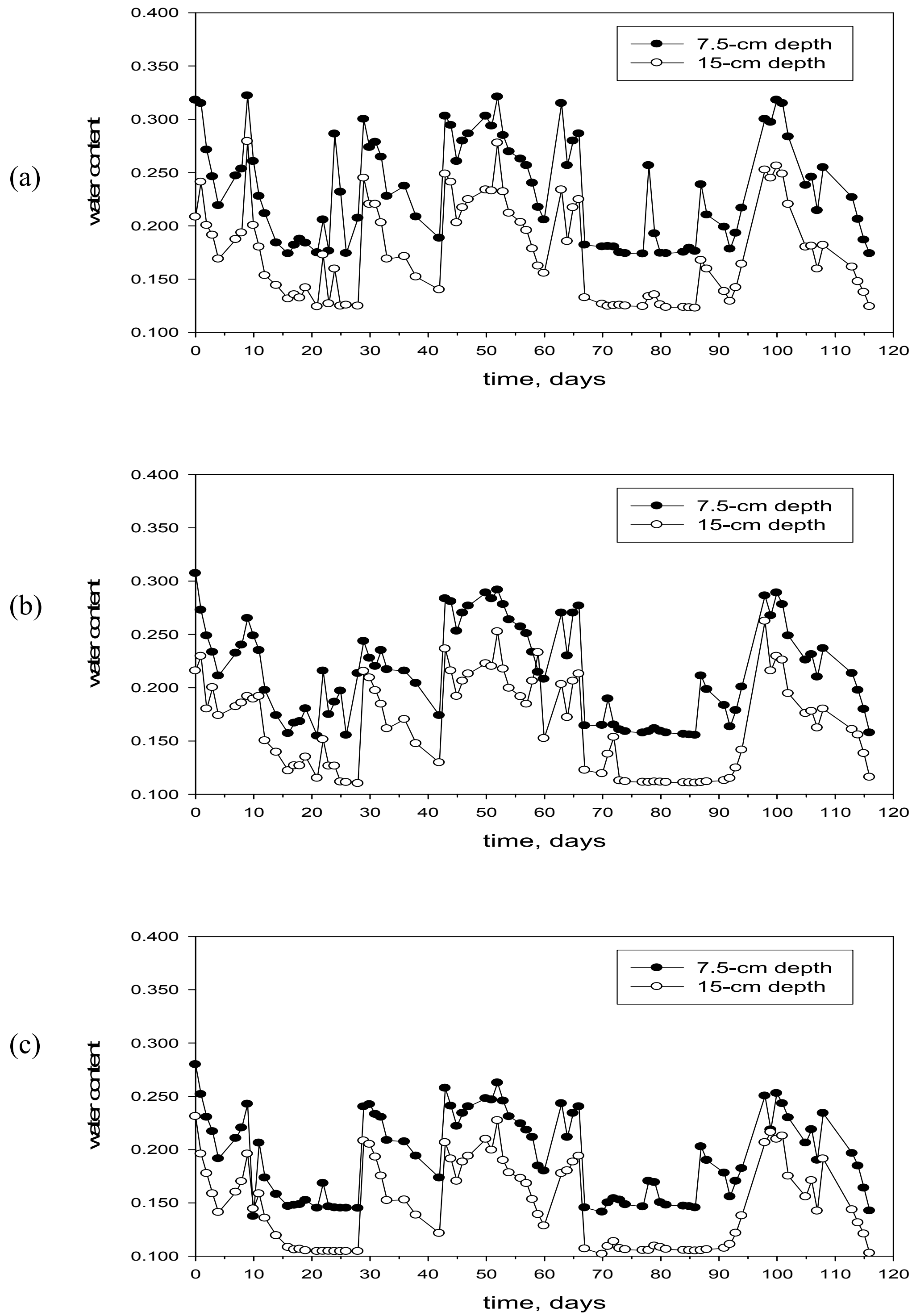


Fig. 2.9. Volumetric water content as a function of time at the 7.5 and 15cm for the 100% ET (a), 80% ET (b) and 60% ET (c) replacement for HB 129 (Thermal Blue) in 2005.

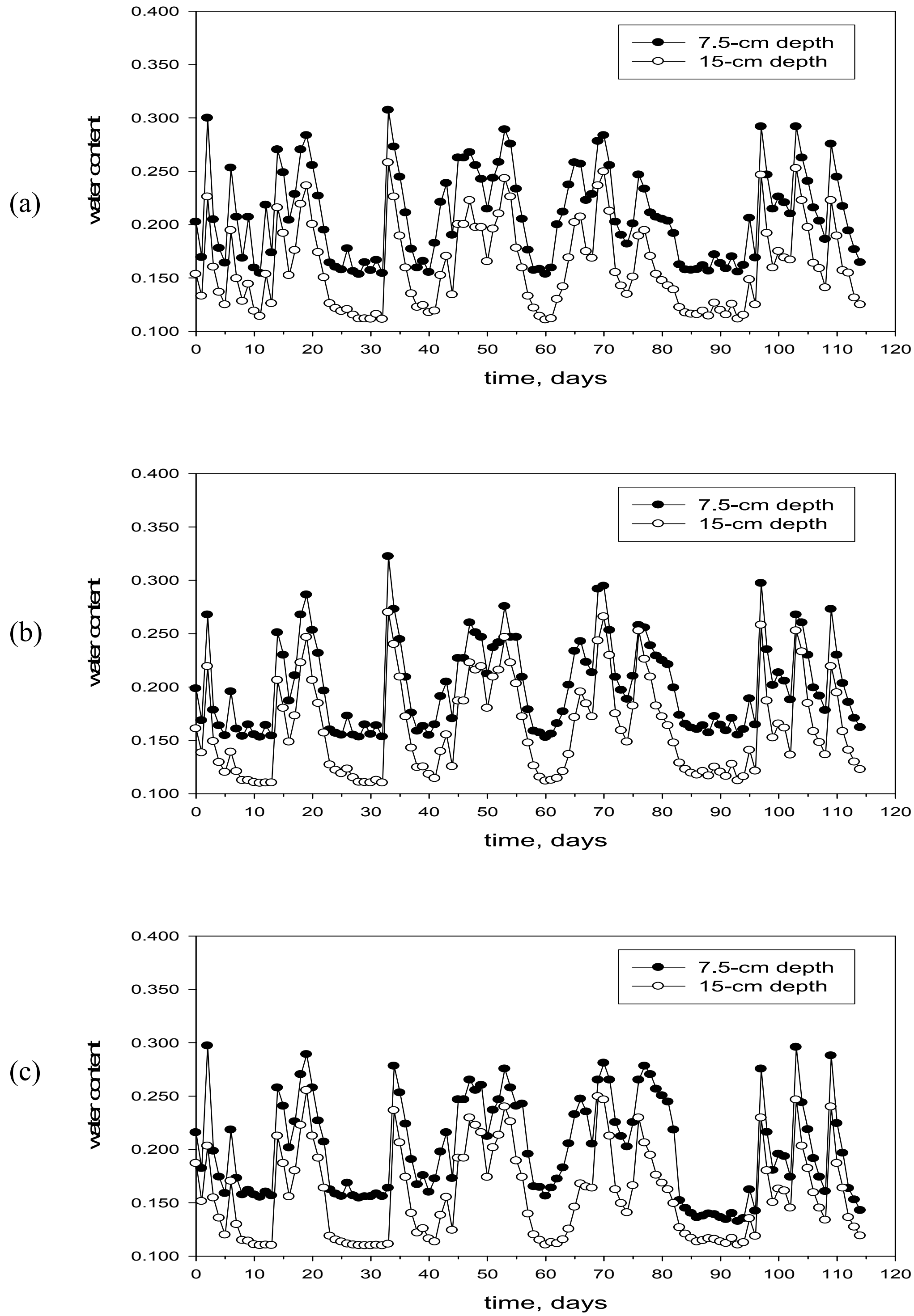


Fig. 2.10. Volumetric water content as a function of time at the 7.5 and 15 cm for the 100% ET (a), 80% ET (b) and 60% ET (c) replacement for HB 129 (Thermal Blue) in 2006.

(a)

(b)

(c)

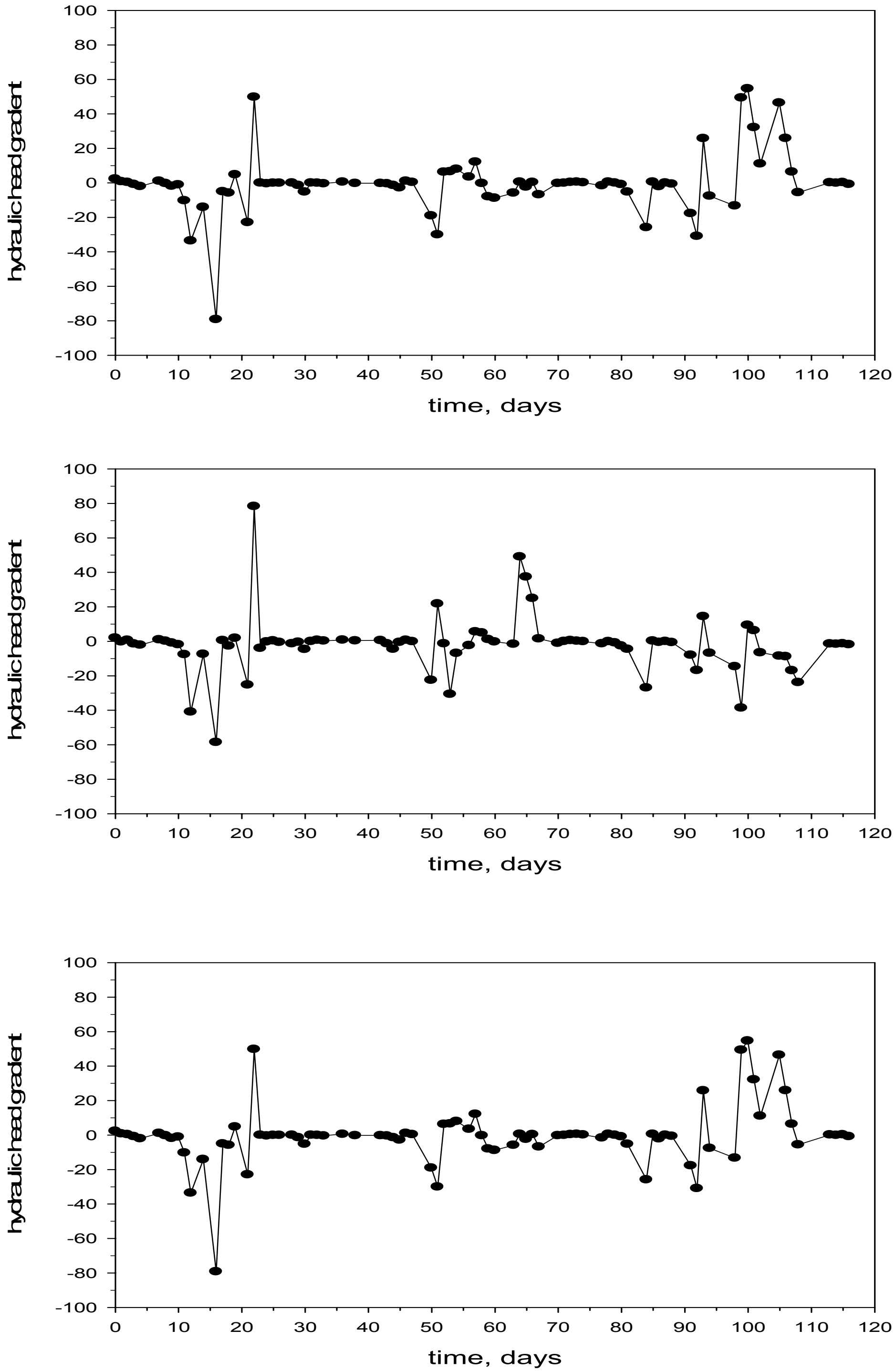
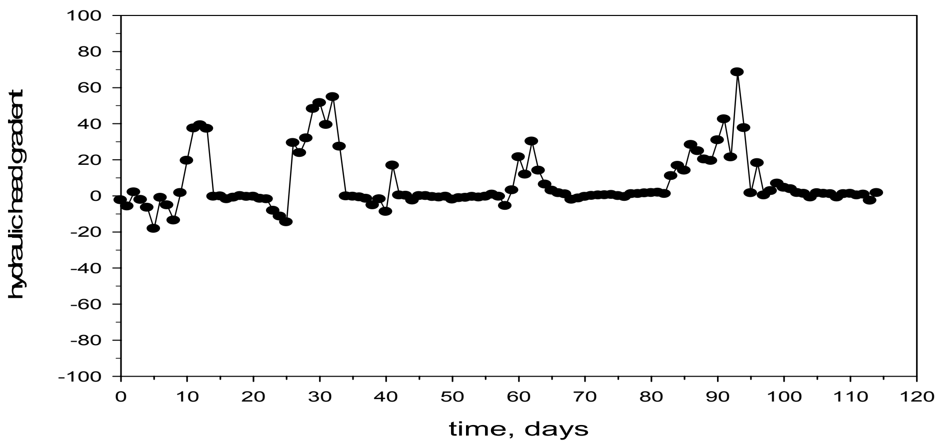
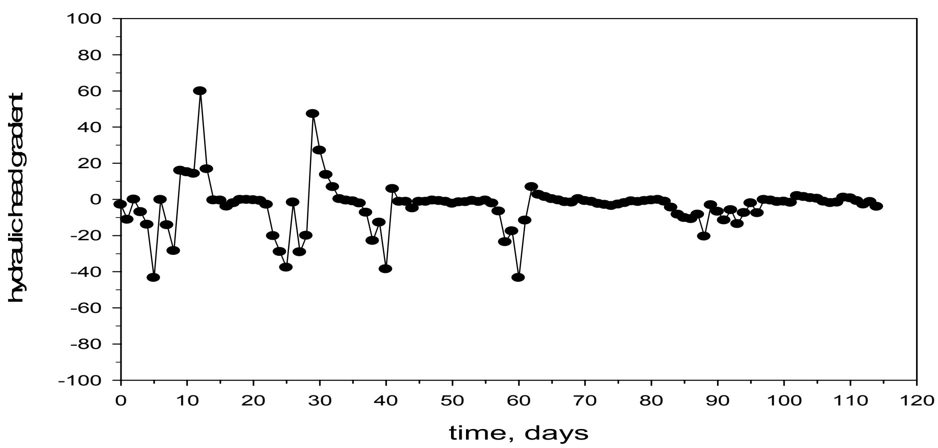


Fig. 2.11. Hydraulic head gradient between 7.5 and 15 cm as a function of time for the 100% ET (a), 80% ET (b) and 60% ET (c) replacement for HB 129 (Thermal Blue) in 2005.

(a)



(b)



(c)

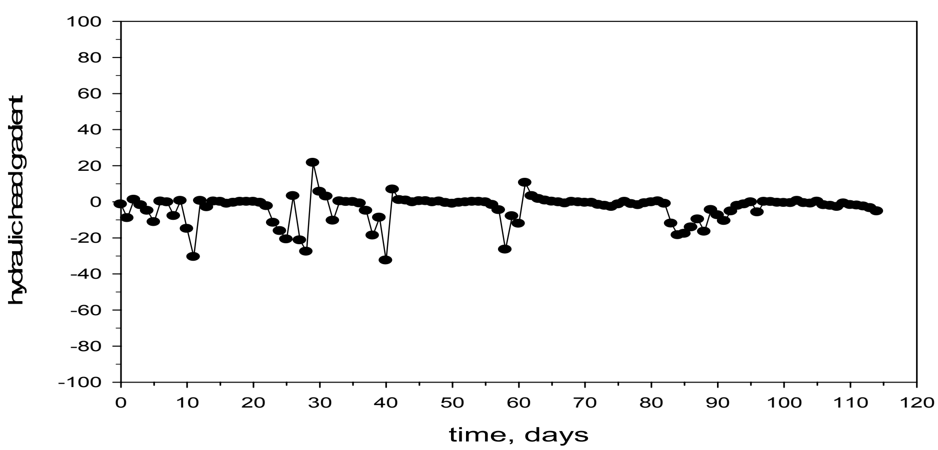


Fig. 2.12. Hydraulic head gradient between 7.5 and 15 cm as a function of time for the 100% ET (a), 80% ET (b) and 60% ET (c) replacement for HB 129 (Thermal Blue) in 2006.

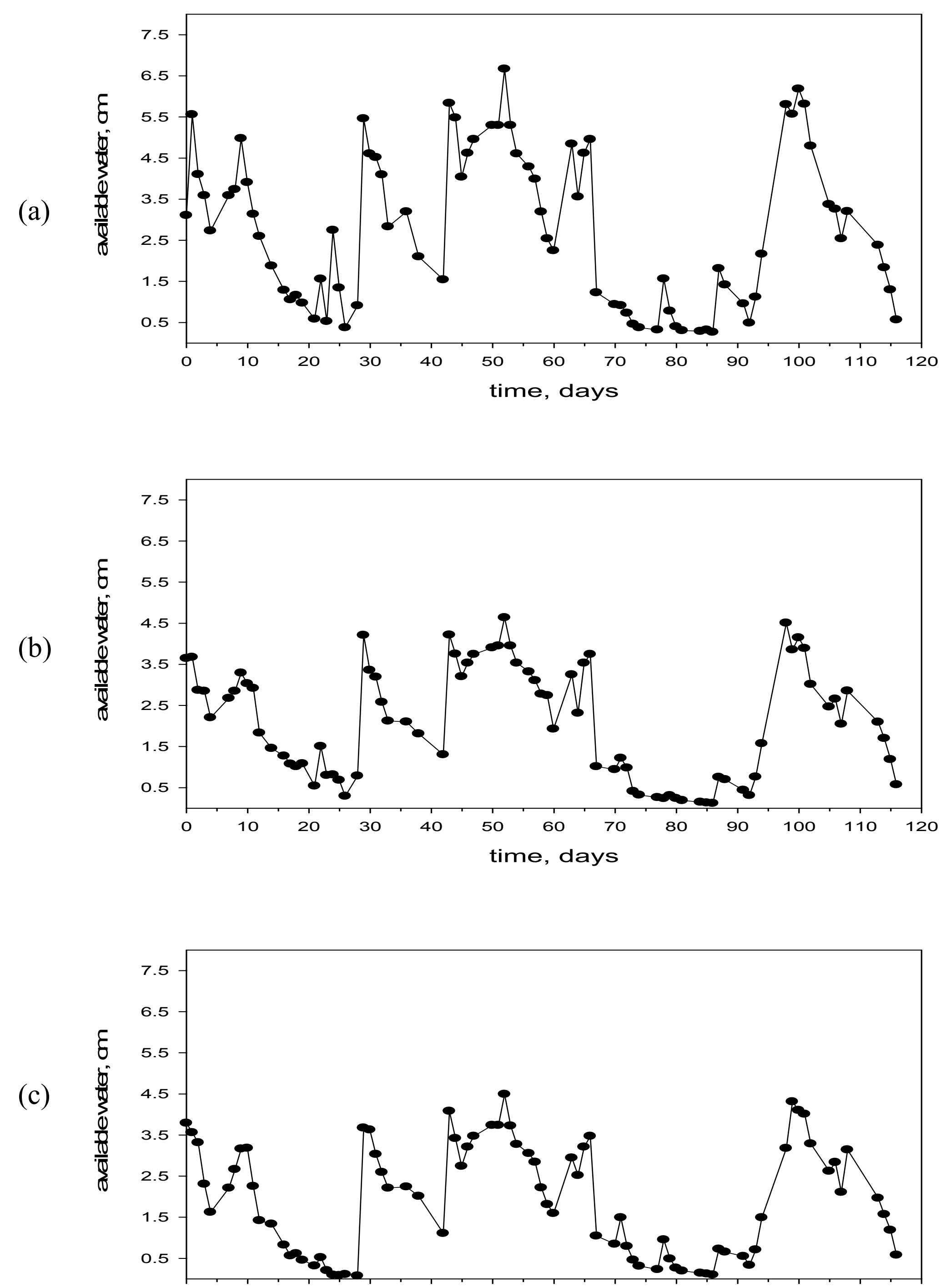


Fig. 2.13. Available water as a function of time in the 30 cm root zone depth for the 100% ET (a), 80% ET (b) and 60% ET (c) replacement for HB 129 (Thermal Blue) in 2005.

