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EVALUATION OF GOLF COURSE WATER USE

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Executive Summary

Golf courses are often in the spotlight when it comes to water consumption practices. However, research is limited on the amount of water a golf course requires to sustain acceptable quality and playability under today's intensive golf course management. Field experiments at five golf courses in the central Florida area were conducted to evaluate the performance of the irrigation system and to evaluate the effects of irrigation amounts on turf quality and rooting depths of golf course turfgrasses. Ten and twenty percent reductions of normal irrigation practices were used to evaluate the relationship between irrigation amounts on turf quality and rooting depths. The average uniformity of the five tested golf courses' irrigation systems ranged from 45 to 63%. Understanding the uniformity of the irrigation system is essential for conserving water on golf courses because low uniformity increases irrigation run times needed to meet the irrigation requirements of dry areas. It was discovered during the study that the manufacturer reported precipitation rates were different than actual irrigation delivery precipitation rates. Irrigation system installation and maintenance also played a role in reduced efficiency.

The average soil moisture uniformity at the five golf courses was greater than 65%. The soils seem to have a moderating effect on the lower distribution of the irrigation system. No compensation was made for previous rainfall. No differences in turf quality existed between the three different irrigation treatments in this study. The greater than normal rainfall during this study contributed to this response. Reducing normal irrigation amounts by ten and twenty percent, by reducing irrigation run times, produced a conditional response resulting in increases in average and maximum rooting depths over the ten-month study period.

The model used to predict water needs of golf courses was not effective using default data. Prediction using default data and actual data was similar only 20% of the time. Due to the above-average rainfall, the model dramatically over-predicted irrigation needs. Turf managers as part of their normal operations used 12 to 55% less water than the model predicted as the irrigation requirement. When using actual environmental data, the model predicted irrigation amounts similar to those used by the turf managers. This was a significant discovery but not very useful for permitting since it is difficult to use current weather for long-term predicted needs.

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Introduction

Golf is a highly popular recreational activity in the United States. In 2000, there were over 15,000 golf facilities in the country (National Golf Foundation [NGF], 2003). Florida has over 1,100 public and private golf courses (NGF, 2003). Water use for irrigation is a critical and growing issue in the state of Florida. With more golf courses than any other state, the Florida golf industry is often in the spotlight with regard to water consumption practices. This is especially true during periods of drought. Florida has a humid subtropical climate with a mean annual rainfall of 52 inches per year (National Oceanic and Atmospheric Administration [NOAA], 2003). This is an amount sufficient to meet turfgrass needs. However, the typically erratic distribution of rain and Florida's predominantly sandy soils make irrigation necessary in order to sustain quality turfgrasses.

Determining the appropriate level of irrigation for turfgrasses is vital to the health of the turfgrass and the conservation of water. Turfgrass water use rates vary from species to species, region to region, and even from location to location within a golf course. Research indicates that the amount of water a golf course uses is dependent on the environmental conditions, design and management of the irrigation system, turfgrass species, course layout, location of the course, amount of inputs, and the level of quality desired (Barrett et al., 2003; Beard et al., 1992; Brown et al., 2001; Carrow, 1995; and Meyer and Camenga, 1985).

Demand for improved aesthetics and playing conditions on golf courses has been increasing in recent years. This is due in large part to the fact that golfers are watching Professional Golf Association (PGA) tournaments on television and seeing the perfectly manicured lush green golf courses. Too often, golf course superintendents come under heavy pressure to maintain the golf course under tournament-like conditions. This often leads to superintendents applying whatever means possible to keep their course green or risk losing their job. This situation seems to encourage over watering.

Efficient water use on golf courses is dependent upon several factors, most notably the irrigation practices of the turf manager and performance of the irrigation system. Deficit irrigation is one means of conserving water. Deficit irrigation is some fractional level of irrigation made in response to some reference water use estimate, such as a Class A Pan, Penman, or some other reference or determination (Kneebone et al., 1992). Of concern to the superintendent would be the quantity of water conserved and any adverse effects on turf quality.