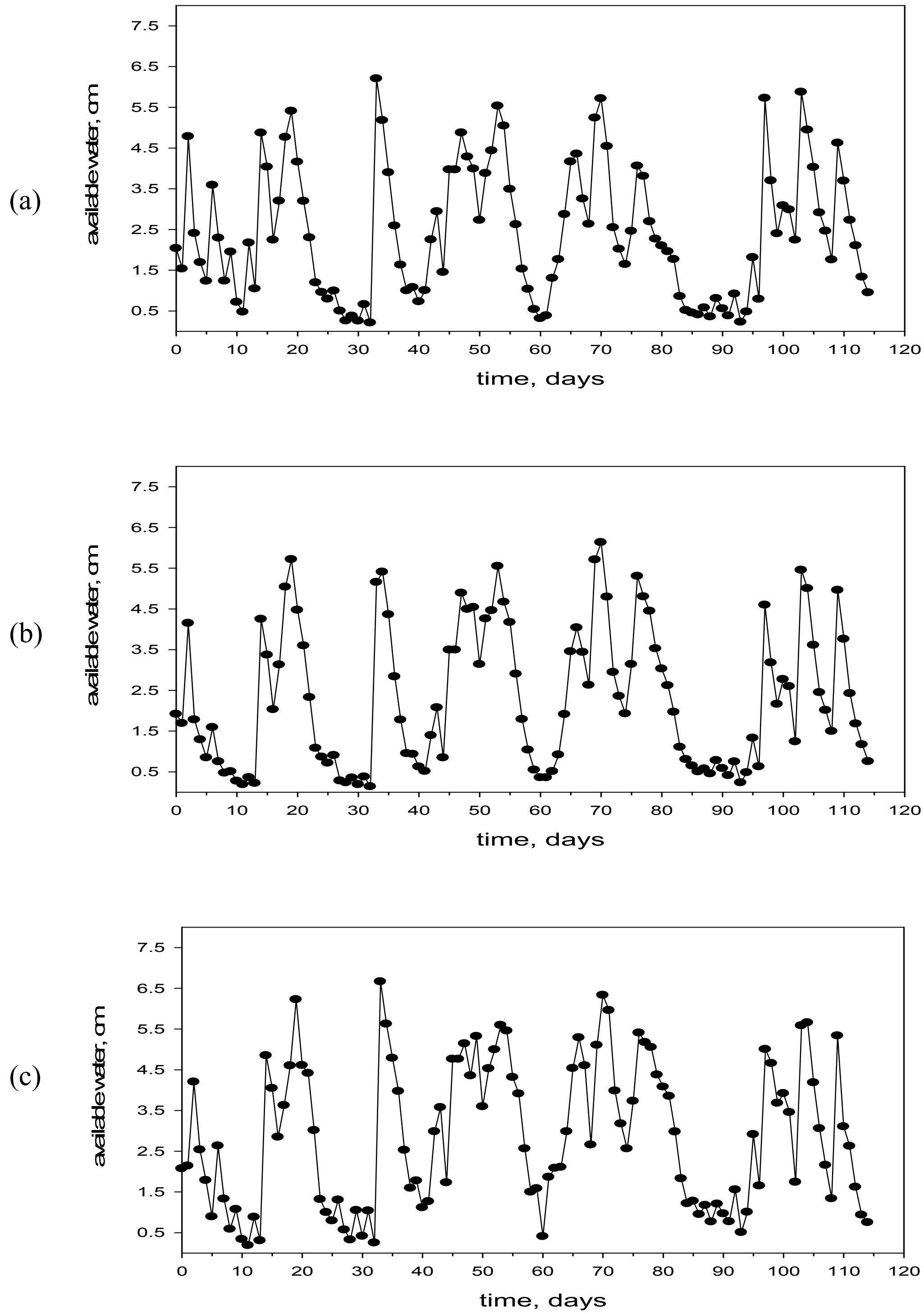


Fig. 2.14. Available water as a function of time in the 30 cm root zone depth for the 100% ET (a), 80% ET (b) and 60% ET (c) replacement for HB 129 (Thermal Blue) in 2006.

III. EVALUATION OF TURF COLOR QUALITY, ROOT LENGTH DENSITY AND ROOT MASS OF HYBRID BLUEGRASS AND TALL FESCUE UNDER IRRIGATION SCHEDULING

ABSTRACT

A 2-year field study was conducted at the turfgrass research facility, Auburn, AL to determine turf color quality, root length density and root dry mass of hybrid bluegrasses [Texas bluegrass (*P. arachnifera* Torr.) × Kentucky bluegrass (*Poa pratensis* L.)], HB 129 ('Thermal Blue'), HB 130, HB 328 and HB 329 ('Dura Blue') and the tall fescue (*Festuca arundinacea* Schreb.) cultivars, 'Green Keeper' and 'Kentucky 31'. These grasses were seeded during the fall of 2004. The experimental design was a 6 by 6 Latin square with six replicates of each treatment combination within an irrigation block. A total of 108 plots, measuring 1.5 m by 2.0 m each were established. Plots were irrigated at rate of 100, 80 and 60% of potential evapotranspiration. The turf quality values were determined using digital images collected once a week, while the root length density and root dry mass values were determined from root samples collected in July and September of 2005 and 2006. The research showed that the hybrid bluegrass performed better than tall fescue cultivars.

The ranking based on root length density and turf color quality was: HB 329 (best) > HB 130 > HB 328 > HB 129 > Kentucky 31 > Green Keeper. The results were inconclusive for the root dry mass.

INTRODUCTION

Turf Color Quality

Turf color is one of the major components of aesthetic quality and it is often evaluated in field studies. Traditional methods of determining turf color have often been based on visual ratings, usually on a scale of 1 to 9, with 1 representing yellow to brown turf and 9 representing optimal, dark green turf (Karcher and Richardson, 2003; 2005). Although visual rating is a quick and convenient method of determining turf color, the rating is subjective and may be prone to bias, especially for an inexperienced researcher. Even among experienced researchers, Karcher and Richardson (2003) reported relatively low correlations ($r < 0.68$) when rating the same turf plot for color. Horst et al. (1984), studying 10 evaluators for their ability to quantify turfgrass quality and color, determined that the variability among evaluators was greater than or equal to the variation among turfgrass cultivars. Digital image analysis provides an objective measure and this method has been used in recent years to quantify both percent turf coverage (Richardson et al., 2001) and turf color (Karcher and Richardson, 2003). Digital images includes information on the amount of red, green, and blue (RGB) light emitted for each pixel in the image. According to Karcher and Richardson (2003), the intensity of red and blue tends to confound how green an image appears. So to enhance interpretation of digital color data, RGB values are converted directly to hue, saturation, and brightness (HSB) values that are based on human perception of color. In the HSB system, hue is an angle on a continuous circular scale from 0 to 360° (0° = red, 60° = yellow, 120° = green, 180° = cyan, 240° = blue, 300° = magenta), saturation is the purity of the color from 0% (gray) to 100% (fully saturated color), and brightness is the relative lightness or darkness of the color from 0% (black) to 100% (white). A procedure has been outlined for the conversion of RGB to HSB using computer algorithms (Adobe Systems, 2002). If *MAX* equals the maximum of the (*R*, *G*, *B*) values and *MIN* the minimum, the following outlined sets of conditions are used:

$$Hue = \begin{cases} \text{undefined}, & \text{if } MAX = MIN \\ 60 \times \dfrac{G - B}{MAX - MIN} + 0, & \text{if } MAX = R \text{ and } G \geq B \\ 60 \times \dfrac{G - B}{MAX - MIN} + 360, & \text{if } MAX = R \\ 60 \times \dfrac{B - R}{MAX - MIN} + 120, & \text{if } MAX = G \\ 60 \times \dfrac{R - G}{MAX - MIN} + 240, & \text{if } MAX = B \end{cases}$$

$$Saturation = \begin{cases} 0, & \text{if } MAX = 0 \\ 1 - \dfrac{MIN}{MAX}, & \text{otherwise} \end{cases}$$

$$Brightness = MAX$$

Root Length Density

The importance of root systems in acquiring water has long been recognized as being crucial to cope with drought conditions (Carrow, 1996 a; Kashiwagi et al., 2006). The decrease in total number of roots and average root length (e.g. at high soil temperatures) reduces plant access to soil water and nutrients (Jordan et al., 2003). High root mortality is undesirable as dead roots provide a food source for soil microbes, which may result in increased respiration and reduced soil oxygen concentrations (Kuzyakov et al., 2001; Jordan et al., 2003). If turfgrasses could be selected with low-shoot-to-high-root ratios with deeper root penetration, significant gain in drought avoidance should be possible (Bonos et al., 2004). Higher soil temperature causes root length density to decline during the summer (Beard and Daniel, 1965) as a result of lower food reserves in the plant root system.

Drought Tolerance of Tall Fescue and Bluegrass Cultivars

Tall fescue (*Festuca arundinacea* Schreb.), a popular turfgrass grown in the northern, transitional, and upper to mid-southern climates of the USA, has been reported to have superior drought avoidance and is able to maintain growth and green color for longer periods between rainfall and irrigation events when compared to many cool-season species. Tall fescue is particularly popular in the transition zone between the adaptative areas of cool-season and warm-season grasses (Sleper and West, 1996). Much of the popularity of tall fescue can be attributed to its adaptation to a wide range of soil, climatic, and management conditions (Asay et al., 2001). Some tall fescue varieties have been reported to have better heat tolerance than many commonly used cool-season turfgrasses (Carrow 1996 a; Carrow and Duncan, 2003). Some studies reported greater drought resistance and avoidance characteristics including lower leaf firing i.e. the total percentage of chlorotic leaf area (Qian et al., 2004), greater rooting depth and higher root length density for ‘Rebel II’ and ‘Arid’ than for bluegrasses (Carrow, 1996 a, b). Under low maintenance, Qian and Engelke (1999) reported that minimum irrigation quantity to prevent drought stress and maintain acceptable quality for tall fescue was 50 to 70% of evaporation from class-A pan. Meyer and Gibeault (1987) reported a similar amount of irrigation replenishment (60% of wind-modified pan evaporation) as sufficient to maintain turf quality. Under intensive management conditions Carrow (1995) reported that irrigation at 80% of pan-evaporation was required to maintain turf quality. The effects of heat stress in combination with drought stress have been found to adversely impact photosynthesis, water relations, and root growth for tall fescue than either of the stresses alone (Jiang and Huang, 2001a, b).

Kentucky bluegrass (*Poa pratensis* L, KBG) is a cool-season grass species used extensively for athletic fields, lawns, and golf courses in the U. S. (Turgeon, 2002). It has good turf quality and forms attractive turf when supplied with adequate water (Meyer and Funk, 1989) but has moderate to low drought resistance (Beard, 1989); hence it requires frequent irrigation to withstand hot and arid summers. The grass usually goes dormant and loses color during periods of high temperature and drought. The lack of drought resistance restricts its use under water deficit conditions (Abraham et al., 2004). Meyer and Gibeault (1987) found that the quality of KBG decreased significantly when irrigated at 60% of wind-modified pan evaporation. While tall fescue has good drought resistance, it is not as fine textured as KBG. Furthermore, some turfgrass managers and home owners prefer the finer texture and recuperative capacity that KBG offers (Bremer et al., 2006).

Hybrid bluegrasses (HBG) are genetic crosses between KBG and Texas bluegrass (*Poa arachnifera* Torr., TBG). The HBG have the desirable appearance of KBG, i.e., fine texture, and like TBG, may withstand higher temperatures and extended drought without going dormant (Abraham et al., 2004; Bremer et al., 2006; Su et al., 2004). Some HBGs have been reported to exhibit lower water-use compared to other cool-season species while maintaining their green color (Supplick-Ploense and Qian, 2005). The latter is important given the increasing competition for water and the rising costs of irrigation (Bremer et al., 2006). Read et al. (1994) reported that in warm season climates such as in the South, Texas bluegrass × Kentucky bluegrass hybrids maintain green color all year long and use significantly less water than many cool-season species. The latter is important given the increasing competition for water and the rising costs of irrigation. One such hybrid is 'Reveille' developed by Texas Agricultural Experiment Station (Read et al., 1999). It has been found to be well adapted to golf courses, home lawns, and commercial and industrial parks. Its foliar characteristics are similar to Kentucky bluegrasses but acts like Texas bluegrasses, as it thrives under heat stress and hot sun, tolerates cold weather and uses less water (Read et al., 1999). Abraham et al. (2004) found that Reveille possesses significantly more extensive root system and lower evapotranspiration compared to Kentucky bluegrass. Two other hybrid bluegrasses HB 129 and HB 329 were recently released by The Scotts Company, Inc. (Carson, 2004). A preliminary evaluation at Auburn University has indicated that these hybrids are able to withstand high summer heat while maintaining good color. Field evaluation by Dane et al. (2006) showed that these hybrid bluegrasses were able to survive stress periods better than tall fescue cultivars. In their study, they subjected HB 129, HB 329, 'Southeast' and 'Rebel III' tall fescue to irrigation at soil water matric head minima of -300 and -600 cm of water pressure, and no irrigation. These treatments represented no, intermediate, and high water stress, respectively. They concluded that the two hybrid bluegrasses were superior to the tall fescue cultivars in their ability to distribute water uptake and to maintain their desirable characteristics (minimal browning). Other hybrids, including HB 130 and HB 328, are experimental lines undergoing research evaluation. Although there is a good potential for using hybrid bluegrasses in lawn and golf courses, sufficient scientific data are lacking on their performance compared to that of tall fescue when subjected to deficit irrigation.

Although HBGs have potential for lawns and golf courses, there is little scientific information available about their performance relative to KBG and tall fescue under different climatic stresses or cultural practices (Bremer et al., 2006). Furthermore, some researchers have often reported contradicting results of HBG performance compared to other cool-season grasses. A study by Su et al. (2004) revealed that HB 129 maintained a higher quality than ‘Dynasty’ tall fescue and ‘Apollo’ KBG cultivar, under high temperatures in a growth chamber. Bremer et al. (2006) reported a better adaptation of tall fescue as compared to HBG in some transition zones with deep soils. Other trials by Stier et al. (2005) in the upper Midwest showed the mean turf color quality of two HBGs, HB 129 and HB 329, to be similar to those of KBG (‘Apollo’ and ‘Unique’) and two tall fescue cultivars (‘Masterpiece’ and ‘Rembrandt’) when mowed at 2.5, 5, and 7.5 cm heights and fertilized with N at either 48 or 144 kg ha^{-1} y^{-1}. Other HBGs, including HB 130 and HB 328 are still experimental lines.

The objectives of this experiment were to i) determine the turf color quality, root length density and root dry mass and ii) compare the performance of the hybrid bluegrasses (HB 129, HB 130, HB 328 and HB 329) with tall fescue cultivars (Green Keeper and Kentucky 31).

MATERIALS AND METHODS

Location of the Experiment

The location of the experiment was the Auburn University Turfgrass Research Facility, Auburn, AL on a Marvyn loamy sand (Fine-loamy, siliceous, thermic Typic Kanhapludults). Six cool-season turf cultivars, viz., four hybrid bluegrasses (HB 129, HB 130, HB 328 and HB 329) and two tall fescue cultivars (Kentucky 31 and Green Keeper) were seeded during the fall of 2004. The experimental design was a 6 by 6 Latin square with six replicates of each treatment combination within an irrigation block. Each of the Latin squares measured 14 m × 16 m and in total there were 108 plots (36 per Latin square) each measuring 1.5 × 2.0 m with buffer strips planted to separate the blocks and the plots. Three ET-based irrigation replacements were applied to meet 100%, 80% and 60% of potential evapotranspiration and irrigation was treated as an external variable. The daily ET values were calculated with the Penman-Monteith formula (Allen et al., 1998) from daily mean air temperature, net solar radiation, relative humidity, and wind speed. These weather data were obtained from a weather station located within two kilometers of the experimental site and maintained by the Agricultural Weather Information Service (AWIS Weather Services, Inc., http://www.awis.com).

Turf Color Determination

To determine the turf color turf images were taken with the aid of a Canon Power Shot G2 digital camera (Canon Inc., Tokyo, Japan), with settings comprising a shutter speed of 1/640 s, an aperture of F4.5, and a focal length of 21 mm. The images were collected by the researchers standing immediately next to the plot while holding the camera at 1.5 m above the turf canopy. This was done once a week for a period of 14 weeks (June 14 through September 20, 2005 and June 13 through September 21, 2006). The images were collected between 9 and 10 a.m. under well illuminated conditions with care to avoid casting shadow on the canopy. The image format was JPEG, with a color depth of 16.7 million colors, and an image size of 2272 × 1704 pixels (about 2.6 megabytes per image). The average RGB levels of the digital images were calculated using SigmaScan Pro version 5.0 software (SPSS, 1999). The digital values of RGB were exported to a MS Excel spreadsheet (Microsoft Corporation, 1999) and using programmed formula, the RGB which are measured on a scale of 0-255 were converted to percentages by dividing each cell by 255. Based on an Adobe Systems (2002) algorithm, described previously, the percent RGB values were converted to HSB values.

Determination of Root Length Density and Mass

Root samples were collected from each plot in July during the early part of the experiment and again in September before terminating the experiment for that year. The sampling depth was 0-10 cm below the surface, with a 2.5 cm diameter core sampler and root excavation was done after scooping out thatch. Prior to each sampling date, about 25 mm depth of irrigation water was added uniformly to the plots in order to loosen the soils and roots. Upon collecting the samples, they were immediately packed in polyethylene bags for preservation in a freezer. To prepare the roots for analysis, the samples were first allowed to thaw overnight. The roots were separated from the soil mass by running tap water on the root-soil mass placed on a 2 mm wire-mesh screen. Sand, silt and clay material would pass through the sieve opening leaving the roots, and gravel on the screen. The gravel was then handpicked and discarded, leaving clean roots. Before scanning, the roots were rinsed, dried using blotting paper and placed in sample bottles. The very fine roots were stained with Congo red dye. During the measurements, the roots were carefully spread on a Comair root scanner (Commonwealth Aircraft Corporation Limited, Melbourne, Australia), calibrated to known lengths and widths of thread. The scanner has a built-in algorithm to calculate root length. Root length density (RLD) was eventually calculated by dividing total root length in centimeters by the volume of the sampler in cubic centimeters. Root dry mass (RDM) was recorded after oven drying for 72 h (to constant weight) at 80 °C.

Statistical Analysis

Mixed models methodology as implemented in PROC MIXED of PC SAS Version 9.13 (SAS Institute, 2006) was used to analyze the response data. For RLD and RDM this involved analysis as a replicated Latin square (cultivars=6, rows=6, columns=6), where irrigation was treated as an environmental factor with three levels. Thus the *F*-test for main effects of irrigation is questionable but all interaction effects involving irrigation may be tested. Irrigation, cultivar, year (2005, 2006), sampling month (July, September), and their interactions were treated as fixed effects. Following the arguments presented by Piepho et al. (2003) column (irrigation level) and row (irrigation level) were treated as random effects because they are based on randomization events. Serial correlation among sampling dates was modeled using the repeated option with various covariance structures. The AICC criterion was used to pick the best-fitting model (Littell et al., 2006). Higher order interactions (4-, and 3-way) were eliminated from the model if $P \geq 0.25$. In case of significant interactions ($P < 0.001$), cultivars were compared using the SLICE option (Littell et al., 2006). Because only two columns, the plots with tensiometers sets (see Fig. 1.1) per irrigation treatment were sampled for turf color, mixed models analysis was based on a RCB design (r=2). In all other respects, analysis was similar to RLD and RDM. Multiple comparison procedures involved the "simulation" option with LSmeans of PROC MIXED. This process uses a simulation approach to adjust the P-values such that the stated Type I error and actual Type I error are close based on the number of comparisons made. If no adjustment is made, too many differences are declared significant since Type I error rate is inflated (Littell et al., 2006).

RESULTS AND DISCUSSIONS

Environmental Conditions

The mean monthly air temperature, solar radiation, relative humidity, wind speed, total precipitation and potential evapotranspiration for the summer months (June-September) in 2005 and 2006 are summarized in Table 3.1. Total precipitation was (539.8 mm) for 2005 and (294.1 mm) for 2006. Compared to the 30-yr (1971-2000) average for the same period (459.0 mm), these results suggest an extreme dry summer for 2006 and a somewhat drier summer than normal for 2005. Mean solar radiation was higher for each month in 2006 than in the corresponding months of 2005. A similar trend was observed for the average air temperature, except for the month of September. The mean monthly relative humidity was lower for each month in 2006 compared to 2005. The higher mean monthly solar radiation could have been the direct cause of higher mean monthly air temperature and lower mean relative humidity in 2006 compared to 2005. The mean monthly wind speeds for the 2 years were comparable. The calculated potential evapotranspiration was higher in 2006 than in 2005.

Root Dry Mass and Root Length Density

The root length density and root dry mass were determined for samples collected in June and September of 2005 and 2006, at a sampling depth from 0-10 cm. In the initial run we included all possible interactions between irrigation replenishment (I), cultivar (C), year (Y) and month (M). The 4-way interactions were non-significant ($P > 0.5$) and were eliminated from the model. The 3-way interactions were all non-significant ($P > 0.5$) and were also eliminated resulting in a model with main effects and 2-way interactions only. For root dry mass, only effects related to sampling month and year were significant ($P < 0.001$; Table 3.2). None of other effects in the model had a $P < 0.12$; hence this response variable will not be discussed any further.

The root length density over the entire 2-year period was significantly ($P = 0.001$) affected by year, month, and cultivar (Table 3.2). As indicated earlier, 3- and 4-way interaction were not significant ($P > 0.50$) and were consequently dropped from the model (data not shown). The irrigation x cultivar interaction had a $P = 0.17$ (Table 3.2). The only important ($P \leq 0.15$) 2-way interactions involving cultivars were the cultivar x month and the cultivar x year interaction (Table 3.2). The Slice option (Littell et al., 2006) was invoked for these interaction means to test month and year effects separately for each cultivar (data not shown). The effect of sampling month (July vs. September) was significant ($P \leq 0.0001$) for every cultivar. In every case the root length density was significantly larger in July than in September (Fig. 3.1, top panel), confirming what is known about root development in cool season grasses during summer. The average root length density across the cultivar was higher in 2005 (7.0 cm cm^{-3}) than 2006 (6.3 cm cm^{-3}). Although year 2006 was dryer than 2005, a higher irrigation rate and more evenness of water application in 2006 may have decreased water stress for each of the turf cultivars leading to a lower mean root length density. Frequent irrigation has been reported to encourage shallow rooting (Madison and Hagan, 1962; Shearman and Beard, 1973), while infrequent irrigation enhance root development on cool-season grasses including bluegrasses (Bennett and Doss, 1960; Madison and Hagan, 1962).

The year effect in C × Y interaction was significant for all cultivars except HB 329 ($P = 0.714$) and HB 328 ($P = 0.084$); root length density was higher (Fig. 2.1 bottom panel) during the close-to-normal year (2005) compared to the extreme dry and hot year 2006, again confirming what is known about root development in response to temperature. In both cases, the significant interaction is primarily a magnitude effect. The cultivar rankings in July and September were identical and almost identical for 2005 and 2006; the only change in rank was for cultivars HB 328, which ranked 3rd in 2005 and 4th in 2006 and HB 329, which switched ranks with HB 328 in 2006. This justifies a main effects only model.

The results for pair-wise comparison showed that in the 2-year period the root length density for HB 130 (average RLD = 8.9 cm cm^{-3}) was significantly ($P \leq 0.001$) higher than that of any other cultivar except HB 129 (Table 4). HB 129, the entry with the second highest RLD of 7.7 cm cm^{-3} had a significantly higher root length density ($P \leq 0.001$) than the tall fescues Green Keeper and Kentucky 31 but did not differ significantly from the remaining hybrid bluegrasses. HB 129 had root length density greater ($P = 0.05$) than that of Kentucky 31. The root length density ranking using the combined means for the 2-year period was HB 130 (8.5 cm cm^{-3}) > HB 129 (7.4 cm cm^{-3}) > HB 329 (7.0 cm cm^{-3}) > HB 328 (6.6 cm cm^{-3}) > Green Keeper (5.3 cm cm^{-3}) > Kentucky 31

(5.1 cm cm^{-3}). Even though not statistically significant, these hybrid bluegrass entries (HB 329 and HB 328) had higher root length densities than the tall fescues, suggesting a general pattern of higher root length densities in hybrid bluegrasses compared to tall fescues. Drought resistance has been correlated with root length, extensive root system or root length density in field crops (Asch et al., 2005; Kashiwagi et al., 2006) and turfgrass (Carrow 1996b; Huang and Gao, 2000; Levitt, 1980; White et al., 1993).

Turf Color Quality

For the entire 2-yr period turf color quality was significantly ($P = 0.05$) different for cultivar (C), year (Y), and week (W). The 4-way interactions among the factors were not significant for any of the three color response variables and hence, this interaction was eliminated from the model (data not shown). The 3-way interactions I × C × Y and C × W × Y were significant, but I × W × Y and I × C × W were not (Table 2.4). For the significant ones, we opted to leave out I × C × Y since as discussed earlier, the ANOVA showed non-significance of irrigation on any response variable. We were left with C × W × Y as the only important 3-way interaction. The C × W × Y interaction has the same main factors as the 2-way interactions C × Y and C × W which are discussed in more details later. Therefore, this interaction will not be discussed any further.

Among the 2-way interactions involving irrigation, only I × C interaction is of interest in the context of evaluating the color response of cultivar. There was no indication ($P > 0.46$) of a differential response to irrigation among cultivars and hence, it will not be discussed any further. The C × Y and C × W interactions were both significant ($P \leq 0.001$) indicating that the turf color trait differences among cultivars were dependent on the year and time of year. Pair-wise comparisons of the turf color traits hue, saturation and brightness (Table 2.5) were evaluated using the simulation option in LSMEAN of PROC MIXED. The average hue for all the cultivars in 2005 was 77° with a range from 69° to 83°. These were slightly higher for 2006, with an average of 80° and a range from 75° to 83 °. All the hybrid bluegrass cultivars had significantly ($P \leq 0.032$) higher hue values than 'Kentucky 31' and 'Green Keeper' tall fescue cultivars in 2005. The ranking of cultivars based on hue angle in 2005 was: HB 328 (83.1°) > HB 329 (82.5°) > HB 129 (78.5°) > HB 130 (77.3°) > Kentucky 31 (71.7°) > Green Keeper (68.9°). While the hue values for all the hybrid bluegrass cultivars remained nearly the same during the 2-yr experimental period, tall fescue (Green Keeper and Kentucky 31) cultivars had considerable hue increase in 2006, changing the ranking based on hue values: HB 329 (83.5°) > Green Keeper (82.8°) > Kentucky 31 (82.7°) > HB 328 (79.4°) > HB 130 (76.4°) > HB 129 (75.4°).

The average saturation for the turf cultivars was lower in year 2005 (37.5 %) than 2006 (38.8 %). There was no particular trend in saturation for the 2-yearr experimental period. Three hybrid blue grasses, HB 328, HB 130 and HB 129 had significantly ($P \leq 0.001$) higher saturation than Green Keeper in 2005. However, there were no significant differences observed in saturation between any two cultivars during year 2006. The effect of water distribution may have eliminated any differences in saturation between cultivars. The ranking based on mean saturation was HB 329 (41.2 %) > Kentucky 31 (40.9 %)> HB 328 (39.8 %) > HB 130 (39.5 %) >HB 129 (35.7 %) > Green Keeper (31.7 %).

For all cultivars, except Green Keeper tall fescue, the brightness values were slightly higher in year 2006 (average 54.4 %) compared to 2005 (average 54.0 %) (Table 2.5).

HB 129 had higher (P = 0.005) brightness than Kentucky 31, while that of HB 130 was higher compared to Green Keeper. Ranking of means based on brightness value was as follows: HB 130 (54.8%) >HB 129 (54.7%) > HB 328 (54.3%) HB 329 (54.0%) > Kentucky 31 = Green Keeper (53.6%). We performed a mean turf quality rating by simply ranking cultivars based on hue, saturation, and brightness. We assigned numbers (1= highest, 6 =lowest) and hence calculated the average. We found the rating to be higher for hybrid bluegrasses compared to tall fescue cultivars (data not shown). The ranking for turf quality was as follows: HB 329 (best) > HB 328 > HB 130 > HB 129> Kentucky 31 > Green Keeper. The ranking based on root length density and turf quality was: HB 329 (best) > HB 130 > HB 328 > HB 129 > Kentucky 31 > Green Keeper.

The results of this study showed that hybrid bluegrasses performed better in terms of root length density and turf color quality, and would withstand drought better than tall fescue cultivars. Furthermore, the authors suggest that hybrid bluegrass cultivars were able to withstand summer heat better than tall fescue. This is collaborated by visual observations and digital pictures which showed considerable browning for the tall fescue plots, but not for hybrid bluegrasses. These results are in agreement with those of other researchers (Abraham et al., 2004; Dane et al., 2006; Read et al., 1994) who reported good performance of hybrid bluegrasses compared to other cool season cultivars.

SUMMARY AND CONCLUSIONS

The root dry mass, root length density and turf color quality for the hybrid bluegrasses HB 129, HB 130, HB 328, and HB 329 and tall fescue cultivars, Green Keeper, and Kentucky 31 were evaluated. Turf color quality was determined from digital images which were analyzed with SigmaScan Pro. Root length density was analyzed using a Comair root scanner while root dry mass from oven-dry weight of collected root samples. Irrigation treatments did not significantly affect turf quality, root length density or root dry mass. The turf color quality and root length density varied significantly among the cultivars but not the root dry mass. The study showed that hybrid bluegrass performed better than tall fescue cultivars. The ranking based on root length density and turf color quality was:

HB 329 (best) > HB 130 > HB 328 > HB 129 > Kentucky 31 > Green Keeper.

REFERENCES

Abraham, E.M., B. Huang, S.A. Bonos, and W.A. Meyer. 2004. Evaluation of drought resistance for Texas bluegrass, Kentucky bluegrass, and their hybrids. Crop Sci. 44:1746–1753.

Adobe Systems. 2002. Adobe Photoshop v. 7.0. Adobe Systems, San Jose, CA.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrig. and Drain. FAO, Rome.

Asay, K.H., K.B. Jensen, and B.L. Waldron. 2001. Responses of tall fescue cultivars to an irrigation gradient. Crop Sci. 41:350–357.

Asch, F, M. Dingkuhn, A. Sow, and A. Audebert. 2005. Drought-induced changes in rooting patterns and assimilate partitioning between root and shoot in upland rice. Field Crop Res. 93: 223-236.

Beard, J.B. 1989. Turfgrass water stress: Drought resistance components, physiological mechanisms, and species-genotype diversity. p. 23–28. *In* Takatoh H. (ed.) Proc. Japanese Soc. Turfgrass Sci., Tokyo, Japan.

Beard, J.B., and W.H. Daniel. 1965. Effect of temperature and cutting height on the growth of creeping bentgrass (*Agrostis palustris* Huds.) roots. Agron. J. 5:249-250.

Bennett, O.L., and B.D. Doss. 1960. Effect of soil moisture level on root distribution of cool-season forage species. Agron. J. 52:204–207.

Bonos S.A., D.Rush, K. Hignight and W.A. Meyer. 2004. Selection for deep root production in tall fescue and perennial ryegrass. Crop Sci. 44:1770–1776.

Bremer, D. J., K. Su, S. J. Keeley, and J. D. Fry. 2006. Performance in the transition zone of two hybrid bluegrasses compared with Kentucky bluegrass and tall fescue. Applied Turfgrass Science.10:1094.

Carrow, R.N. 1995. Drought resistance aspects of turfgrasses in the southeast: ET and crop coefficients. Crop Sci. 35:1685–1690.

Carrow, R.N. 1996 a. Drought avoidance characteristics of diverse tall fescue cultivars. Crop Sci. 36:371–377.

Carrow, R.N. 1996 b. Drought resistance aspects of turfgrasses in the Southeast: Root-shoot responses. Crop Sci. 36:687–694.

Carrow, R.N., and R.R. Duncan. 2003. Improving drought resistance and persistence in turf-type tall fescue. Crop Sci. 43:978-984.

Carson, T. 2004. Beating the heat but not the blues. Golf Course Management, September issue.

Dane, J.H., R.H. Walker, L. Bahaminyakamwe and J.L. Belcher. 2006.Tall fescue and hybrid bluegrass response to soil water matric head limits. Agricultural Water Management. 86:177-186.

Horst, G.L., M.C. Engelke, and W. Meyers. 1984. Assessment of visual evaluation techniques. Agron. J. 76:619–622.

Huang, B. and H. Gao. 2000. Root physiological characteristics associated with drought resistance in tall fescue cultivars. Crop Sci. 40:196-203.

Jordan, J.E., R.H. White, D.M. Vietor, T.C. Hale, J.C. Thomas, and C.M. Engelke. 2003. Effect of irrigation frequency on turf quality, shoot density, and root length density of five bentgrass cultivars. Crop Sci. 43:282–287.

Jiang, Y., and B. Huang. 2001 a. Drought and heat stress injury to two cool-season turfgrasses in relation to antioxidant metabolism and lipid peroxidation. Crop Sci. 41:436-442.

Jiang, Y., and B. Huang. 2001 b. Physiological responses to heat stress alone or in combination with drought: A comparison between tall fescue and perennial ryegrass. HortScience. 36:682–686.

Karcher, D.E., and M.D. Richardson. 2003. Quantifying turfgrass color using digital image analysis. Crop Sci. 43:943–951.

Karcher, D.E., and M.D. Richardson. 2005. Batch analysis of digital images to evaluate turfgrass characteristics. Crop Sci. 45:1536–1539.

Kashiwagi, J., L. Krishnamurthy, J.H. Crouch and R. Serraj. 2006. Variability of root characteristics and their contributions to seed yield in chickpea (*Cicer arietinum* L) under terminal drought stress. Field Crops Res. 95:171-181.

Kuzyakov, Y., H. Ehrensberger, and K. Stahr. 2001. Carbon partitioning and below ground translocation by *Lolium perenne*. Soil Biol. Biochem. 33:61–74.

Levitt, J. 1980. Responses of plants to environmental stresses. Vol. II. Academic Press, New York.

Littell, R.C, G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS for Mixed Models. 2nd ed. SAS Inst., Cary, NC.

Madison, J.H., and R.M. Hagan. 1962. Extraction of soil moisture by Merion bluegrass (*Poa pratensis* L. 'Merion') turf, as affected by irrigation frequency, mowing height, and other cultural operations. Agron. J. 54:157–160.

Meyer, W.A., and C.R. Funk. 1989. Progress and benefits to humanity from breeding cool-season grasses for turf. *In* Contributions from Breeding Forage and Turf Grasses. Crop Sci. Soc. Am. Spec. Publ. No.15. Madison, WI.

Meyer, J.L., and V.A. Gibeault. 1987. Turfgrass performance when under irrigated. Appl. Agric. Res. 2:117–119.

Piepho, H.P., A. Buchse, and K. Emrich. 2003. A hitchhiker's guide to mixed models for randomized experiments. J. Agron. and Crop Sci. 189:310-322.

Qian, Y., and M.C. Engelke. 1999. Performance of five turfgrasses under linear gradient irrigation. HortScience 34:893–896.

Qian, Y. L., R. F. Follett, S.Wilhelm, A. J. Koski, and M. A. Shahba. 2004. Carbon isotope discrimination of three Kentucky bluegrass cultivars with contrasting salinity tolerance. Agron J. 96:571-575.

Read, J. C., D. Walker, and B. W. Hipp. 1994. Potential of Texas bluegrass × Kentucky hybrids for turfgrass. Agronomy Abstracts. ASA, Madison, WI.

Richardson, M.D., D.E. Karcher, and L.C. Purcell. 2001. Quantifying turfgrass cover using digital image analysis. Crop Sci. 41:1884–1888.

SAS Institute. 2006. SAS user's guide: Statistics. v. 9.1.3. SAS Inst., Cary, NC.

Shearman, R.C., and J.B. Beard. 1973. Environmental and cultural preconditioning effects on the water use rate of *Agrostis palustris* Huds. Crop Sci. 13:424–427.

Sleper, D.A., and C.P. West. 1996. Tall fescue. p. 471–502. *In* Moser L.E. (ed.) Cool-season forage grasses. Agron. Mon. 34. ASA, CSSA and SSSA, Madison, WI.

Stier, J. E., Koeritz, and Frelich, J. 2005. Fertility and mowing response of heat tolerant bluegrass and tall fescue in the upper Midwest. *In* Annual meetings abstracts. ASA, CSSA, and SSSJ, Madison, WI.

Su, K., D. J. Bremer, S. J. Keeley, and J. D. Fry. 2004. High temperature and drought effects of a Texas bluegrass hybrid compared with Kentucky bluegrass and tall fescue. *In* Annual meetings abstracts. ASA, CSSA, and SSSA, Madison, WI.

Supplick-Ploense, M. R., and Qian, Y. 2005. Evapotranspiration, rooting characteristics, and dehydration avoidance: Comparisons between hybrid bluegrass and Kentucky bluegrass. Int. Turfgrass Soc. Res. J. 10:891-898.

SPSS. 1999. Sigma Scan Pro v. 5.0. SPSS Science Marketing Dep., Chicago, IL.

Turgeon, A.J. 2002. Turfgrass management. 6th ed. p. 1-20. Prentice Hall, Englewood Cliffs, NJ.

White, R.H., A.H. Bruneau and T.J. Cowett. 1993. Drought resistance of diverse tall fescue cultivars. Int. Turfgrass Soc. Res. 7:607–613.

Table 3.1. Monthly and total seasonal average weather conditions during the experimental period from June to September 2005 and 2006 at Auburn, Alabama. Evapotranspiration, precipitation and applied irrigation are given as monthly (seasonal) totals.

Month	Air temp.	Solar rad.	Rel. humidity	Wind speed	ET	Prec.	Irrigation (% ET) 100	80	60
	ºC	MJ $m^{-2}d^{-1}$	%	ms^{-1}	------------------- mm --------------------				
				2005					
June	24.8	17.7	98.7	6.7	181.1	147.6	82.6	66.0	49.5
July	26.0	17.9	100.0	7.6	184.7	191.3	15.2	12.2	9.1
Aug	25.4	18.2	98.2	7.2	193.4	158.0	18.5	14.8	11.1
Sept	25.4	18.0	98.2	7.2	190.1	42.9	101.6	81.3	61.0
Season	25.4	18.0	98.8	7.2	749.3	539.8	217.9	174.3	130.8
				2006					
June	26.1	27.3	58.3	8.2	228.6	123.4	121.2	96.9	72.7
July	28.1	24.3	64.0	7.1	209.8	85.3	118.6	94.9	71.2
Aug	27.9	22.3	70.3	7.0	177.0	34.8	25.4	20.3	15.2
Sept	23.3	19.3	66.4	6.7	172.7	50.5	50.8	40.6	30.5
Season	26.3	23.3	64.7	7.2	788.1	294.1	316.0	252.8	189.6

Table 3.2. Results from mixed models analysis of variance for root mass and root length density (RLD). Four- and three-way interactions were dropped from the model because of *P*-values ≥ 0.50.

Source of	Degrees of freedom		P > F	
variation	Numerator	Denominator	Root mass	RLD
Irrigation (I)	2	16	0.144	0.059
Cultivar (C)	5	160	0.382	<0.001
I × C	10	160	0.937	0.170
Year (Y)	1	160	<0.001	<0.001
I × Y	2	160	0.683	0.001
C × Y	5	160	0.373	0.060
Month (M)	1	207	<0.001	<0.001
I × M	2	207	0.120	0.437
C × M	5	207	0.295	0.027
M × Y	1	207	<0.001	0.056

Table 3.3. Pair-wise differences for root length density (RLD) among four hybrid bluegrass cultivars (HB 129, HB 130, HB 328, HB 329) and two tall fescue cultivars (Green Keeper, Kentucky 31). Differences are given below the diagonal and P-values above the diagonal. Adjusted P-values were calculated using the simulation option within LSMEANS of SAS® PROC MIXED).

Cultivar	HB 129	HB 130	HB 328	HB 329	G. Keeper	KY 31	Avg. RLD ($cmcm^{-3}$)
HB 129		0.083	0.307	0.618	0.001	< 0.001	7.7
HB 130	1.19		< 0.001	0.001	< 0.001	< 0.001	8.9
HB 328	-0.91	2.10		0.996	0.215	0.093	6.8
HB 329	-0.69	-1.88	0.22		0.071	0.024	7.1
G. Keeper	-1.91	-3.10	-1.00	1.22		0.999	5.8
KY 31	-2.08	3.27	1.17	1.39	0.17		5.7

Table 3.4. Results from mixed models analysis of variance for turf color response variable hue, saturation, and brightness. Four-way interactions were dropped from the model because *P*-values ≥ 0.25.

Source of	Degrees of freedom		*P* > F		
variation	Num	Den	Hue	Saturation	Brightness
Irrigation (I)	2	3	0.686	0.129	0.495
Cultivar (C)	5	15	<0.001	<0.001	<0.001
I × C	10	16	0.551	0.872	0.461
Year (Y)	1	3	0.009	0.001	0.122
I × Y	2	3	0.126	0.090	0.848
C × Y	5	585	<0.001	<0.001	<0.001
I × C × Y	10	585	<0.001	<0.001	0.019
Week (W)	13	585	<0.001	<0.001	<0.001
I × W	26	585	0.008	0.005	0.090
C × W	65	585	<0.001	<0.001	0.001
I × C × W	130	585	1.000	1.000	0.829
W × Y	12	585	<0.001	<0.001	<0.001
I × W × Y	24	585	<0.001	0.007	0.221
C × W × Y	60	585	<0.001	<0.001	<0.001

Table 3.5. Probability of pair-wise differences for hue, saturation, and brightness among hybrid bluegrasses and tall fescue cultivars). For each trait, adjusted P-values for 2005 are given above the diagonal and for 2006 below the diagonal. These values were calculated using the simulation option within LSMEANS of SAS® PROC MIXED).