Study Objectives

1. To evaluate the performance of the irrigation systems on three holes at five golf courses located in the central Florida sand ridge and determine the performance characteristics for the tees, fairways, and greens at each course.

2. To evaluate the effects of reducing irrigation runtimes by ten and twenty percent on turf quality and rooting depths.
3. To process field data in the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) water use modeling and compare default model estimates to model estimates using site-specific data.

Review of Tasks

1. Purchase all necessary operational capital outlay (OCO) equipment to perform data collection and sample analysis.

   Equipment was purchased, installed, calibrated, and maintained by UF. Following an incident of vandalism, an additional weather station was budgeted but fortunately was not needed.

2. Evaluate total water use on five golf courses within District and in the sand ridge areas of Marion, Lake, and Orange counties and attempt to determine water use on specific areas of the golf course utilizing their computer controlled irrigation systems and detailed water use data.

   The purpose of this task was to find several golf courses to provide a replication of treatment responses for monitoring. It was difficult to find five golf courses willing to cooperate that are permitted in the St Johns River Water Management District. The five courses represented in this study used the two major irrigation control systems commonly found in the industry. Due to difficulty in downloading data from these systems and without District assistance in completing this task, hand-recorded logs were the last resort to complete the on-site data collection. Results of this task are presented throughout the report. Data are summarized in Figures 10 through 14 and Table 6.

3. Monitor environmental factors that may influence turf water use in the test area.

   Environmental factors evaluated included the parameters required by Ref-ET and the Penman-Monteith equation. Soil moisture data was collected immediately before and after operating the irrigation system for the irrigation audits. Comprehensive weather information was incorporated into the calculation of potential evapotranspiration (ET_p) and is presented throughout the report. A study such as this would benefit from a longer monitoring period. Data are summarized in Figures 4 through 8.

4. Assess turfgrass water needs on the golf course testing areas and ascertain how much water use can be reduced and still maintain acceptable turfgrass quality and meet desired golfing playability.

Water status was evaluated under normal irrigation and rainfall amounts. In addition, holes receiving 10 and 20 percent reductions in runtimes (compared to control) were also evaluated. Visual turf quality and rooting depths were evaluated in response to the watering practices. This task should be completed over a longer period of time than was possible in this study due to the atypical weather pattern (rainfall) recorded during this study. Soil types for this study were limited specifically to the highly permeable soils of the central sand ridge area. Additional data collection on golf courses with a heavier soil may be beneficial, even though total water requirements per acre may be less. Data are summarized in Tables 4 and 7.

5. Determine irrigation system uniformity at each site at specific locations.

   This task was addressed after identifying the golf courses. The data can be found throughout this report. Data are summarized in Tables 2 and 5 and Figures 1 through 3. Reports suggest that evaluating alternative nozzles in existing irrigation heads can prove beneficial for improvement of irrigation uniformity.

6. Collect and process data that can be used for water use modeling (e.g. AFSIRS).

   This task was initiated with task 5 and continued throughout the study. These data were subject to analysis in AFSIRS along with sensitively analysis of AFSIRS (not specifically part of the task) to determine the relationship of data ranges to irrigation requirement predictions. Data are summarized in Tables 3 and 8 and Figures 9, 15, 16, and 17.

7. Assemble findings of study, combined with published information, into a "Water Use" Management Practices manual. This manual should include suggested times of irrigation including duration and when to or not to irrigate, and amounts of irrigation water applied for greens, tees, and fairways. Suggestions to improve irrigation efficiencies through irrigation design or use of weather stations should also be included. Recommendations should be made for the possible reduction of water use on golf courses that would not compromise the playability or quality of the turfgrass.

   The technical report includes a section that outlines water use management practices, including items such as alternative water sources, irrigation system design, irrigation system performance, irrigation scheduling, golf course design, best management practices, water conservation, and water conservation plans. All components of this task are mentioned in the manual. The determination of suggestions for times of irrigation including duration and amounts was not specifically addressed. This study could not formulate a hypothesis to address this part of the objective, nor could it find relative information in the literature to specifically address this question. Irrigation scheduling, including amounts and durations was discussed in the context of reference ET. The amount of attention focused on each subject is relative to study findings and available published information. This document should be used to enhance professional knowledge and *provide insight into potential alternative practices. The manual should not be viewed as a regulatory standard or an endorsement by the University of Florida-IFAS.*

8. Complete a literature review detailing the use of soil for turfgrass growth, specifically addressing how amendments impact water efficiency. Address alternative turfgrass use and turfgrass use at salt-affected sites. The literature review shall include recommendations for future and more in depth investigations of factors influencing or reducing water use on golf courses.

   A detailed literature review was conducted to identify amendment work in relation to turfgrass establishment and culture (Appendix E). There is a very small body of information that directly relates to amendment use on golf courses except for the golf green area specifically. The literature review did not include specific recommendations for future investigations, but it should be apparent from the lack of information related to golf course turf uses that on-site investigations are warranted. These investigations should address the diversity of organic composts and limitations specific to golf course use. An existing document, CIR 1244 by L.E. Trenholm and J.B. Unruh, UF-IFAS University of Florida, was adapted to this report to address turfgrass use at salt-affected sites (Appendix F).

Golf Course Description

Greens, tees, fairways, and roughs are irrigated on Florida golf courses. The green is especially prepared for putting (Beard, 1985; Beard, 2001). The tee is specifically prepared for hitting the first shot of each hole (Beard, 2001). The fairway is the turfed area between the tee and green. The turfed area surrounding the green, tee, and fairway is commonly referred to as the rough. The intensity of maintenance on rough areas varies from golf course to golf course. Some golf courses will have primary rough, higher cut turf immediately adjacent to the fairway; intermediate rough, turf located parallel and between the fairway; and the rough that interfaces with adjacent homeowners (if applicable) is often referred to as secondary rough. Most modern golf courses are constructed with a minimum amount of secondary rough (Beard, 1982).

Golf Course Area

A typical 18-hole golf course is 133 acres consisting of 4 par 3-holes, 4 par 5-holes, and ten par 4-holes (McCarty et al., 2001). Putting greens occupy between 2.1 - 3.3 acres on a typical 18-hole golf course (McCarty et al., 2001). Greens ranging from 5000 - 7500 square feet in size are the most common (Beard, 2001). Longer holes (par 4 and par 5) usually have larger greens and the smaller greens are typically used on par 3 holes (Beard, 2001).

Early golf courses were built from a mixture of soil, organic matter and sand from the construction site. Often soil was pushed up and the greens were slightly rounded to promote the runoff of water (Beard, 1982). While many courses still feature greens like this, others have greens built to United States Golf Association (USGA) green specifications. A USGA golf green profile consists of 12 to 14 inches of rootzone medium (finest textured) over a 2 to 4 inch coarse sand layer (choker layer) which covers a 4 inch layer of gravel (Higgins and McCarty, 2001). Drainage on USGA greens is provided by drain lines embedded in the gravel layer.

Tees comprise between 0.4 - 3 acres of a golf course (McCarty et al., 2001). Sizes range from 100 - 200 square feet per thousand rounds of golf annually for par 4 and par 5 holes to 200 - 357 square feet per thousand rounds of golf annually for par 3 holes (Beard, 1985). Total fairway area covers 30 - 60 acres, the average being approximately 49 acres (Beard, 1985). This is dependent on the playing length (par 4 or par 5) of the hole and width of the fairway. Fairway widths vary from 25 - 60 yards with the typical fairway width being 35 yards (Beard, 2002). The size of the rough on a golf course is dependent on total acreage and design of the course. Golf courses encompassing 140 - 200 acres typically have a rough area of 65 - 120 acres (Beard, 2001).