							Average	
Cultivar	HB 329	G. Keeper	HB 130	HB 328	KY 31	HB 129	2005	2006
				Hue				
							--- degree ---	
HB 329		<0.001	0.053	1.000	<0.001	0.213	83	83
G. Keeper	1.000		0.001	<0.0001	0.703	<0.001	69	83
HB 130	0.003	0.008		0.025	0.032	0.999	77	76
HB 328	0.187	0.389	0.516		<0.001	0.110	83	79
KY 31	1.000	1.000	0.009	0.419		0.007	72	83
HB 129	0.001	0.002	1.000	0.197	0.002		78	75
				Saturation				
							--- % ---	
HB 329		0.005	0.026	0.970	1.000	0.006	42	40
G. Keeper	0.011		<0.001	<0.001	0.015	<0.001	29	34
HB 130	0.989	0.083		0.251	0.009	0.998	37	42
HB 328	0.858	0.214	1.000		0.741	0.055	39	40
KY 31	1.000	0.013	0.995	0.897		0.001	41	41
HB 129	0.987	0.085	1.000	1.000	0.995		36	35
				Brightness				
							--- % ---	
HB 329		0.960	0.041	0.954	0.991	0.023	54	54
G. Keeper	0.037		0.349	1.000	0.449	0.218	54	53
HB 130	0.484	<0.001		0.367	0.005	1.000	55	55
HB 328	0.997	0.005	0.948		0.433	0.229	54	55
KY 31	0.873	0.475	0.038	0.355		0.003	53	54
HB 129	0.963	0.003	0.993	1.000	0.211		55	55

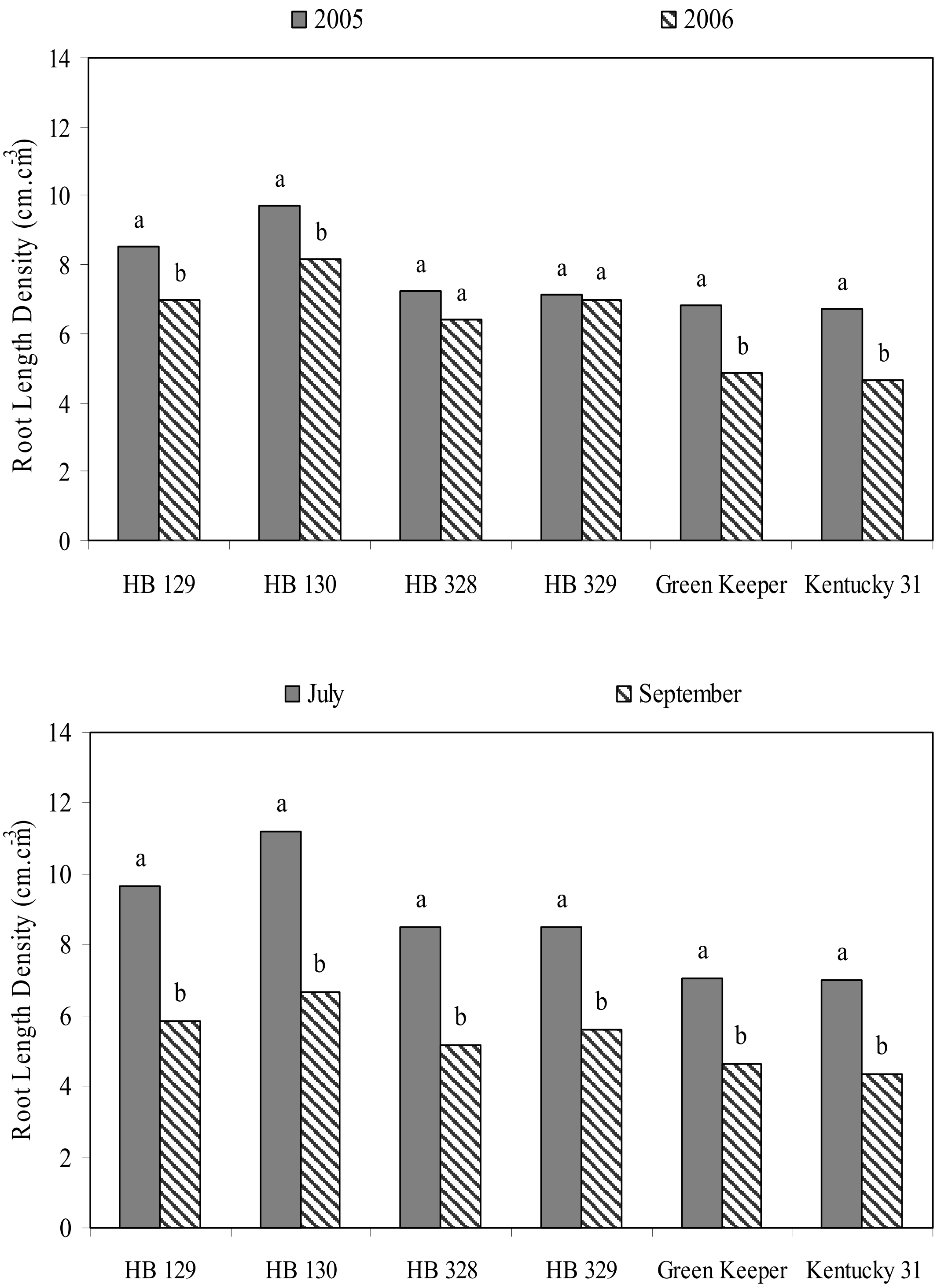


Fig. 3.1. Cultivar x month (top panel) and cultivar x year (bottom panel) interaction means for root length density.

IV. EVALUATION OF PHYSICAL AND HYDRAULIC PROPERTIES OF INORGANIC AMENDMENTS USED IN TURFGRASS ROOT ZONES

ABSTRACT

Root zone amendments offer a number of benefits for improving sand-based root zones. Inorganic amendments are more suitable than organic amendments because of their resistance to biodegradation. The objectives of this study were i) to evaluate and compare the physical and hydraulic properties of un-amended sand (100% sand) and seven commercially available inorganic amendments used in sand-based root zones, viz., zeolites (Clinolite and Ecolite), calcined diatomaceous earth (Isolite and Axis) and calcined clays (Moltan plus, Profile, and Pro’s Choice), and ii) to evaluate the physical and hydraulic properties of amendment-sand mixtures (15% amendment with 85% sand v/v). The physical and hydraulic properties analyzed were bulk density, particle density, porosity, particle size distribution, saturated hydraulic conductivity, water retention and available water. All amendments and mixtures had properties that closely matching the requirements of the USGA root zone requirements. Calcined diatomaceous earths showed comparatively superior physical and hydraulic characteristics, including water retention and available water, with the Axis amendment showing the best properties. Available water determined by a standard laboratory method showed lower values compared to the bioassay method, suggesting more water in pores than can be extruded using the laboratory method but which is accessible to plant roots.

INTRODUCTION

Sports fields are usually constructed on sand-based root zones which provide an ideal medium for turf systems with respect to physical and hydraulic characteristics, viz., high infiltration and hydraulic conductivity that enhance rapid drainage, reduced soil compaction, and increased aeration for root growth (Beard, 1973; Bingaman and Kohnke, 1970). However, sand has low water and nutrient holding capacities, which leads to water and nutrient stresses in the root zone that may lower turf quality. Taylor and Blake (1981) reported that when sand is subjected to years of continuous traffic, individual sand particles can be displaced and become tightly packed.

Root Zone Specification for Putting Green

The United States Golf Association, (USGA ,1993) has provided specifications for root zone construction for golf putting greens (Table 4.1), which are composed predominantly of sand mixed with amendments (Kussow, 1987). The idea is to provide a mixture that improves compaction resistance, water infiltration and retention, nutrient retention, and root zone aeration (Wehtje et al., 2000).

Amendments Use in the Root Zone

Modification by applying organic and inorganic amendments in the root zone is a suggested method of reducing compaction and leaching, while increasing plant available water and nutrient holding capacity (Waltz Jr. et al., 2003). Addition of organic amendments offers benefits of increased soil water retention, reduced bulk density, improved root zone aeration, increased nutrient retention, and improved turfgrass germination (McCoy, 1992; Juncker and Madison, 1967; Bigelow et al., 1999).

Sphagnum moss or reed sedge and peat are the most common amendments used in putting green construction (Waddington, 1992). However, organic amendments decompose over time losing their desirable characteristics (Huang and Petrovic, 1995). Decomposition of organic matter has been reported to reduce hydraulic conductivity and air-filled porosity compared to unamended sand (McCoy, 1992). Peat has limited effectiveness in reducing nitrate leaching (Ervin et al., 1999). Furthermore, since peat is a naturally occurring resource, the supply is limited (Waltz Jr. et al., 2003). Suitable amendments for putting green root zones are being sought for possible replacement of peat, and those that retain physical properties for extended periods are desired. In recent years there has been a trend towards use of inorganic amendments in sports-type turf and these amendments can either be incorporated into the rooting media prior to turf establishment or applied to the surface after core-aeration (Wehtje et al., 2000). Inorganic amendments such as pumice, perlite, expanded shale, sintered fly ash, slag, calcined clays, diatomaceous earths and zeolites have been identified as possible substitutes for peat in high sand content root zones (Carrow, 1993; Ervin et al., 1999; Ok et al., 2003; Waltz Jr. et al., 2003). They are more resistant to decomposition, more permanent additions to the root zone, and may reduce the potential to harbor pathogenic organisms. Some of these materials possess high cation exchange capacities (CECs) and water holding capacities without reducing air-filled porosity (Huang and Petrovic, 1994). Wehtje et al. (2000) reported that most of the amendment products on the market are produced from three types of natural deposits: clays including montmorillonite and attapulgite; zeolites, which are predominantly composed of the mineral clinoptile; and diatomaceous earths, which are the siliceous skeletal remains of diatoms. The minerals are screened to a narrow particle range, approximately equivalent to that of coarse sand (0.5-1.0 mm) to maintain high percolation rates (Bigelow et al, 2004). The clays and diatomaceous earth-based amendments are calcined (fired) at 1,500 to 1,700 °C to make the particles stable. Zeolite based amendments are usually not calcined. Evaluation of inorganic materials as potential soil conditioners has been limited to zeolites, mainly clinoptilolite (Ferguson et al., 1986; Huang and Petrovic, 1995) and calcined clays (Waddington et al., 1974). Previous research has reported conflicting results on the success of inorganic amendments (Bigelow et al., 2004; Waddington et al., 1974; Ferguson et al., 1986; Kussow, 1996; McCoy and Stehouwer, 1998; Waltz et al., 2003; Wehtje et al., 2000). A disadvantage that has been reported on the use of inorganic amendments is that much of the water held internally may be too tightly held for plant extraction and is, therefore, unavailable to turfgrass. Knowledge of the physical and hydraulic properties of inorganic amendments is essential for understanding the suitability of amending sand-based root zones. An ideal amendment or amendment mixture should possess both micropores and macropores. Macropores enhance drainage and aeration while micropores help to retain water. Limited information has been collected to compare the effects of most amendments on the soil physical properties of a sand-based golf putting green (Li et al., 2000). The objectives of this study were i) to evaluate and compare the physical and hydraulic properties of seven commercially available inorganic amendments used in sand-based root zones and ii) to evaluate the physical and hydraulic properties of the amendment-sand mixtures (15% amendment with 85% sand v/v).

MATERIALS AND METHODS

Amendments

Seven amendments {Clinolite (Scientific Turf Products, 207 Fox Crossing, Burnet, TX 78611), Ecolite (Western Organics, Inc., 420 E. Southern Ave., Tempe, AZ 85282), Pro's Choice (Pro's Choice Products, P.O. Box 20, Barington, IL 60011), Moltan Plus (Moltan Co., 3555 Moltan Drive, Memphis, TN 38115), Isolite (Davidson Golf Inc., 4252 North Point Road, Unit 109, Baltimore, MD 21222), Profile (Applied Industrial Materials Corp., 750 Lake Cook Road, Suite 440, Buffalo Grove, IL 60089), Axis (Eagle-Picher Minerals Inc., P.O. Box 12130, Reno, NV 89510)}, all marketed in the southeastern U.S. and sand were evaluated. The mineralogical description and chemical composition of each of the amendments is shown in Table 4.2. All the amendments are comprised mainly of silica (SiO_2) with minor constituents of metal oxides (Al_2O_3 and Fe_2O_3). A series of laboratory experiments was conducted to measure the physical and hydraulic properties of amendments and amendment-sand mixtures at a ratio of 15% amendment to 85% sand (volume basis). The parameters measured were bulk density, particle density, particle size distribution, saturated hydraulic conductivity, water retention and available water. Each of the air-dried amendments and amendment-sand mixtures was packed in a standard metal cylinder (6-cm height and 5.35-cm inside diameter). During packing successive amounts of about 5 cm^3 of material were added, stirred with the previous added material to avoid layering and the cylinder tapped gently, until it was completely full. All amendments and amendment-sand mixtures were packed in triplicate and parameter values calculated from the average of the three values.

Physical Properties Determination

The bulk density was calculated from the mass of the air-dry material and the volume of the cylinder. The particle density was determined by the pycnometer method (Flint and Flint, 2002). Prior to determining the particle density, the amendments and the amendment-sand mixtures were slightly wetted using an aspirator bottle and placed in zip-lock bags and allowed to equilibrate overnight. This was done to minimize hydrophobicity.

Particle size analysis was achieved by passing the amendments and the amendment-sand mixtures through 2.0, 1.0, 0.5, 0.25, 0.1, and 0.05 mm sieves followed by weighing and using the United States Department of Agriculture particle-size limits (Gee and Or, 2002). Total porosity was calculated from particle and bulk density using the following equation:

$$\phi = \left(1 - \frac{\rho_b}{\rho_p}\right) \qquad [4.1]$$

where ϕ is the total porosity (cm^3 cm^{-3}), ρ_b is the bulk density (g cm^{-3}), and ρ_p is the particle density (g cm^{-3}). Capillary porosity was defined as the amount of pores retaining water at -40 cm H_2O (Bigelow et al., 2004; Waltz Jr. et al., 2003), while macroporosity was calculated as the difference between the total porosity and capillary porosity.

Hydraulic Properties Determination

Saturated hydraulic conductivity was determined on the same samples, using the constant head method upon substitution of the ceramic plate by cheesecloth (Bootlink and Bouma, 2002).

A Marriott flask was used to set the constant head and a wetting solution of 0.005 M $CaCl_2$ was used to prevent particle dispersion. Prior to saturating the samples, we flushed the samples with CO_2 to replace the air present in the pores. The CO_2 readily dissolved in the de-aerated wetting solution during the wetting of the materials, preventing the presence of entrapped air. Water flowing through the sample for the first 10 minutes was discarded. After that, water was allowed to flow through the sample for 6 minutes with 6 subsamples collected at 1-minute intervals. The measured volumes were used to calculate the hydraulic conductivity according to Darcy's law:

$$q = \pm\frac{V}{At} = -K_s\frac{\Delta H}{\Delta L} \qquad [4.2]$$

where q is the flux density ($cm^3\ cm^{-2}\ s^{-1}$), V is the volume of water flowing through a cross-sectional area of porous medium (cm^3), A is the cross-sectional area (cm^2), t is time (s), K_s is the saturated hydraulic conductivity ($cm\ s^{-1}$), ΔH is hydraulic head difference between the top and bottom of the sample (cm) and ΔL is the height of the sample (cm). The flux is positive for upward and negative for downward flow.

Water retention at various pressure heads was determined using Tempe pressure cells (Dane and Hopmans, 2002) and the pressure plate method. The samples were vacuum saturated with a 0.005 M $CaCl_2$ solution to avoid possible particle dispersion. Upon saturation, the materials were allowed to reach static equilibrium at atmospheric pressure. Hence, water under the porous ceramic plate was kept at about atmospheric pressure, while a gas phase was applied to the sample at pressures greater than atmospheric.

Water flow out of the samples through the porous plate was measured at each applied pressure (1, 6, 15, 20, 25, 35, 45, 50, 55, 60, 70, 100, 120, 150, 250, and 500 cm H_2O) after static equilibrium was established between the soil water and the bulk water in the system below the porous plate. For higher pressures (1000, 2500, 5000, 10000 and 15000 cm H_2O), a ceramic plate extractor was used. After applying the highest pressure, the volumetric water content of the samples was determined using the gravimetric method and all other water content values were calculated from the respective outflow volumes. The matric head was calculated from the applied pressure using the relation of Dane and Hopmans (2002):

$$h_m = -(P_a - P_{atm})/\rho_w g = -h_a \qquad [4.3]$$

where h_m is the matric head (cm), P_a and P_{atm} (= 0), refer to applied air and atmospheric pressures (Pa), respectively, and h_a is the applied air pressure head (cm). Matric head (h_m) and volumetric water content (θ) point data were plotted. These data were then fitted to the van Genuchten (van Genuchten, 1980) and Brooks-Corey (Brooks and Corey, 1964) models, executed in the RETC program (Soil Salinity lab, 1999). The van Genuchten relation is:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha |h_m|)^n}\right]^m$$

$$K(h) = K_s S_e^{\,l}\left[1 - (1 - S_e^{\,1/m})^m\right]^2 \qquad [4.4]$$

$$m = 1 - 1/n \quad , \quad n > 1$$

where S_e is the effective water content (-), θ the volumetric water content (cm^3 cm^{-3}), θ_r is the residual volumetric water content (cm^3 cm^{-3}), θ_s is the saturated volumetric water content (cm^3 cm^{-3}), h_m is the matric head (cm), and α , m , and n are curve fitting parameters, *K(h)* is the hydraulic conductivity as a function of pressure head, while K_s is the saturated hydraulic conductivity and l is a pore-connectivity parameter (-) which is estimated to be about 0.5 as an average for many soils (Mualem, 1976). The Brooks-Corey relation is:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{h_d}{h_m}\right]^{\lambda} \quad for\ h_m < h_d$$

$$S_e = 1 \quad for\ h_m > h_d \qquad [4.5]$$

$$K = K_s S_e^{2/(n+l+2)}$$

where h_d is the displacement pressure (cm), i.e., the matric head value at which water is being displaced by air, and λ is the pore size distribution index (-). The basic difference between the van Genuchten and Brooks-Corey relationships is that Brooks-Corey recognizes the air entry value, i.e., the matric head value at which the biggest pores will drain. That is, as long as this air entry value is not reached, the soil will remain saturated.

The van Genuchten and Brooks-Corey parameters were determined, and using these parameters the volumetric water content (θ) at any pressure (matric) head was calculated. We defined the available water (AW) as the difference between the permanent wilting point and field capacity, with permanent wilting point defined as the water held at h_m = -15000 cm H_2O and field capacity as the water held at h_m = -40 cm H_2O as suggested by Bigelow et al. (2004). We divided the AW into easily available water (-500

< h_m <-40 cm H_2O), moderately available water (-5000 < h_m < - 500 cm H_2O) and difficult available water (-15000 < h_m < - 1500 cm H_2O).

RESULTS AND DISCUSSIONS

Physical Properties of the Amendments

The amendments and the amendment-sand mixtures had higher total porosity values (> 0.40 $cm^3\ cm^{-3}$) than 100% sand (0.22 $cm^3\ cm^{-3}$) (Table 4.3). The total porosity value for the diatomaceous earth Axis was the highest for all the amendments (0.79 $cm^3\ cm^{-3}$), while the other diatomaceous earth, Isolite, showed an intermediate value (0.70 $cm^3\ cm^{-3}$). Similarly, the calcined clays had intermediate total porosity values of 0.68, 0.73, and 0.71 $cm^3\ cm^{-3}$, respectively, for Moltan Plus, Profile, and Pro's Choice. The zeolites had the lowest total porosity value of the amendments, viz., 0.58 $cm^3\ cm^{-3}$ for Clinolite and 0.59 $cm^3\ cm^{-3}$ for Ecolite, but these values were still higher than the total porosity value of 100% sand. Capillary porosity followed the same pattern as total porosity, being highest for Axis (0.50 $cm^3\ cm^{-3}$), intermediate for Isolite, Moltan plus, Profile and Pro's Choice (0.37, 0.36, 0.39, and 0.32 $cm^3\ cm^{-3}$, respectively), and lowest for Clinolite and Ecolite (0.25 $cm^3\ cm^{-3}$). The lowest capillary porosity for the amendments was, however, still much higher compared to that of sand (0.07 $cm^3\ cm^{-3}$). The macroporosity values for all amendments were higher than the maximum value of 0.30 $cm^3\ cm^{-3}$ that is recommended for the USGA and Californian systems (Table 4.1), with the exception of the Axis amendment (0.29 $cm^3\ cm^{-3}$). The amendment-sand mixtures showed ~ 70% lower values for total, macro-, and capillary porosity values compared to pure amendments. However, the values were still within the recommendations for the USGA construction system.

Compared to 100% sand, the results show that addition of amendments to sand increased the total and capillary porosity values, which is in agreement with previous findings (Bigelow et al., 2004; Li et al., 2000; McCoy and Stehouwer, 1998; Waltz et al., 2003). The high capillary porosity values of the amendments suggest the presence of large internal surface areas, which enhance water and nutrient retention, while the low capillary porosity of sand (0.07 cm^3 cm^{-3}) suggests that it would be very difficult to manage a sand-based root zone without incorporating amendments.

The K_s values for the amendments and amendment-sand mixtures were higher than for 100% sand (0.41 m h^{-1}). Isolite, Ecolite and Clinolite had higher K_s values (1.29 - 1.56 m h^{-1}) compared to the rest of the amendments, which had values ranging between 0.60 to 0.76 m h^{-1}. With K_s values ranging from 0.47 to 0.78 m h^{-1}, the amendment-sand mixtures showed lower values compared to pure amendments, while the recommended USGA range is 0.15-0.61 m h^{-1}. Only Clinolite-sand (0.78 m h^{-1}) and Ecolite-sand (0.76 m h^{-1}) mixtures had higher values than the USGA recommended range. Although a high K_s value is important to enhance drainage in the sand-based root zone, values exceeding the USGA recommendations, as is the case with Clinolite and Ecolite, are unsuitable and suggest it would require frequent irrigation to replenish water lost by drainage. Our results agree with previous findings by Smalley et al. (1962) and Waltz et al. (2003), who reported increased K_s values for amendment-sand mixtures compared to 100% sand.

The results for the geometric mean diameter, particle size distribution, particle density and bulk density (Table 4.4) show that all amendments had larger particles than sand, which had a geometric mean diameter of 0.31 mm. The Isolite amendment had the largest particles with a geometric mean diameter of 0.92 mm, while the rest of the amendments had very similar geometric mean diameter values (~0.50 mm). Classification of particle-size fractions following the USDA particle-size limit placed the amendments in the range of medium-to-very-coarse sand (0.50–2.0 mm), except Isolite which was distributed from coarse-to-very-coarse sand (1.0–2.0 mm). The zeolites and calcined clays had >85% of the particles on a weight basis in the coarse-to-very-coarse sand classes, while 100% sand had particles distributed from fine-to-coarse sand classes. The diatomaceous earth amendments, Axis and Isolite had the lowest particle density values, 2.20 and 2.18 g cm^{-3}, respectively, and bulk density values, 0.47 and 0.64 g cm^{-3}, respectively. The calcined clays had intermediate particle density values of 2.25, 2.24, and 2.31 g cm^{-3}, for Moltan Plus, Profile, and Pro's Choice, respectively, and bulk density values of 0.71, 0.66 and 0.67 g cm^{-3}, respectively. The zeolites Clinolite and Ecolite showed the highest particle density value of 2.40 g cm^{-3} and bulk density values of 0.97 and 0.95 g cm^{-3}, respectively. All amendments had lower particle and bulk density values compared to sand (2.67 g cm^{-3}; 0.67 g cm^{-3}). The amendment-sand mixtures had higher particle and bulk density values compared to 100% sand, with particle density ranging from 2.60 to 2.65 g cm^{-3}, and bulk density from 1.49 to 1.57 g cm^{-3}. A lower bulk density relative to the particle density value is important as it leads to an increase in pore space, which enhances the potential for aeration and increased water content. According to Bigelow et al. (2004), bulk density alone is not considered to be an adequate indicator of a successful root zone mixture.

Available Water-Holding Capacity

The relationships between matric head and volumetric water content show that the amendments and the amendment-sand mixtures had higher water content values at corresponding matric head values compared to 100% sand (Fig. 4.1). Fitting the van Genuchten and the Brooks-Corey equations through the data points resulted in model parameters and high correlations ($r^2 \geq 0.94$) between the input and the fitted values (Tables 4.5 and 4.6). Compared to the rest of the amendments, the calcined diatomaceous earths Axis and Isolite showed the highest volumetric water content at saturation (θ_s), viz., 0.79 $cm^3\ cm^{-3}$ and 0.71 $cm^3\ cm^{-3}$, respectively. Calcined clays exhibited medium saturation with θ_s values of 0.64 $cm^3\ cm^{-3}$, 0.69 $cm^3\ cm^{-3}$, and 0.62 $cm^3 cm^{-3}$, respectively, for Moltan Plus, Profile, and Pro's Choice, while zeolites exhibited the lowest θ_s values, viz., 0.61 $cm^3\ cm^{-3}$ for Clinolite and 0.58 $cm^3\ cm^{-3}$ for Ecolite. The 100% sand exhibited a lower θ_s value (0.37 $cm^3\ cm^{-3}$) compared to the amendments. The θ_s should be identical to the total porosity values, which was indeed observed for the amendments and the amendment-sand mixtures. For the 100% sand the θ_s was less than the total porosity value, which was attributed to the entrapment of air during wetting. The amendments and the amendment-sand mixtures showed the most drainage for $-40 < h_m < -1$ cm H_2O, which is due to drainage of larger pores (macropores), many of which had similar sizes.

Results are presented for the available water (AW), categorized into easily available water (EAW), moderately available water (MAW) and difficult available water (DAW), and determined using the Brooks-Corey (Fig. 4.2) and the van Genuchten (Fig. 4.3) models. Both models showed similar trends for the pure amendments and the amendment-sand mixtures, although compared to the Brooks-Corey model, the van

Genuchten revealed higher AW values, with most of the available water in the EAW and MAW categories. From the Brooks-Corey model results, Axis showed the highest AW (0.145 $cm^3\ cm^{-3}$) of the amendments, with most (> 66%) of the available water in the EAW and the MAW categories. Isolite showed AW value (0.135 $cm^3\ cm^{-3}$) close to Axis, however, most (70%) of the available water was in DAW category. Calcined clays had intermediate AW values, viz., 0.124 $cm^3\ cm^{-3}$ for Moltan Plus, 0.134 $cm^3\ cm^{-3}$ for Profile and 0.124 $cm^3\ cm^{-3}$ for Pro's Choice, but about 50% of the AW was in the DAW category. Zeolites showed the least AW, viz., 0.036 $cm^3\ cm^{-3}$ for Clinolite and 0.037 $cm^3\ cm^{-3}$ for Ecolite. The AW for the amendment-sand mixtures using the Brooks-Corey method show a similar trend as the pure amendments, but with lower AW values, but still higher than the value for the 100% sand (0.010 $cm^3\ cm^{-3}$).

Axis shows the highest AW (0.214 $cm^3\ cm^{-3}$), then Isolite (0.200 $cm^3\ cm^{-3}$), while Calcined clays have intermediate values, viz., 0.117 $cm^3\ cm^{-3}$ for Moltan plus, 0.189 $cm^3\ cm^{-3}$ for Profile and 0.180 $cm^3\ cm^{-3}$ for Pro's Choice, while Clinolite and Ecolite zeolites show the lowest values (0.062 $cm^3\ cm^{-3}$) for the amendments. All amendments show most of the available water in EAW and MAW categories using the van Genuchten model. The 100% sand shows an AW value of 0.012 $cm^3\ cm^{-3}$. Although the calculated AW values for the inorganic amendments and amendment-sand mixtures are higher than the values calculated for 100% sand, apparently, only < 0.25 $cm^3\ cm^{-3}$ is available for plant use. Furthermore, most amendments have considerable amounts of AW in the DAW, at least using the Brooks-Corey model, except for the Axis amendment. Bigelow et al. (2004) attributed this apparently low AW value to water discontinuity in the big pores between the aggregate particles. To address this disparity, we designed a plant uptake (bioassay) experiment to determine the plant available water and compare the results with AW determined by the Tempe Cell-pressure cell method. Bahiagrass (*Paspalum notatum* Flugge) was selected for this experiment due to its extensive root system. The grass was seeded at a rate of 150 kg ha^{-1} and grown in the greenhouse (35/20 ºC day/night) for 8 weeks on each of the amendment materials and the amendment-sand mixtures. The grass was well watered and fertilized with a soluble fertilizer (20-20-20 N-P_2O_5-K_2O) at a rate of 100 kg ha^{-1} with a concentration of 5 mL L^{-1}. The grass was not mowed to maximize evapotranspiration. With the grass well established, the grass was irrigated up to saturation. Thereafter, drought stress was imposed and the canopy monitored daily for signs of wilting.

Water content was determined gravimetrically at field capacity (72 hours after irrigation), and at wilting point (when the grass first showed signs of wilting that persisted during the day and night). The results for the AW determined by the bioassay method (Fig. 4.4) showed 20-70% and 40-50% higher AW compared to values determined using the Brooks-Corey and the van Genuchten model, respectively, except for Profile and Pro's Choice. Calcined diatomaceous earths showed the highest AW values of the amendments, viz., 0.40 cm^3 cm^{-3} for Axis and 0.37 cm^3 cm^{-3} for Isolite. Calcined clays showed intermediate values, viz., 0.20 cm^3 cm^{-3}, 0.18 cm^3 cm^{-3} and 0.15 cm^3 cm^{-3}, respectively, for Moltan Plus, Profile, and Pro's Choice. Compared to the rest of the amendments, zeolites (Clinolite and Ecolite) showed the lowest AW value (0.13 cm^3 cm^{-3}), but this value was still higher than for 100% sand (0.03 cm^3 cm^{-3}). Similar trends were observed for the amendment-sand mixtures, although the AW was lower compared to pure amendments. The AW values determined by the bioassay method for the amendment-sand mixtures were 0.28, 0.21, 0.18, 0.14, 0.12, 0.08, and 0.08 cm^3 cm^{-3}, respectively, for Axis, Isolite, Moltan Plus, Profile, Pro's Choice, Clinolite and Ecolite. The bioassay results suggest that bahiagrass plants were able to extract more water from the amendments and the amendment-sand mixtures than from 100% sand. These results suggest that inorganic amendments hold considerably more available water than the amount revealed using the Tempe Cell-pressure cell method.

SUMMARY AND CONCLUSIONS

Experiments were conducted to evaluate and compare the physical and hydraulic properties of commercially available inorganic amendments used in sand-based root zones and amendment-sand mixtures (15% amendment with 85% sand v/v). Seven commercially available amendments were used in this study, viz., zeolites (Clinolite and Ecolite), calcined diatomaceous earth (Isolite and Axis) and calcined clays (Moltan plus, Profile, and Pro's Choice). All amendments showed better physical and hydraulic properties compared to 100% sand. Although pure amendments showed better properties compared to the amendment-sand mixtures, the latter had most of their physical and hydraulic properties within the limits specified for USGA root zones. Furthermore, it should be noted that 100% amendments are rarely used in root zones due to their relatively high cost. Calcined diatomaceous earths showed comparatively superior physical and hydraulic characteristics including water retention and available water, with Axis showing the best properties. Determination of available water by laboratory methods showed lower values compared to the bioassay method. These finding suggest that inorganic amendments hold more water in pores than is not extruded using the Tempe Cell-pressure cell method, but which is accessible to plant roots.

REFERENCES

Beard, J.B. 1973. Turfgrass: Science and culture. Prentice-Hall, Englewood Cliffs, N.J.

Bigelow, C.A., D.C. Bowman, and K. Cassel. 1999. Germination and establishment with root-zone amendments. Golf Course Manage. 67:62–65.

Bigelow, C.A., D.C. Bowman, and D.K. Cassel. 2004. Physical properties of three sand size classes amended with inorganic materials or sphagnum peat moss for putting green root zones. Crop Sci. 44:900–907.

Bingaman, D.E., and H. Kohnke. 1970. Evaluating sands for athletic turf. Agron. J. 62:464–467.

Bootlink H.W.G. and J. Bouma. 2002. Saturated and Field-Saturated Water Flow Parameters. Steady Flow Soil Column Method. p. 812-814. *In* Dane, J.H. and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

Brooks, R.H. and A.T. Corey. 1964. Hydraulic properties of porous media. Hydrol. paper 3., Colorado State Univ., Fort Collins, CO.

Carrow, R.N. 1993. Eight questions to ask: Evaluating soil and turf conditioners. Golf Course Manage. 61:56-70.

Dane, J.H., and J.W. Hopmans. 2002. Water retention and storage: Laboratory. p. 688–690. *In* Dane, J.H. and G.C. Topp (eds.) Methods of soil analysis. Part 4. SSSA Book Ser. 5. SSSA, Madison, WI.

Ervin, E.H., C. Ok, B. S. Fresenburg, J. H. Dunn and S. Dunn. 1999.Turfgrass Research and Information Report from the University of Missouri-Columbia Turfgrass Research Center. Primo for sustaining zoysiagrass quality in the shade.

Flint A.L. and L.E. Flint. 2002. 2.2 Particle Density. 2.2.3.2 Pycnometer Method. p. 230-233. *In* Dane, J.H. and G.C. Topp (eds.). Methods of Soil Analysis, Part 4 - Physical Methods. Soil Sci. Soc. Am. Book Ser. 5. Madison, WI.

Ferguson, G.A., I.L. Pepper, and W.R. Kneebone. 1986. Growth of creeping bentgrass on a new medium for turfgrass growth: Clinoptilolite zeolite-amended sand. Agron. J. 78:1095–1098.

Gee, G.W., and D. Or. 2002. Particle-size Analysis. Introduction p. 255-256. *In* J.H. Dane and G.C. Topp (eds.). Methods of Soil Analysis, Part 4. Physical Methods. Soil Sci. Soc. Am. Book Ser. 5. Madison, WI.

Huang, Z.T., and A.M. Petrovic. 1994. Clinoptilolite zeolite influence on nitrate leaching and nitrogen use efficiency in simulated sand based golf greens. J. Environ. Qual. 23:1190–1194.

Huang Z.T., and A.M. Petrovic 1995. Physical properties of sand as affected by clinoptilolite zeolite particle size and quality. J. Turfgrass Manage.1:1-15.

Juncker, P.H., and J.J. Madison. 1967. Soil moisture characteristics of sand–peat mixes. Soil Sci. Soc. Am. Proc. 31:5–8.

Kussow, W.R. 1987. Peats in greens: Knowns, unknowns and speculations: USGA Greens Section Record. 25:5–7.

Kussow, W.R. 1996. Putting green quality as affected by rootzone mix composition. Wis. Turf Res. 14:41–44

Li, D., Y.K. Joo, N.E. Christians, and D.D. Minner. 2000. Inorganic soil amendment effects on sand-based sports turf media. Crop Sci. 40:1121–1125

Ok, C., S. H. Anderson, and E.H. Ervin. 2003. Amendments and construction systems for improving the performance of sand-based putting greens. Agron J. 95: 1583-1590.

McCoy, E.L. 1992. Quantitative physical assessment of organic materials used in sports turf root zone mixes. Agron. J. 84:375–381.

McCoy, E.L., and R.C. Stehouwer. 1998. Water and nutrient retention properties of internally porous inorganic amendments in high sand content root zones. J. Turfgrass Manage. 2(4):49–69.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res. 12:513–522.

Smalley, R.R., W.L. Pritchett, and L.C. Hammond. 1962. Effects of four amendments on soil physical properties and on yield and quality of putting greens. Agron. J. 54:393–395.

Taylor, D.H., and G.R. Blake. 1981. Laboratory evaluation of soil mixtures for sports turf. Soil Sci. Soc. Am. J. 45:936-940.

United States Golf Association. 1993. Recommendations for a method of putting green construction. USGA Green Section. Agron. J. 52:569–572.

Van Genuchten, M.Th. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898.

Waddington, D.V. 1992. Soils, soil mixtures, and soil amendments. p. 331–383. *In* Waddington, D.V. (ed.) Turfgrass. Agron. Mon. 32. ASA, Madison, WI.

Waddington, D.V., T.L. Zimmerman, G.J. Shoop, L.T. Kardos, and J.M. Duich. 1974. Soil modification for turfgrass areas. I. Physical properties of physically amended soils. Prog. Rep. 337. Pennsylvania State Univ., College of Agriculture, Agric. Exp. Stn., University Park, PA.

Waltz Jr., F.C., V.L. Quisenberry, and L.B. McCarty. 2003. Physical and hydraulic properties of rootzone mixes amended with inorganics for golf putting green. Agron. J. 95:395–404.

Wehtje, G., R. H. Walker, and J. N. Shaw. 2000. Pesticide retention by inorganic soil amendments. Weed Sci. 48:248-254.

Wehtje, G.R., J.N. Shaw, R.H. Walker, and W. Williams. 2003. Bermudagrass growth in soil supplemented with inorganic amendments. HortScience 38:613–617.

Table 4.1. Specification for porosity and saturated hydraulic conductivity for the USGA and California construction systems.

System	Porosity			K_s
	Total	Macro	Capillary	
	Volumetric content m^3m^{-3}			$m\ h^{-1}$
USGA	0.35-0.55	0.15-0.30	0.10-0.20	0.76
California	0.35-0.55	0.15-0.30	0.15-0.25	0.68

Table 4.2. Mineralogical description of the materials used for this study.

Amendment	Mineralogical description	Chemical composition
Axis	Calcined diatomaceous earth; poorly crystalline silica	SiO_2 (90.0%), Al_2O_3 (6.5%), Fe_2O_3 (2.3%), CaO, MgO, K_2O, Na_2O and TiO_2 (1.2%)
Clinolite	Zeolite; mainly clinoptilolite	SiO_2 (74%), Al_2O_3 (11%), Fe_2O_3 (5%), CaO, MgO, K_2O, Na_2O and TiO_2 (5%)
Ecolite	Zeolite; mainly clinoptilolite	SiO_2 (69.1%), Al_2O_3 (11.9%), K_2O (3.8%), Fe_2O_3, MnO, CaO, MgO, Na_2O and TiO_2 (3.3%)
Isolite	Calcined diatomaceous earth; crystalline silica	SiO_2 (78%), Al_2O_3 (12%), Fe_2O_3 (5%) K_2O, MnO, CaO, MgO, Na_2O and TiO_2 (5%)
Moltan Plus	Fired clay; crystalline silica and minor phyllosilicate	SiO_2 (74%), Al_2O_3 (11%), Fe_2O_3 (5%), CaO, MgO, K_2O, Na_2O and TiO_2 (<5%)
Profile	Fired ceramic; phyllosilicate (illite)	SiO_2 (74%), Al_2O_3 (11%), Fe_2O_3 (5%), CaO, MgO, K_2O, Na_2O and TiO_2 (<5%)
Pro's Choice	Fired clay; crystalline silica and minor phyllosilicate	SiO_2 (74%), Al_2O_3 (11%), Fe_2O_3 (5%), CaO, MgO, K_2O, Na_2O and TiO_2 (<5%)
Red Sand	Quartz	SiO_2 (100%)

Table 4.3. Porosity and saturated hydraulic conductivity of the amendments and amendment-sand mixtures.

Amendments / sand mixtures	Porosity			K_s
	Total	Macro porosity	Capillary porosity†	
	——Volumetric content m^3m^{-3}——			$m\ h^{-1}$
Axis	0.79	0.29	0.50	0.76
Axis-sand	0.56	0.25	0.31	0.60
Clinolite	0.58	0.32	0.25	1.42
Clinolite-sand	0.41	0.25	0.16	0.78
Ecolite	0.59	0.34	0.25	1.29
Ecolite-sand	0.42	0.26	0.16	0.76
Isolite	0.70	0.33	0.37	1.56
Isolite-sand	0.44	0.19	0.26	0.52
Moltan Plus	0.68	0.32	0.36	0.60
Moltan Plus-sand	0.42	0.17	0.26	0.51
Profile	0.73	0.34	0.39	0.60
Profile-sand	0.42	0.28	0.14	0.47
Pro's Choice	0.71	0.40	0.32	0.72
Pro's Choice -sand	0.53	0.21	0.32	0.54
Sand	0.22	0.15	0.07	0.41

†Capillary porosity refers to water retained at –40 cm water

Table 4.4. Particle size distribution, geometric mean diameter, particle and bulk densities of the amendments and mixtures.

Amendments / sand mixtures	Particle-size fractions, mm						Geometric mean diameter	Particle density	Bulk density
	VCS† 1.0-2.0	CS‡ 0.5 -1.0	MS# 0.25-0.50	FS¶ 0.10-0.25	VFS± 0.05-0.10	silt + clay < 0.05			
	% by weight						mm	g cm^{-3}	
Axis	26.4	52.2	19.9	1.5	0.0	0.0	0.51	2.20	0.47
Axis-sand	5.4	39.4	44.0	11.0	0.1	0.0	0.34	2.60	1.49
Clinolite	22.3	69.7	6.6	1.4	0.0	0.0	0.55	2.40	0.97
Clinolite-sand	5.0	42.0	42.0	10.8	0.1	0.0	0.35	2.65	1.57
Ecolite	38.1	52.1	9.1	0.7	0.0	0.0	0.60	2.40	0.95
Ecolite-sand	7.2	39.5	42.3	10.9	0.1	0.0	0.35	2.65	1.56
Isolite	88.0	11.8	0.2	0.0	0.0	0.0	0.92	2.18	0.64
Isolite-sand	14.9	33.4	40.9	10.8	0.1	0.0	0.40	2.60	1.52
Moltan Plus	1.2	91.7	6.2	0.9	0.0	0.0	0.47	2.25	0.71
Moltan Plus-sand	1.8	45.3	41.8	10.9	0.1	0.0	0.33	2.61	1.53
Profile	0.0	88.0	12.0	0.0	0.0	0.0	0.46	2.24	0.66
Profile-sand	1.5	44.8	42.7	10.9	0.1	0.0	0.33	2.60	1.52
Pro's Choice	0.0	92.9	7.0	0.1	0.0	0.0	0.48	2.31	0.67
Pro's Choice-sand	1.3	45.6	42.1	10.9	0.1	0.0	0.34	2.62	1.52
Sand	2.0	37.2	48.0	12.7	0.1	0.0	0.31	2.67	1.67

†VCS, very coarse sand ‡CS, coarse sand #MS, medium sand ¶ FS, fine sand ±VFS, very fine sand

Table 4.5. The Van Genuchten parameters from fitted water retention data points.

Amendment	θ_r	θ_s	α	n	r^2
Axis	0.453	0.895	2.157	0.126	0.979
Clinolite	0.232	0.582	2.373	0.116	0.960
Ecolite	0.225	0.581	3.163	0.104	0.981
Isolite	0.357	0.709	3.332	0.139	0.978
Moltan Plus	0.329	0.656	3.899	0.064	0.977
Profile	0.364	0.696	5.876	0.056	0.983
Pro's Choice	0.299	0.621	5.232	0.053	0.992
Sand	0.039	0.227	4.274	0.039	0.999

Table 4.6. The Brooks-Corey parameters from fitted water retention data points.