The areas of a golf course are managed with varying levels of inputs and often require different amounts of water. Greens usually receive the highest levels of maintenance followed by the tees, fairways, and rough. The amount of water depends on the grasses being irrigated, rooting depth, level of maintenance, amount of inputs, and the desired effect.

Turfgrass and Cultural Systems

Bermudagrasses are the most common turfgrasses used on Florida golf courses (Lowe, 2003; Sartain et al., 1999). Typical mowing heights for bermudagrass turf are 0.15 to 0.185 inches; with some dwarf varieties able to tolerate mowing at 0.10 to 0.125 inches. 'Tifdwarf', a low growing hybrid released in 1965 by the United States Department of Agriculture-Agricultural Research Service (USDA-ARS), has been one of the most prominent cultivars installed on putting greens. Other cultivars seen on greens are the "ultradwarf" bermudagrasses 'Floradwarf ' (Dudeck and Murdoch, 1998,), 'Champion' (Beard, 1998) and 'TifEagle' (Hanna and Elsner, 1999).'Tifway' (a.k.a. '419') bermudagrass is the primary cultivar used for tees, fairways, and roughs. The bermudagrass cultivars 'GN1' and 'Tifsport' have seen limited use since being released in 1995.

Turf breeding in the 1990's has resulted in an alternative to bermudagrasses. Seashore paspalum cultivars have seen increased use on golf courses in the state since 2000 because of their excellent tolerance to saline or recycled waters (Lowe, 2003). According to Todd Lowe, USGA Agronomist, six courses of entirely seashore paspalum will exist by 2004 and interest in its uses is increasing, especially in South Florida.

Water Consumption

It was estimated that total water use by Florida golf courses in the year 2000 was 172 billion gallons (Haydu and Hodges, 2002). Based on this survey, nearly 85 billion gallons came from reclaimed water, 49 billion gallons from surface water, 35 billon gallons from on-site wells, and 1.2 billion gallons from municipal sources (Haydu and Hodges, 2002). The average water use per golf course was estimated at 133 million gallons per year. The mean water consumption was 1.23 million gallons per acre or 3.75 acre feet applied (Haydu and Hodges, 2002).

Golf Course Irrigation Components

Golf course irrigation systems usually consist of pump stations, water distribution lines, electronic controllers, control valves, and sprinklers (Barrett et al., 2003). In the last decade significant technological changes have been introduced in pumps and controllers.

Pump stations may range from a single main pump to an elaborate multiple pump arrangement with appropriate controls and valves. The function of the pumping station is to draw water from a source, such as a tank, lake, or well and subsequently release the water to the irrigation system at the pressure and flow required by the irrigation system design specifications (Beard, 2001).

Most water distribution lines for golf course irrigation systems are permanently installed underground. The piping involves relatively large main lines at the pump discharge point, with the piping gradually sized downward through the more distant lateral lines to the most distant sprinkler heads (Beard, 2001). Modern golf course irrigation systems utilize polyvinyl chloride (PVC) pipe. PVC pipe is used because of its relatively light weight, resistance to corrosion and chemicals, long life expectancy, and ease of installation (Pira, 1997).

Irrigation controllers have been significantly impacted by technology. Modern golf course irrigation systems have a PC based central controller and several field controllers (Barrett et al., 2003; Pira, 1997). This type of system offers the flexibility of globally adjusting every station on the property as a single group, fine-tuning an individual station, or operating the system via radio from anywhere on the property with just a few keystrokes (Barrett et al., 2003). A pocket PC may also be used to remotely control golf course irrigation. It has the added feature of allowing the operator to view programming data, make various site adjustments, and if available view a map of the irrigation system (Barrett et al., 2003).

Field controllers, often called satellite controllers, are available in a variety of configurations. Most have the ability to operate as stand-alone controllers or as satellites under the management of the central controller (Barrett et al., 2003; Pira, 1997). Current controllers can operate 8 to 100 stations (Barrett et al., 2003; Pira, 1997).