Amendment	θ_r	θ_s	h_d *(cm H_2O)*	λ	r^2
Axis	0.401	0.791	-5.164	0.589	0.936
Clinolite	0.222	0.612	-5.441	1.219	0.959
Ecolite	0.213	0.582	-5.438	1.098	0.972
Isolite	0.352	0.708	-4.915	1.458	0.978
Moltan Plus	0.324	0.640	-12.436	1.972	0.981
Profile	0.357	0.691	-13.791	2.499	0.986
Pro's Choice	0.293	0.617	-13.955	2.222	0.991
Sand	0.036	0.223	-15.000	1.957	0.996

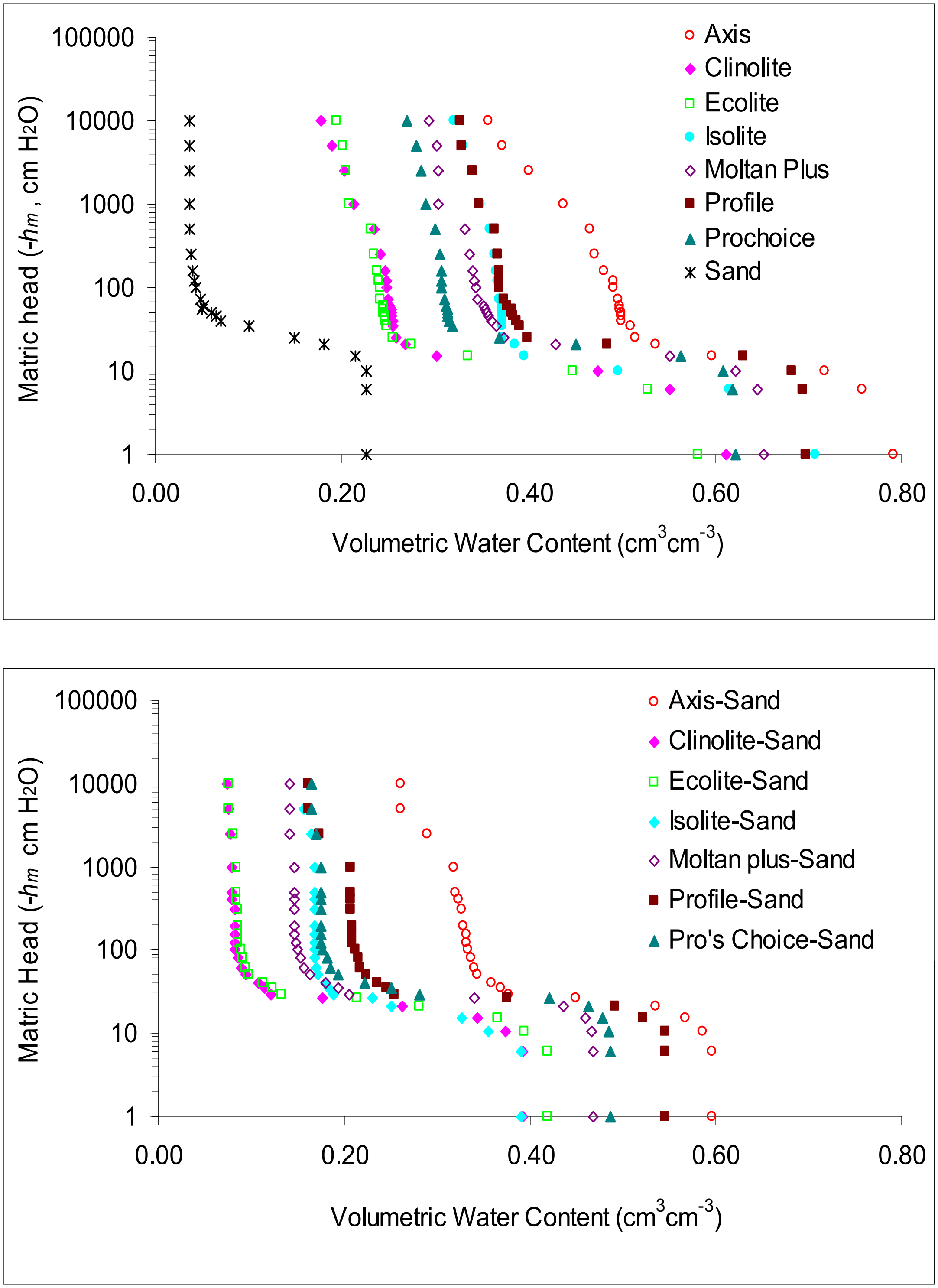


Fig. 4.1. Water retention curves for pure amendments (top panel) and amendment-sand mixtures at 15% amendment and 85% sand by volume (bottom panel) determined by Tempe pressure cells and ceramic plate extractor.

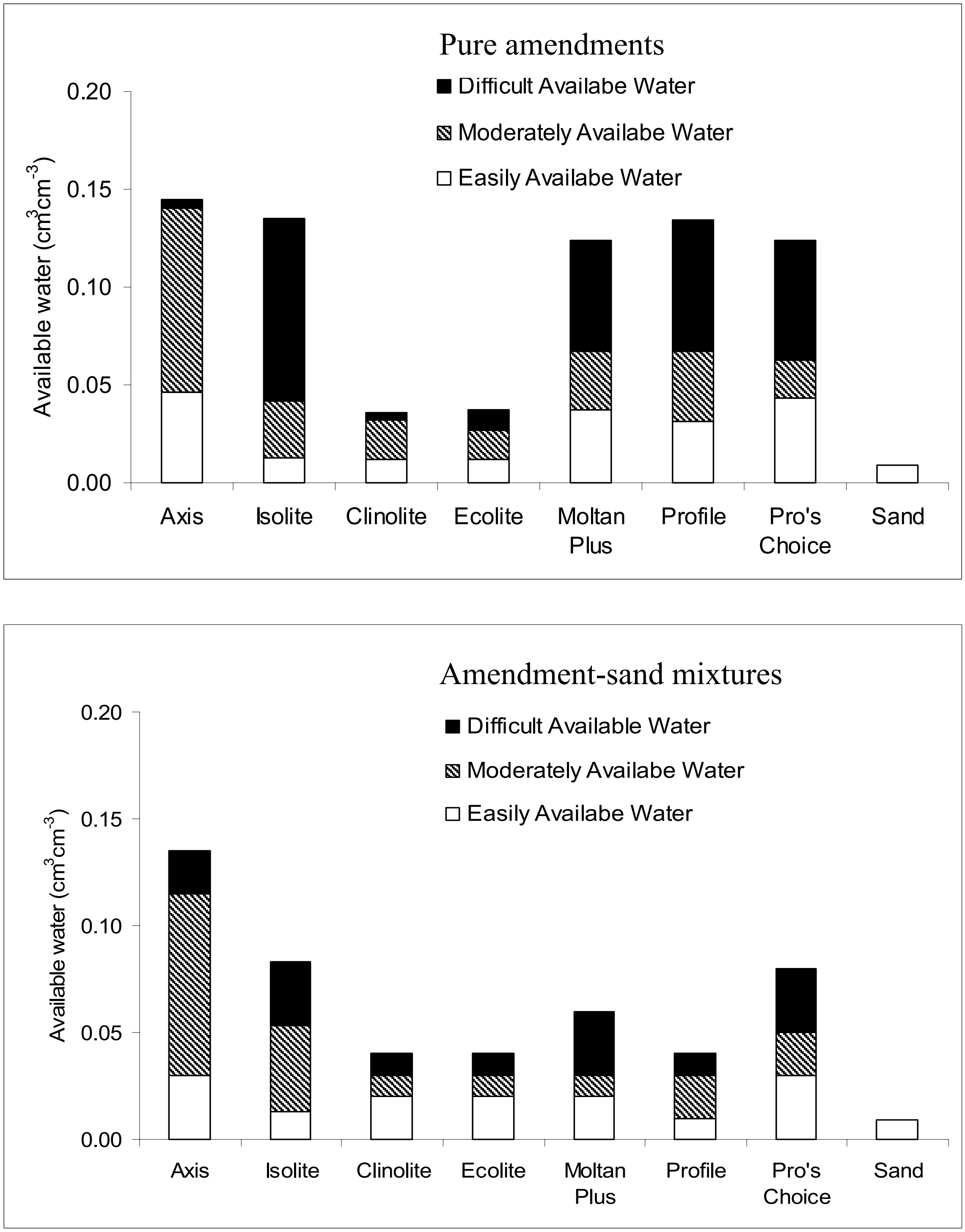


Fig. 4.2. Available water determined by Brooks-Corey relations for pure amendments (top panel) and amendment-sand mixtures at 15% amendment and 85% sand by volume (bottom panel). Easily Available Water is retained between -40 and -500 cm H_2O, Moderately Available Water is retained between -500 and -5000 cm H_2O, and Difficult Available Water is retained between -5000 and -15000 cm H_2O.

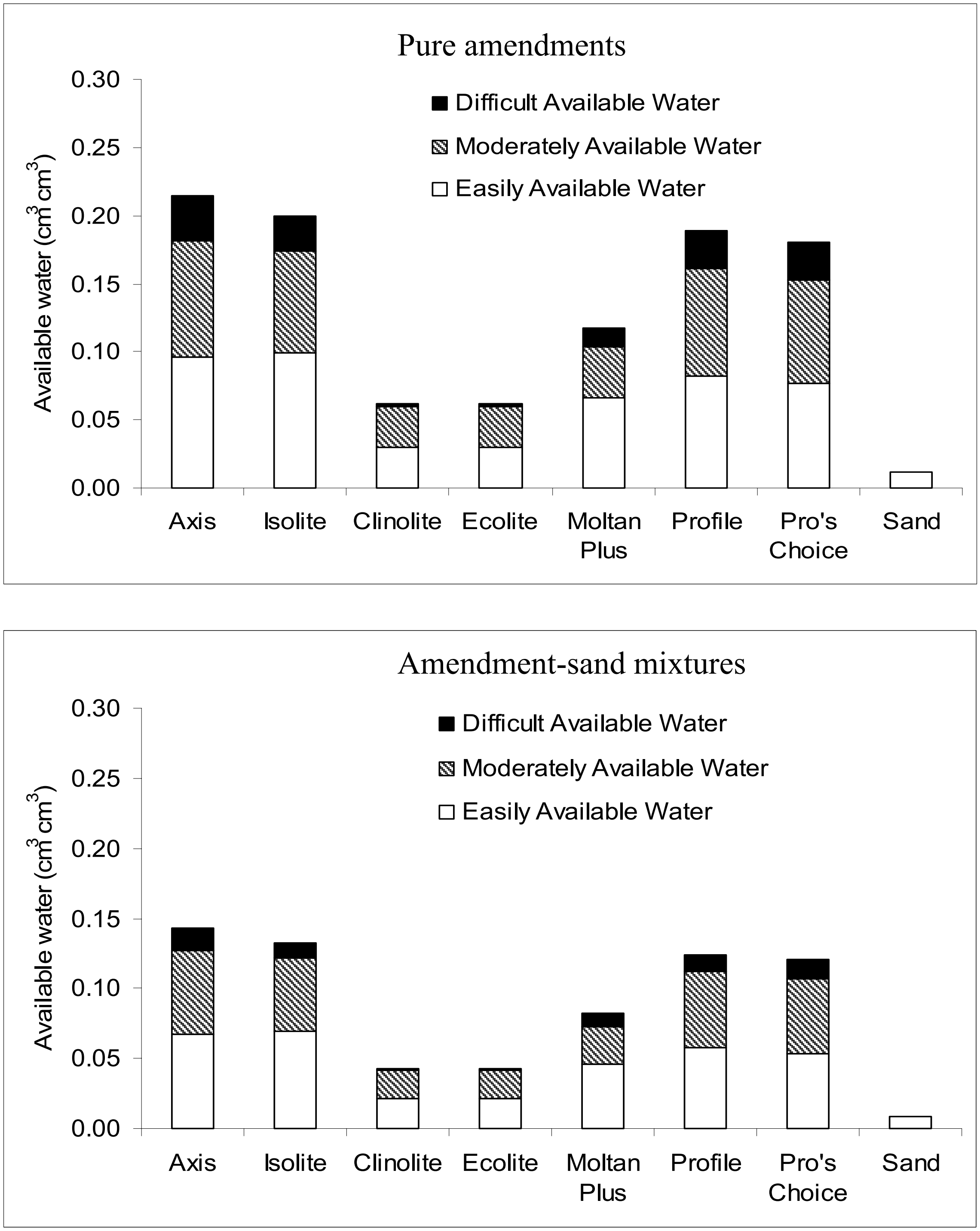


Fig. 4.3. Available water determined by van Genuchten relations for pure amendments (top panel) and amendment-sand mixtures at 15% amendment and 85% sand by volume (bottom panel). Easily Available Water is retained between -40 and -500 cm H_2O, Moderately Available Water is retained between -500 and -5000 cm H_2O, and Difficult Available Water is retained between -5000 and -15000 cm H_2O.

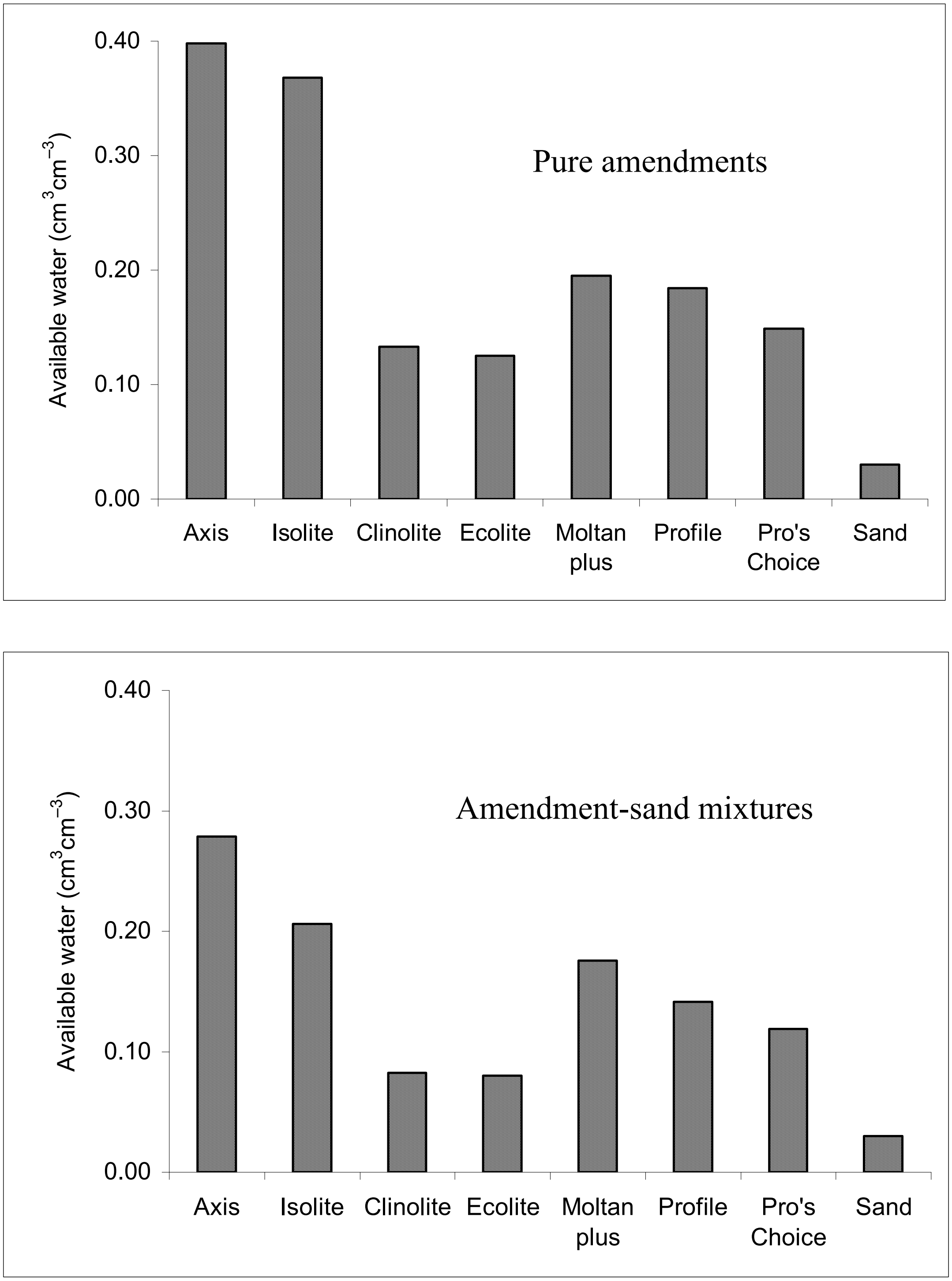


Fig. 4.4. Available water determined by a bioassay method for pure amendments (top panel) and amendment-sand mixtures at 15% amendment and 85% sand by volume (bottom panel).

V. MODELING TURFGRASS ROOT WATER UPTAKE FOR A USGA ROOT ZONE DESIGN MODIFIED WITH INORGANIC AMENDMENTS

ABSTRACT

Water uptake by roots plays an important physiological role in crop growth. Through root uptake, translocation and eventually water loss by evapotranspiration process, plant regulates temperature, while water and chemicals, including nutrients move in the soil-water-plant system. The objective of this study was to model water movement with root uptake for an USGA sand-based root zone modified with inorganic amendments, viz., calcined diatomaceous earths (Axis and Isolite), zeolites (Clinolite and Ecolite), and calcined clays (Moltan Plus, Profile, and Pro's Choice). A numerical model was applied to simulate soil water movement with root water uptake for a scenario with (15% amendment plus 85% sand v/v), and without amendment incorporation (100% sand).

The simulation results showed reduced surface dryness, higher volumetric water content and storage, and higher initial root water uptake rate for the root zones modified with amendments. The highest simulated water storage was observed for root zones modified with calcined diatomaceous earths, especially Axis.

INTRODUCTION

Water is required by all plants, turfgrasses included, for germination, growth and reproduction, mechanical support, photosynthesis, as well as forming part of the plant system. The water absorbed by turf is transpired into the atmosphere, and as it moves, there is nutrient uptake from the soil, as well as elimination of heat buildup from solar radiation. Several studies have been conducted focusing on the process of water movement with root uptake and generally two approaches have been developed. One approach deals with water-flow to a single root (radial flow), where a root is considered to be an infinitely long, hollow, cylindrical sink of uniform radius (Mathur and Rao, 1999). This approach is often referred to as a microscopic approach (Phillip, 1957; Gardner, 1960; Nobel and Alm, 1993; Steudle 1994, Doussan et al., 1998; Personne et al., 2003). The disadvantage of microscopic approach is that it requires detailed information on the geometry of root system which is practically impossible to acquire (Wu et al., 1999; Vrugt et al., 2001). The other approach considers the root system as a single unit and it does not take into account the effects of individual roots due to the difficulty in measuring the time-dependent geometry of the root system (Mathur and Rao, 1999), and is referred to as a macroscopic approach (Gardner, 1964; Mathur and Rao, 1999). Most soil water simulation models with plant water uptake use the macroscopic approach, in which water extraction by plant roots is treated as a sink term distributed in the root zone (Wu et al., 1999). The entire root system is assumed to extract water from each differential volume of the root zone at some rate, and the uptake is represented by a volumetric sink term incorporated into Richards equation (Richards, 1931) that describes water movement in variably saturated soils (Jury et al., 1991). Mathur and Rao (1999) noted that some researchers classified the water uptake models into a third category - a hybrid approach to take into account root density, root permeability, and root water extraction in the extraction relationship.

Although macroscopic models of root water uptake do not give a complete insight into the physical processes of root-water-uptake, it only needs the soil and plant parameters that are readily available. Hence the use of macroscopic approach is generally favored in many application-oriented hydrological models (Li et al., 2001). Some macroscopic approaches model water potential and hydraulic functions inside plant roots (Hillel et al., 1976), while others are based on transpiration rate, rooting depth and soil water potential (Feddes et al., 1974). The parameters for the latter are easier to collect and this approach is the one mainly implemented into numerical models (Simunek et al., 1992).

The numerical models using macroscopic description of root water uptake include HYDRUS (Simunek et al., 1998), SWAP (van Dam et al., 1997), UNSATCHEM (Suarez and Simunek, 1996), and HYSWASOR (Dirksen et al., 1993).

MATERIALS AND METHODS

Simulation Experiment

Root water uptake was simulated for an USGA-specific sand based root zone (Figure 5.1). Two scenarios were specified, one with amendment incorporated at a rate of 15% amendment and 85% sand by volume, and one without amendment (100% sand). HYDRUS-1D (Simunek et al., 1998) code was used which is a Galerkin finite-element method that numerically solves the Richards equation modified to incorporate a sink term to account for water uptake by plant roots.

Water retention was determined for sand and amendment-sand mixtures using the Tempe pressure cells (Dane and Hopmans, 2002) for pressure range 0-500 cm H_2O and a ceramic plate extractor for 1000-15000 cm H_2O pressure. The samples were packed in the standard rings and fixed on the pressure cells until equilibration at atmospheric pressure. The water under the porous ceramic plate was then kept at about atmospheric pressure, while a gas phase was applied to the sample at pressures greater than atmospheric. Water flow out of the sample through the porous plate was measured at each of applied pressures and after static equilibrium was established between the soil water and the bulk water in the system below the porous plate. The volume of water flow corresponding to the applied pressure was measured.

For higher pressure a ceramic plate was used and this was first soaked fully in water before placing the samples of known weight on the plate. To ensure good contact between the sample and the ceramic plate, the surface of the plate was sprayed with water using a squeeze bottle. Each of the pressure was applied until static equilibrium when water flow stopped and the samples were weighed to determine the amount of water extracted. After applying the highest pressure, the volumetric water content of the samples was determined using the gravimetric method. The matric head was calculated from the applied pressure using the relation from Dane and Hopmans (2002):

$$h_m = -(P_a - P_{atm}) / \rho_w g = -h_a \quad [5.1]$$

where h_m is the matric head (cm), P_a and P_{atm} refer to applied air and atmospheric pressures, respectively (cm), and h_a (cm) is the applied air pressure head.

Hydraulic Parameters Using RETC Code

Point data for the relationship between matric head (h_m) and volumetric water content (θ) were plotted. To establish the water retention curve and the hydraulic properties of unsaturated amendment-sand mixtures from the point data, the RETC code (van Genuchten et al., 1991 was used. In RETC code, the water retention curve is described with the equations of Brooks and Corey (Brooks and Corey, 1964) and van Genuchten (van Genuchten, 1980), with the pore-size distribution models of Burdine and Mualem used to parameterize $h(\theta)$ and $K(h)$ characteristics (van Genuchten et al., 1991). The RETC code may be used to fit any one, several, or all of these parameters simultaneously to the observed data and uses a non-linear least-squares optimization approach to estimate the unknown model parameters from observed retention and/or conductivity or diffusivity data (van Genuchten et al., 1991). The approach is based on the partitioning of the total sum of squares of the observed values into a part described by the fitted equation and a residual part of observed values around those predicted with the model. The aim of the curve fitting process is to find an equation that maximizes the sum of squares associated with the model, while minimizing the residual sum of squares, SSQ, which reflects the degree of bias and the contribution of random errors.

The van Genuchten relation is:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha |h_m|)^n} \right]^m$$

$$K(h) = K_s S_e^{\,l} \left[1 - (1 - S_e^{1/m})^m \right]^2 \qquad [5.2]$$

$$m = 1 - 1/n \qquad , \qquad n > 1$$

where S_e is the effective water content, θ the volumetric water content, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, h_m is the matric head (cm), and α , m , and n are curve fitting parameters, l is a pore-connectivity parameter which is estimated to be about 0.5 as an average for many soils (Mualem, 1976), $K(h)$ is the hydraulic conductivity as a function of pressure head (cm h^{-1}), and K_s is the hydraulic conductivity at saturation (cm h^{-1}).

The Brooks-Corey relation is:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{h_d}{h_m}\right]^{\lambda} \quad for\ h_m < h_d$$

$$S_e = 1 \quad for\ h_m > h_d \qquad [5.3]$$

$$K = K_s S_e^{2/n+l+2}$$

where h_d is the displacement pressure, i.e., the matric head value at which water is being displaced by air, and λ is the pore size distribution index. The basic difference between the van Genuchten and Brooks-Corey relationships is that Brooks-Corey recognizes the air entry value, i.e., the matric head value at which the biggest pores will drain. That is, as long as this air entry value is not reached, the soil will remain saturated. The HYDRUS-1D code (Simunek et al., 1998) was used to fit the van Genuchten relation with Mualem-based restriction, (m=1-1/n) for the Tempe-pressure cell data. The Brooks-Corey parameters were obtained using the RETC code.

Equations Governing Flow

The relationship between the flux and the hydraulic gradient for unsaturated conditions is calculated using the Darcy's equation:

$$q = -K(h)\frac{\partial H}{\partial z} \qquad [5.4]$$

where q is the flux ($cm^3\ cm^{-2}\ h^{-1}$), *K(h)* is the hydraulic conductivity as a function of pressure head ($cm\ h^{-1}$), H is the hydraulic head (cm), and is the sum of the pressure head (h) and gravitational head (z) (cm), i.e. $H = h + z$, hence:

$$q = -K(h)\left(\frac{\partial h}{\partial z} + \frac{\partial z}{\partial z}\right) = -K(h)\left(\frac{\partial h}{\partial z} + 1\right) \qquad [5.5]$$

To solve the equation of flow practically, the continuity equation is employed:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} \qquad [5.6]$$

where t is time (h). For homogeneous porous media, equation 5 is combined with 6 to yield:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] \qquad [5.7]$$

which describes unsaturated vertical flow through soil, and is called the Richards equation. The equation states that changes in water content over time, $\partial \theta / \partial t$, results from the pressure gradient, the first term in the parenthesis, and gravity flow, the second term in the parenthesis.

Root Uptake Function Using HYDRUS 1-D Code

The root water uptake involves introduction of a sink term into the Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] - S \qquad [5.8]$$

where S is the sink term (cm^3 cm^{-3} h^{-1}). To solve equation 5.8, one needs 2 boundary conditions, one initial condition, the soil water retention as a function of matric head, $\theta(h_m)$, and the hydraulic conductivity as a function of water content, $K(\theta)$. The $\theta(h_m)$ and $K(\theta)$ for the van Genuchten and the Brooks-Corey relations are given by equation 5.2 and 5.3, respectively. To set the boundary conditions, we specified the upper boundary condition as zero flux ($\partial H / \partial z = 0$ at z = 0) and the lower boundary condition as unit hydraulic head gradient ($\partial H / \partial z = 1$ at z = -L), and we began simulation with saturation as the initial condition:

$$h(z,0) = h_i(z,0) \qquad \text{for} \qquad -L \le z \le 0 \qquad [5.9]$$

where $h(z,0)$ is the pressure head as a function of depth, $h_i(z,0)$ is the initial pressure head as a function of depth, and L the total depth of soil profile(cm).

Assuming a single relationship between the volumetric water content and matric head, referred to as the water capacity, C, the water content form (Eq. 5.8) can be changed to a pressure form of Richards equation.

$$C = \frac{\partial \theta}{\partial h_m} \qquad [5.10]$$

$$C \frac{\partial h_m}{\partial t} = \frac{\partial}{\partial z}\left[K \frac{\partial h_m}{\partial z} + K \right] - S \qquad [5.11]$$

According to Skaggs et al. (2006), the sink term, S, is the volume of water removed from a unit volume of soil per unit time due to plant water uptake. The sink term may be a function of the water pressure head, the osmotic pressure head, root characteristics, and transpiration. Feddes et al. (1978) and van Genuchten (1987) described the sink term, which include osmotic stress as follows:

$$S(h,h_\phi)=\alpha(h,h_\phi)S_p \qquad [5.12]$$

where S_p (cm^3 cm^{-3} h^{-1}) is the potential extraction rate, $\alpha(h,\ h_\phi)$ is the reduction function depending on soil water pressure (h) and osmotic (h_ϕ) head.

Figure 5.2 shows a schematic of the stress response function as used by Feddes et al. (1978). The water uptake is assumed to be zero close to saturation (i.e., wetter than some arbitrary "anaerobiosis point", h_1). For $h < h_4$ (the wilting point pressure head), water uptake is also assumed to be zero. Water uptake is considered optimal between pressure heads h_2 and h_3, whereas for pressure head between h_3 and h_4 (or h_1 and h_2), water uptake decreases (or increases) linearly with h. The variable S_p in Eq. 5.12 is equal to the water uptake rate during periods of no water stress i.e. $\alpha(h,\ h_\phi)=1$.

When the potential water uptake rate is equally distributed over the root zone, the potential extraction rate is described as a function of transpiration and root zone depth:

$$S_p=\frac{1}{R_L}T_p \qquad [5.13]$$

where T_p is the potential transpiration rate (cm h^{-1}) and R_L the depth of the root zone.

Introducing a non-uniform distribution of the potential water uptake rate over a root zone of arbitrary shape then:

$$S_p=\beta(z)T_p \qquad [5.14]$$

where β(z) is the normalized water uptake distribution (cm^{-1}). This function describes the spatial variation of the potential extraction term, S_p, over the root zone (Fig. 5.3), and is obtained by normalizing any arbitrarily measured or prescribed root distribution function, $\beta'(z)$:

$$\beta(z)=\frac{\beta^{'}(z)}{\int_{R_L}\beta^{'}(z)dz} \qquad [5.15]$$

where R_L (cm^{-1}) is the region occupied by the root zone. Normalizing the uptake distribution ensures that $\beta(z)$ integrates to unity over the flow domain, i.e.,

$$\int_{R_L}\beta^{'}(z)dz=1 \qquad [5.16]$$

Substituting Eq. 11 to Eq. 9, we get

$$S(h,h_\phi,z)=\alpha(h,h_\phi,z)\beta(z)T_p \qquad [5.17]$$

The actual transpiration is obtained by integrating Eq. 14:

$$T_a=\int_{R_D}Sdz=T_p\int_{R_D}\alpha(h,h_\phi,z)\beta(z)dz \qquad [5.18]$$

where the integrals are across the depth of the root zone, R_D (cm).

The rooting zone depth can either be constant or variable during the simulation and HYDRUS assumes that the actual root depth is the product of the maximum rooting depth and a growth coefficient (Simunek and Suarez, 1993):

$$R_D(t)=R_M C_r(t) \qquad [5.19]$$

where R_D (cm) is the actual root depth, R_M (cm) the maximum rooting depth and C_r (-) is a growth coefficient. For the root growth coefficient, C_r, HYDRUS uses the classical Verhulst-Perarl logistic growth function:

$$C_r(t)=\frac{R_0}{R_0+(R_M-R_0)e^{-rt}} \qquad [5.20]$$

where R_0 (cm) is the initial value of the rooting depth at the beginning of the growing season, and r (cm) the growth rate and is calculated either from the assumption that 50%

of the rooting depth will be reached after 50% of the growing season has elapsed, or from given data (Simunek et al., 1998).

RESULTS AND DISCUSSIONS

Modeling results are presented for amended (15% amendment with 85% sand) and non-amended (100% sand) root zones. Due to similarity in the modeled parameters obtained for the amended root zones, we decided to present only the results for the Axis amendment. The water flow parameters were determined from the water retention data points using the RETC code and specifying the Brooks-Corey water retention model. In total 22 retention data points were used. The observed and fitted values using the Brooks-Corey model (Fig. 5.4) show a relatively high correlation (r^2=0.94) and a distinct air entry value (at -10 cm H_2O), i.e. the value when most of the large pores begin to drain.

The depth of the simulation was 40 cm (30 cm root zone underlain by a 10 cm thick gravel layer) and the linear element size was taken as 1 cm. The total simulation period was 10 days with a time step of 1 h. The initial condition was specified in the pressure head (-25 cm H_2O) which corresponds with a volumetric water content of 0.20 $cm^3\ cm^{-3}$ for the non-amended root zone and between 0.20-0.70 $cm^3 cm^{-3}$ for the amended root zones. The root water uptake parameters for turfgrass were specified in the model. These values were -10 cm H_2O for h_4 (the wilting point pressure head), -25 cm H_2O for h_3 (value of the pressure head below which roots extract water at the maximum possible rate), -300 cm H_2O for h_2 (pressure head below which roots cannot longer extract water at the maximum rate) and -8000 cm H_2O for h_1 (wilting point). We specified the initial root uptake rate of 0.5 cm d^{-1} and used the Brooks-Corey model hydraulic model, assuming a case with no hysteresis.

The modeling results showed a greater rate of pressure head decrease with depth for the non-amended as compared to the amended root zones. The volumetric water content followed a similar pattern, being lower for the non-amended root zone (0.18 $cm^3 cm^{-3}$) compared to the amended (0.62 cm^3cm^{-3}) (Fig. 5.5).

The modeled root water uptake rate decreased with time for the entire 10-day simulation period (Fig. 5.6). The initial root water uptake rate was 0.5 cm d^{-1} and this reduced to 0.02 cm d^{-1}. For the non-amended root zone the reduction to the minimum is after 2 days while it is after 7 days for the amended root zone. The cumulative root water uptake at the end of simulation period is about 0.5 cm for the non-amended root zone while it is 1.8 cm for the amended (Fig. 5.7).

The results for the water storage in the soil profile for the non-amended profile show initial water storage of 7.2 cm which decreases to 6.6 cm after 10-day simulation period (Fig. 5.8a). For the amended profile the initial water storage is 21.2 cm, decreasing to 19.0 cm after 10 days (Fig. 5.8b).

CONCLUSIONS

The results obtained show higher volumetric water content, greater root water uptake and greater storage for the simulated root zones modified with amendments compared to non-amended root zones. Of the amendments Axis show the highest volumetric water content, highest root water uptake and root zone water storage (data not shown).

REFERENCES

Brooks, R.H. and A.T. Corey. 1964. Hydraulic properties of porous media. Hydrol. pap.3., Colorado State Univ., Fort Collins, CO.

Dane, J.H. and J.W. Hopmans. 2002. 3.3 Water Retention and Storage. Pressure Cell. p. 684-688. *In* Dane J.H. and G.C. Topp (eds.). Methods of Soil Analysis. Part 4. Physical Methods. Soil Sci. Soc. Am. Book Ser. 5. Madison, WI.

Dirksen, C., J.B. Kool, P. Koorevaar, and M.Th. van Genuchten. 1993. HYSWASOR-Simulation model of hysteretic water and solute transport in the root zone. p. 99–122. *In* Russo D. and G. Dagan (eds.) Water flow and solute transport in soils. Springer-Verlag, NY.

Doussan, C., L. Pagès, and G. Vercambre. 1998. Modelling the hydraulic architecture of root systems: An integrated approach to water absorption. Ann. Bot. 81:213–223.

Feddes, R.A., E. Bresler, S.P. Neuman. 1974. Field test of a modified numerical model for water uptake by root systems. Water Resour. Res. 10:1199–1206.

Feddes, R.A., P. Kowalik, and H. Zaradny. 1978. Simulation of field water use and crop yield. Simulation Monographs. PUDOC, Wageningen, 189 pp.

Gardner, W.R. 1960. Dynamic aspects of water availability to plants. Soil Sci. 89:63–73.

Gardner, W.R. 1964. Relation of root distribution to water uptake and availability. Agron. J. 56:41–45.

Hillel, D., H. Talpaz, and H. Van Keulen. 1976. A macroscopic-scale model of water uptake by a non-uniform root system and of water and salt movement in the soil profile. Soil Sci. 121:242–255.

Jury, W. A., W. R. Gardner, and W. H. Gardner. 1991. Soil physics. p.328. John Wiley & Sons, Inc., NY.

Li, K.Y., R. De Jong, J.B. Boisvert. 2001. An exponential root-water-uptake model with water stress compensation. J. Hydrol. 252:189–204.

Mathur, S. and S. Rao. 1999. Modeling water uptake by plant roots. J. Irrigation Drainage Eng. 125:159–165.

Mualem Y. 1976. A new model predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res.12:513-522.

Nobel, P. S., and D. M. Alm. 1993. Root orientation vs. water uptake simulated for monocotyledonous and dicotyledonous desert succulents by root-segment model. Funct. Ecol. 7:600–609.

Personne, E., A. Perrier, and A. Tuzet. 2003. Simulating water uptake in the root zone with a microscopic-scale model of root extraction. Agron. 23:153–168.

Philip, J.R. 1957. The physical principles of soil water movement during the irrigation cycle. *In* Proc. of the 3rd Congress on Int. Comm. Irr. Drainage. 8:125–8:154.

Richards, L. A. 1931. Capillary conduction of liquids in porous mediums. Physics. 1:318–333.

Simunek J., T. Vogel, and M. van Genuchten. 1992. The SWMS-2D code for simulating water flow and solute transport in two dimensional variably saturated media, v.1.1. Research Report 126, U.S. Salinity Lab, ARS USDA, Riverside, CA.

Simunek J. and D. Suarez. 1993. Modeling of carbon dioxide transport and production in soil 1. Model development. Water Resour. Res. 29:487–497

Simunek, J., M. Th. van Genuchten, and M. Sejna. 1998. The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media. Version 2.0. Int. Ground Water Model. Ctr., Golden, CO.

Skaggs, T. H., Shouse, P. J., Poss, J. A.2006. Irrigating Forage Crops with Saline Waters: 2. Modeling Root Uptake and Drainage. Vadose Zone J. 5:824-837

Steudle, E. 1994: Water transport across roots. Plant Soil. 167:79–90.

Suarez, D.L., and J. Simunek. 1996. UNSATCHEM code for simulating one-dimensional variably saturated water flow, heat transport, carbon dioxide production and transport, and multicomponent solute transport with major ion equilibrium and kinetic chemistry. U.S. Salinity Laboratory Tech. Report 129.

van Dam, J.C., J. Huygen, J.G. Wesseling, R.A. Feddes, P. Kabat, P.E.V. van Walsum, P. Groenendijk, and C.A. van Diepen. 1997. Theory of SWAP v. 2.0: Simulation of water flow, solute transport, and plant growth in the soil–water–atmosphere–plant environment.

van Genuchten, M.Th. 1980. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898.

van Genuchten, M.Th., 1987. A numerical model for water and solute movement in and below the root zone. Research Report, US Salinity Laboratory, Riverside, CA.

van Genuchten, M.Th., F.J. Leij, and S.R. Yates. 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils, U.S. Salinity Laboratory Report EPA/600/2-91/065, USDA, Riverside, CA.

Vrugt, J. A., J. W. Hopmans, and J. Simunek. 2001. Calibration of a two-dimensional root water uptake model. Soil Sci. Soc. Am. J. 65:1027–1037.

Wu, J., R. Zhang and S. Gui. 1999. Modeling soil water movement with water uptake by roots. Plant Soil. 215:7–17.

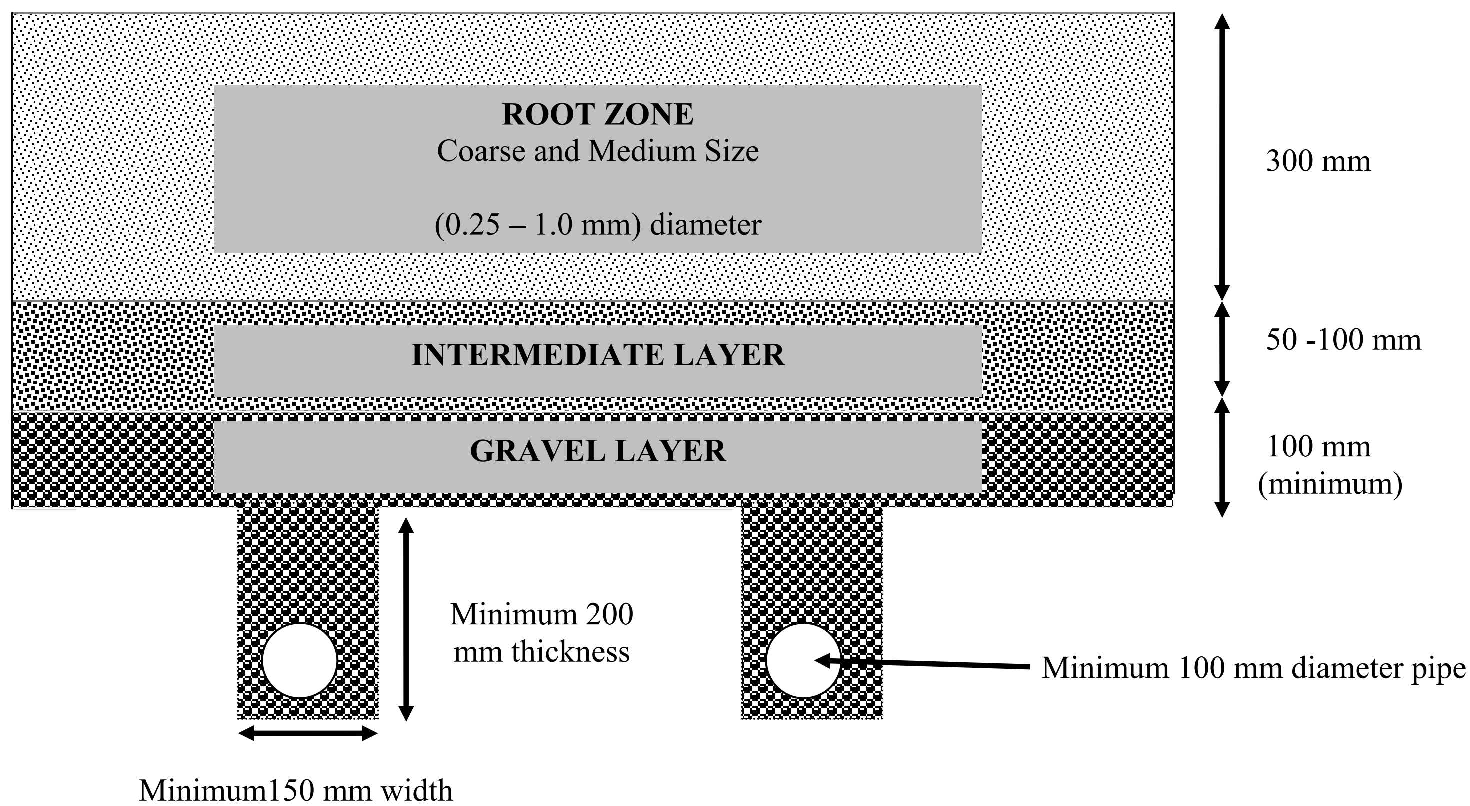


Fig. 5.1. The USGA recommendation for a putting green root zone design.