An alternate to a field controller based irrigation system is a decoder system (Bertauski, 2002). Similar to traditional satellite control, decoders use two-wire communication between central computer, valves and sprinklers to execute various commands for the entire irrigation program (Barrett et al., 2003; Bertauski, 2002). Engineered in waterproof, resin-encapsulated shells, individually buried decoders are capable of powering one to six sprinkler heads (Barrett et al., 2003).

Control valves are used to release water into either the distribution line or sprinkler head. The number of control valves is dependent on how the sprinklers are zoned. Sprinklers are grouped 1-5 per valve on modern golf courses (Barrett et al., 2003; Pira, 1997). Irrigation systems with one sprinkler per valve are often termed valve in-head systems and are very common in arid climates where irrigation is the primary source of water for turfgrass. These systems incorporate a valve in the sprinkler itself and eliminate the need for a remote control valve. Each sprinkler on every green, tee, fairway, and even in the rough is a controllable station to offer the ultimate in control capabilities to minimize wet and dry areas (Barrett et al., 2003).

Irrigation systems that mix paired and individually controlled sprinklers are more common in Florida where irrigation supplements precipitation (Barrett et al., 2003). These systems can be very effective as long as heads are zoned to respond to the moisture needs of small areas. A typical Florida golf course will irrigate the tees as a group, usually having two sprinklers per valve. Fairways and roughs can range from 2-5 heads per valve. The uniformity of irrigation and precision of control are more important on the green than any other part of the golf course. A typical green has four individually controlled part- circle sprinklers throwing onto the putting surface and four part- circle sprinklers throwing away from the putting surface (Barrett et al., 2003; Pira, 1997). This is done to account for the different water requirements of the rough and green. However, due to the irregular shape of greens, additional heads are installed for the putting surface to achieve maximum uniformity (Barrett et al., 2003; Pira, 1997; Watkins, 1978).

Pop-up rotary sprinklers are the most common sprinkler used in golf course irrigation systems (Watkins, 1978; Barrett et al., 2003). Rotary sprinklers are available in multiple nozzle configurations. Sprinkler manufacturers test these configurations and produce sprinkler performance data in accordance with ASAE Standard S398.1 (American Society of Agricultural Engineers [ASAE], 1993), that outline the proper testing and reporting for a sprinkler's radius of throw (Barrett et al., 2003). Performance data usually will provide the radius of throw, base pressure, and flows of the different sprinkler/nozzle configurations (Watkins, 1978; Barrett et al., 2003). Flow ranges from 15-75 gallons per minute (gpm) and radius varies from 20 to 100 feet (IA, 2003).

Sprinkler spacing is important in irrigation uniformity. Irrigation design is typically based on spacing sprinklers head-to-head. That means that if a sprinkler head has a radius-of-throw of 80 feet, it should be spaced no more than 80 feet from other sprinkler heads (Watkins, 1978). Current philosophy in golf course irrigation designs usually will space irrigation heads at shorter distances than the radius of throw to accommodate for the actual profile of the sprinkler (Barrett et al., 2003). Cost considerations often cause changes to be made to the original design intent. These changes often are manifested as using fewer heads or greater head spacing. The sprinkler profile is affected by the size of the nozzle, shape of the nozzle, operating pressure, rotation speed of the sprinkler and average wind speeds for the region (IA, 2003). A change in any one of these variables will change the profile and may adversely affect uniformity. Therefore, irrigation designers will use 45 to 75% of the radius of throw as a means of spacing irrigation heads with the lower percentages used to compensate for wind effects (Barrett et al., 2003; Pira, 1997; Watkins, 1978).