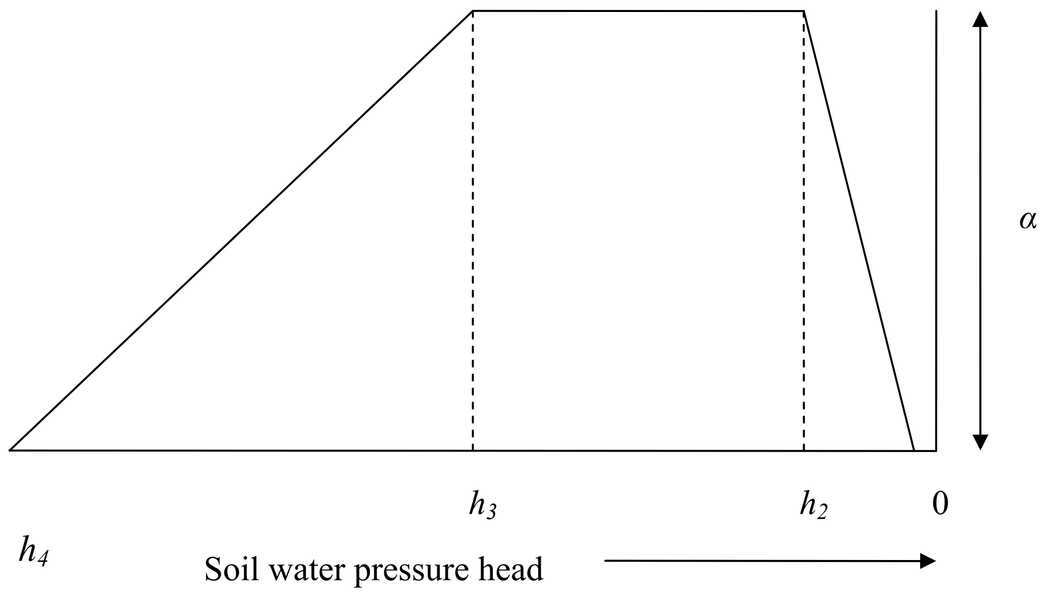


Fig. 5.2. Dimensionless sink term variable α as a function of soil water pressure head, h.

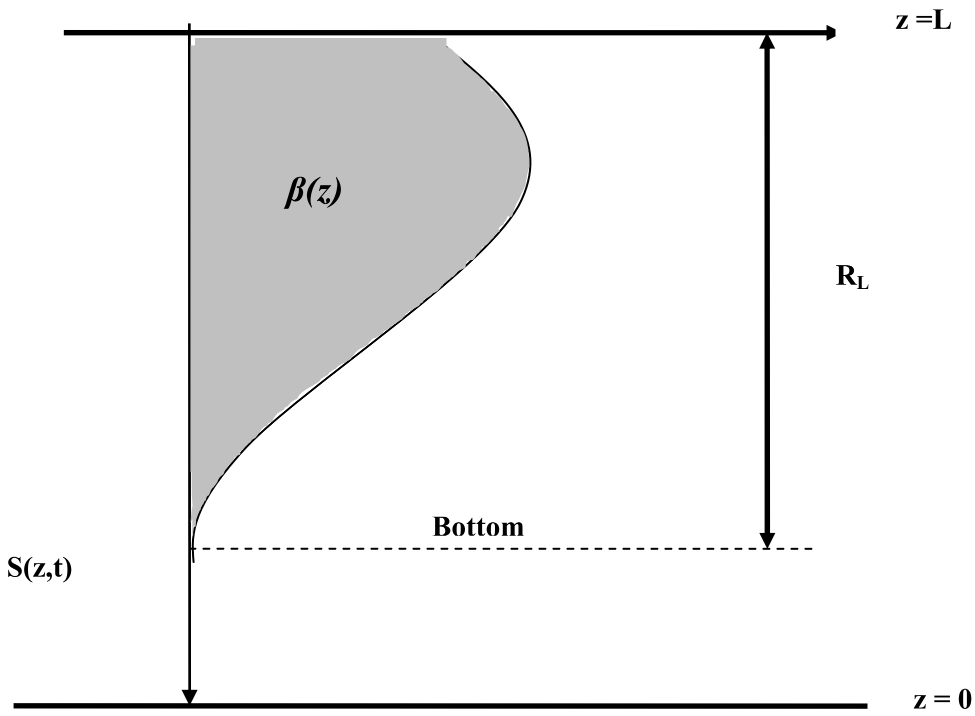


Fig. 5.3. Schematic of the potential water uptake distribution function, $\beta(z)$, in the soil root zone; the shaded area equals 1.

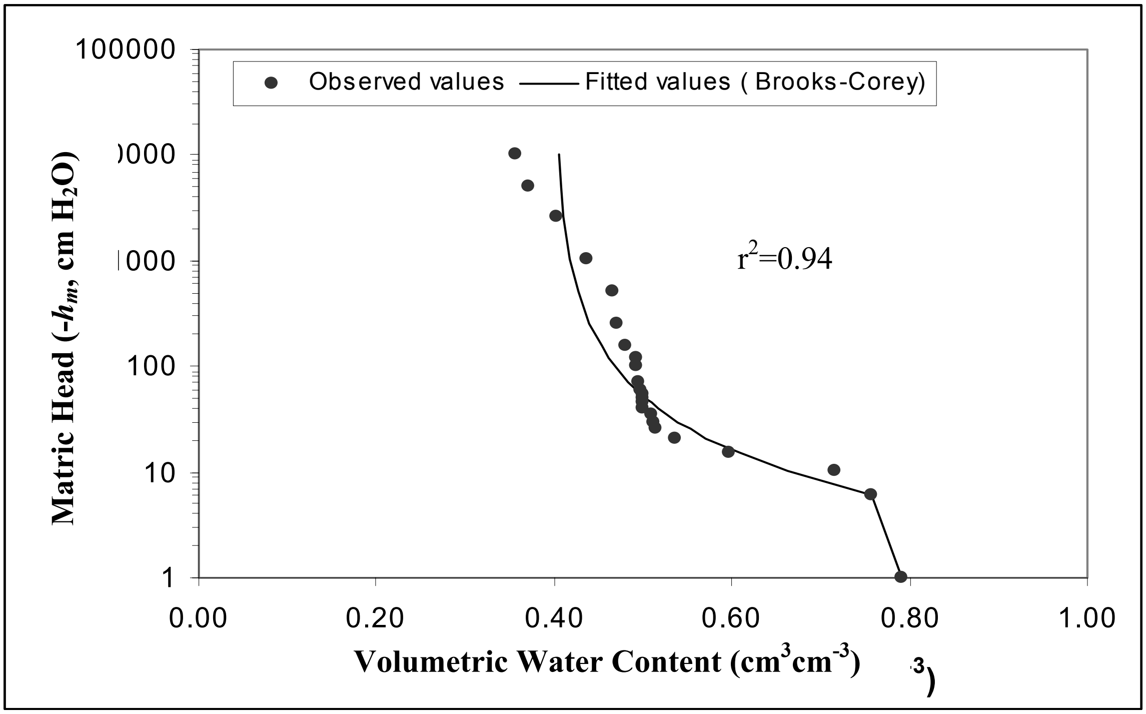
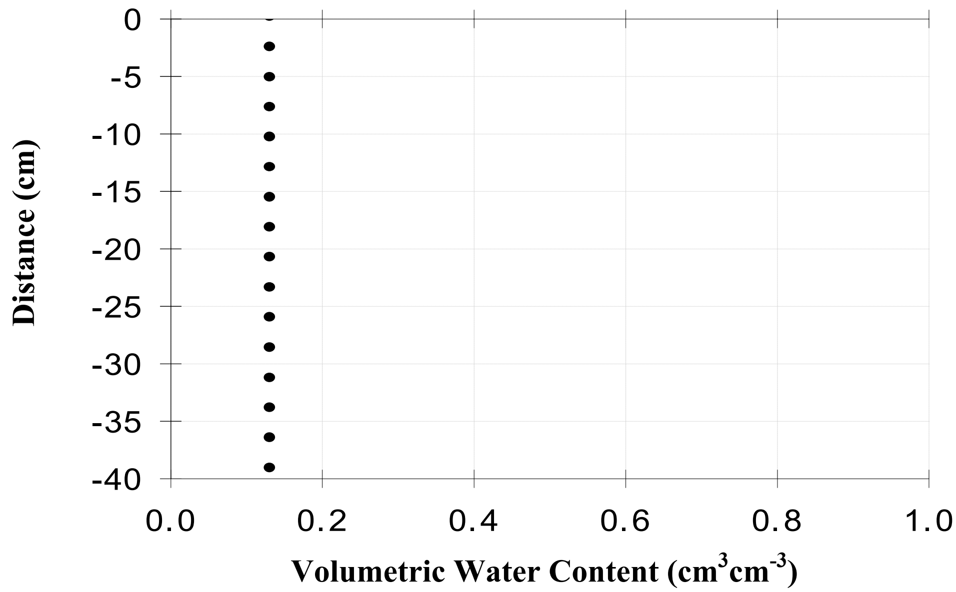
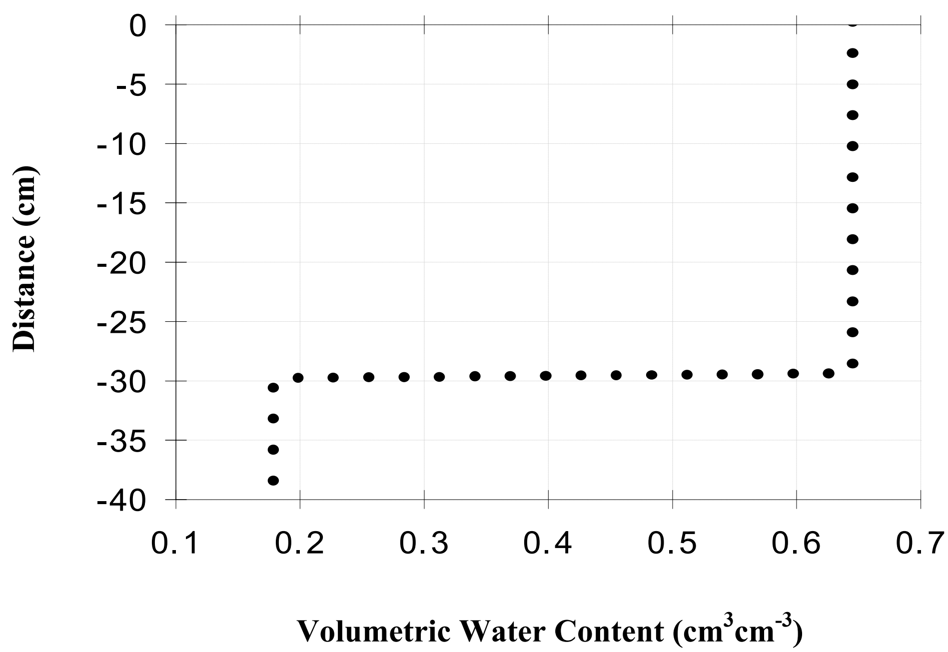


Fig. 5.4. Observed and fitted (Brooks-Corey) values of matric head versus the volumetric water content for the Axis amendment.

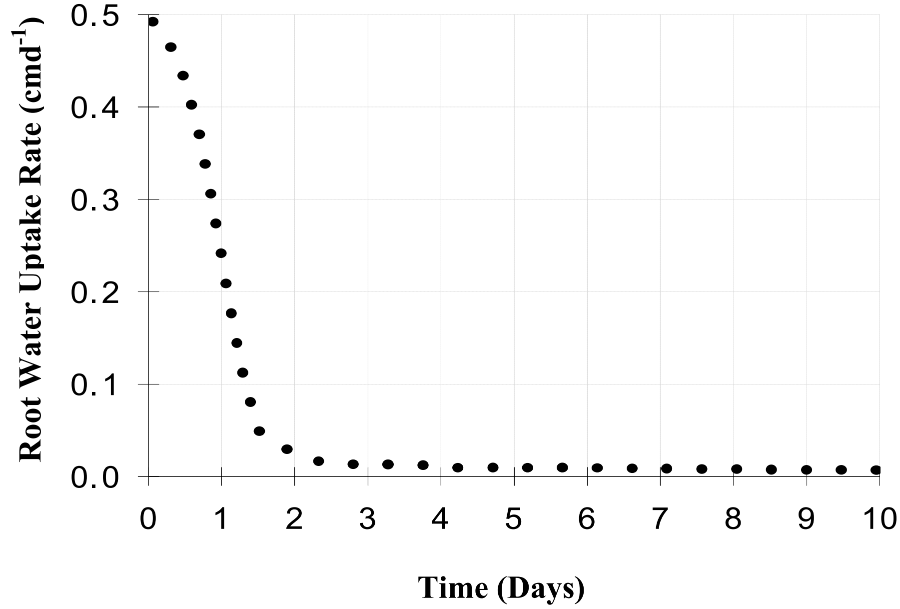


(A) Non-amended root zone (100% sand)

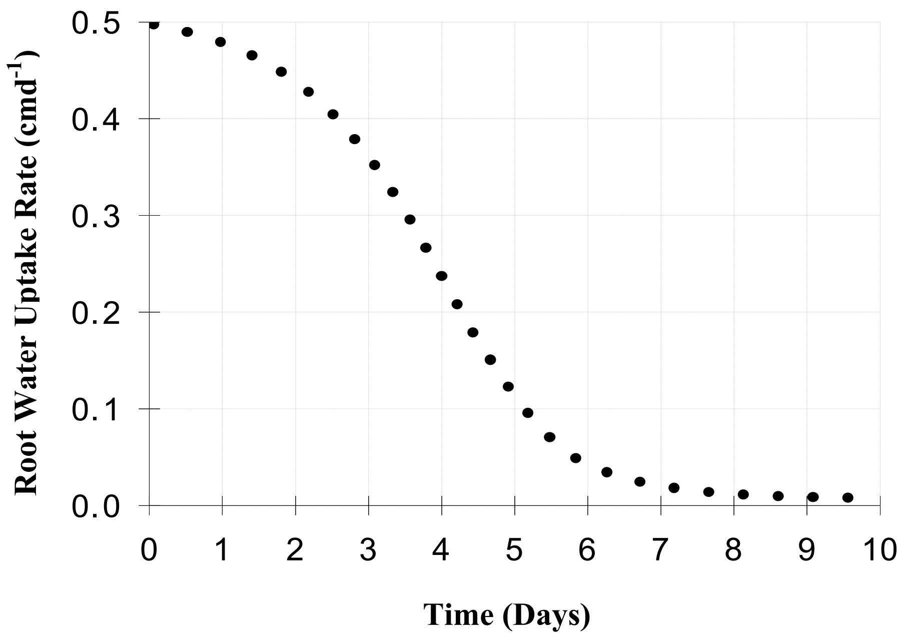


(B) Amended root zone (15% Axis + 85% sand)

Fig. 5.5. Variation in volumetric water content with depth for a 10-day simulation period for (A) Non-amended and (B) Amended root zone.

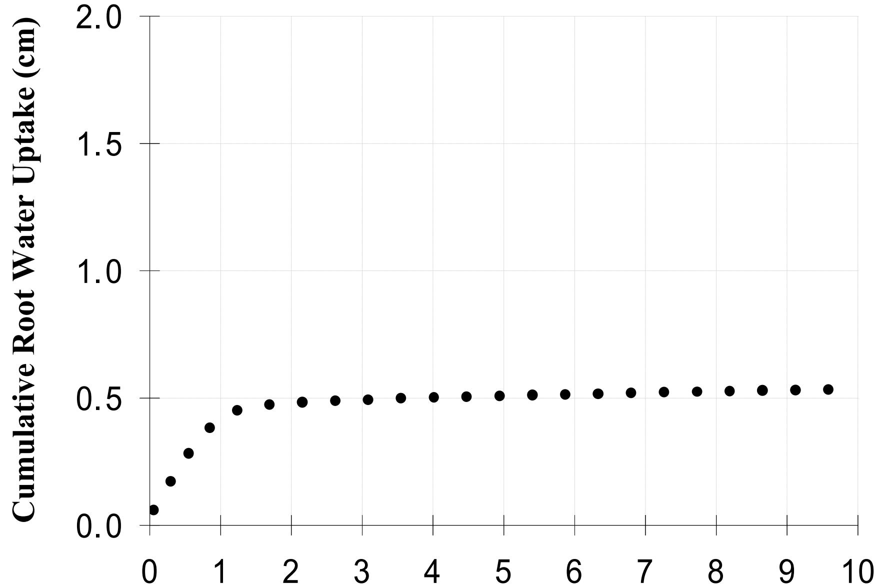


(A) Non-amended root zone (100% sand)

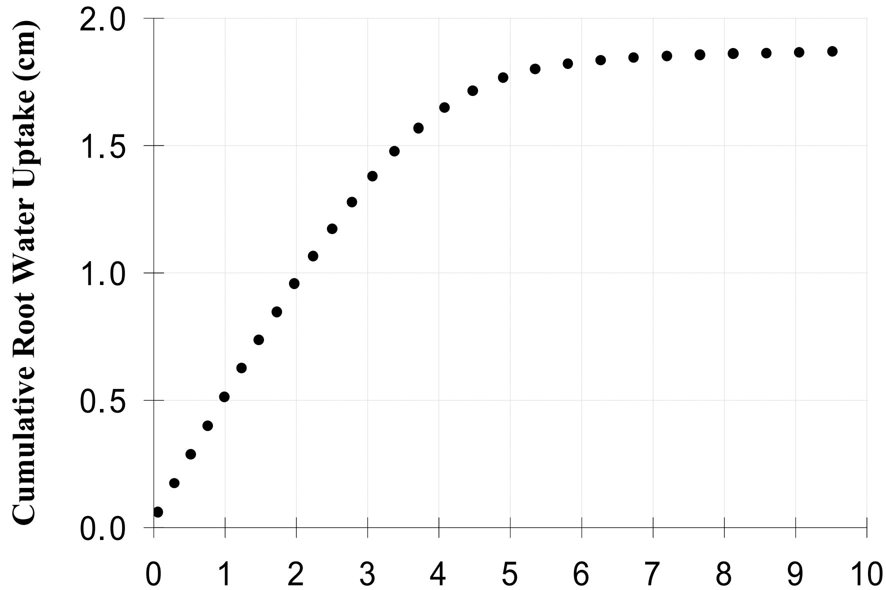


(B) Amended root zone (15% Axis + 85% sand)

Fig. 5.6. Root water uptake rate for a 10-day simulation period for (A) Non-amended and (B) Amended root zone.

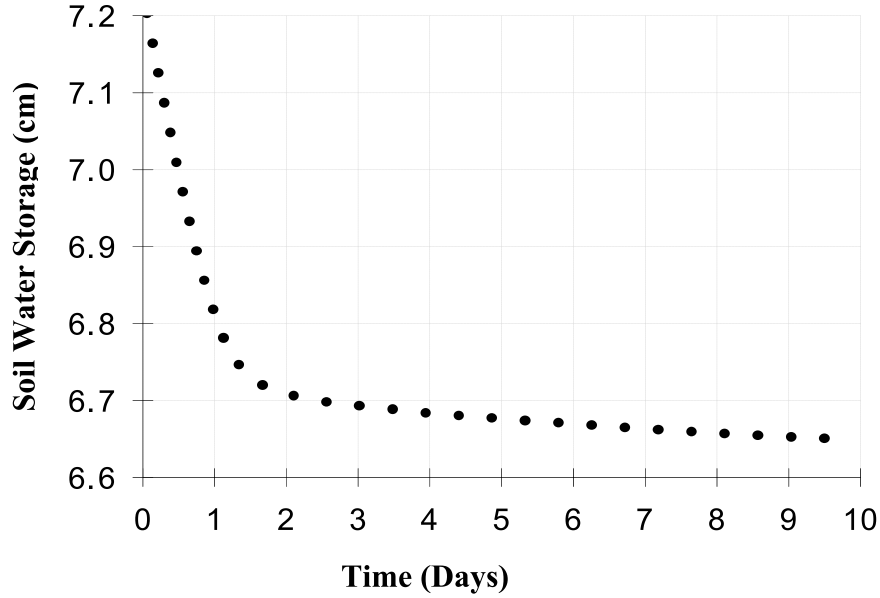


(A) Non-amended root zone (100% sand)

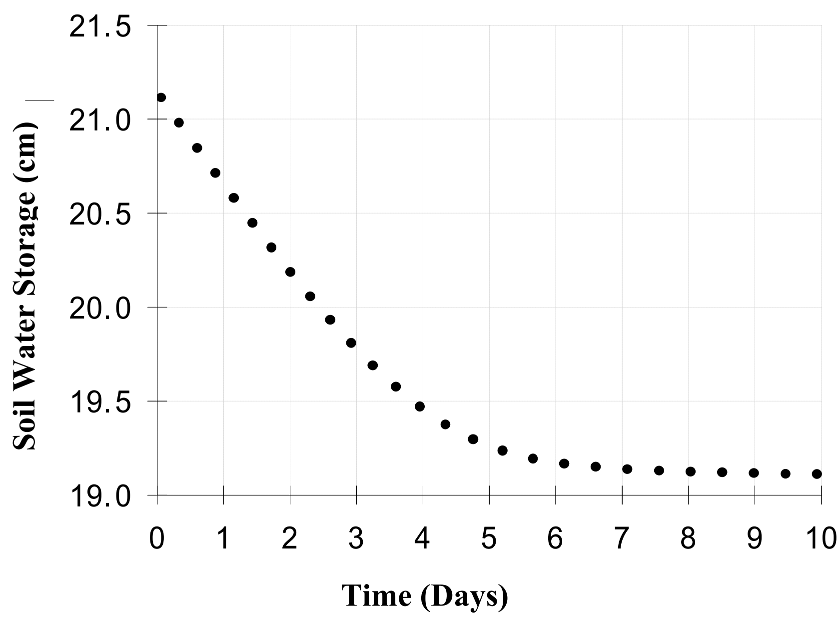


(B) Amended root zone (15% Axis + 85% sand)

Fig. 5.7. Cumulative root water uptake rate for a 10-day simulation period for (A) Non-amended and (B) Amended root zone.



(A) Non-amended root zone (100% sand)



(B) Amended root zone (15% Axis + 85% sand)

Fig. 5.8. Soil water storage for a 10-day simulation period for (A) Non-amended and (B) Amended root zone.