The number of sprinklers on a golf course can range from 250 to 500 heads on a simple system to over 2000 sprinklers on a complex system (IA, 2003). Golf courses with fewer heads will normally have sprinklers with larger spacing patterns. The spacing pattern on a typical single row system is 90 to 100 feet (Barrett et al., 2003; Watkins, 1978). Typically, heads spaced at farther distances tend to have poor uniformities (Barrett et al., 2003). Poor uniformity means that the system must over-irrigate some areas in the pattern to apply enough water to the drier areas to keep the turf there from dying (Huck, 1997; Wilson and Zoldoskie, 1997). Modern irrigation (two and three row) systems utilizing shorter radius sprinklers spaced closer together, 60 to 80 feet, will normally have higher uniformities (Barrett et al., 2003; Pira, 1997; Watkins, 1978). The down side to this design is the increased material and installation costs.

Irrigation Distribution Uniformity

Irrigation system performance is described in terms of distribution uniformity and the precipitation rate. Distribution uniformity is an important component of any irrigation system design. The more uniform a water application, the less operating time an irrigation system needs to make up for poor coverage (Wilson and Zoldoske, 1997). Uniformity is based on the nozzling and spacing of individual sprinklers (Barrett et al., 2003). Depending on its radius of throw, each sprinkler applies a specific amount of water over a specific area in a specific amount of time. This is the precipitation rate, and it is usually measured in inches per hour (Bowman et al., 2001). If the precipitation rate varies significantly over the area being irrigated, uniformity is poor; a precipitation rate that is nearly equal throughout the area provides good uniformity (Huck, 1997; Meyer and Camenga, 1985; Pira, 1997).

There are several ways to calculate distribution uniformity, but the method most commonly used for turfgrass is called the Lower Quarter Distribution Uniformity or DU_{LQ} (IA, 2003). This method has been used since the 1940s by the United States Department of Agriculture (USDA) (Ascough and Kiker, 2002). The DU_{LQ} is the average water applied in the twenty-five percent of the area receiving the least amount of water, divided by the average water applied over the entire test area. The largest volumes could also be used to express DU, but since the low values are more critical in irrigation, the smallest values are used (Burtt et al., 1997).

Pitts et al. (1996) evaluated the performance of 385 irrigation systems. They reported that the average DU_{LQ} for agricultural sprinklers, micro-irrigation, furrow irrigation and turf irrigation were 65, 70, 70, and 49 percent, respectively. Thirty-seven turf irrigation systems were evaluated, 40 percent of which had DU_{LQ}'s less than 40%. No explanation was provided why the systems tested had a lower than expected DU. The turf area tested in their study ranged from 1 – 30 acres. However, historical averages show DU_{LQ}'s on golf courses range from 55 to 85 percent (Thompson, 2002). The Irrigation Association (IA) states in their manual that 70 percent uniformity is what should be expected on golf course irrigation systems that are properly installed and functioning (IA, 2003).

Analysis in the central Florida study revealed that DU_{LQ} was influenced by golf course and location within golf course. The lower quarter distribution uniformities (DU_{LQ}) for golf courses can be classified by the IA (2003) system quality rating scale. Table 1 contains general head considerations provided by the IA in their Auditor Handbook. The average DU_{LQ} for the five golf courses tested was 55% and would be classified in the "poor range" for rotor systems. The systems were tested without previously evaluating for improper installation parameters or management problems that may have existed. It was assumed that the systems were functioning and in good repair. The golf course managers could have made any necessary repairs before the audit if they desired because they knew which holes were to be evaluated and the dates of the evaluations. Of the five golf courses tested, only two courses' average DU_{LQ} would be classified as having "poor" uniformities. None of the courses evaluated had an average DU_{LQ} that equaled or exceeded the DU_{LQ} of 70% needed to be classified in the good range, but there were greens within golf courses that did meet or exceed the 70% DU_{LQ}. Four of the five golf courses evaluated had average DU_{LQ} values greater than the 49% average DU_{LQ} reported by Pitts et al. (1996) for large turf irrigation systems. Unfortunately, the Pitts et al., is currently the only available published article documenting actual golf course irrigation systems in use.

Table 1. Irrigation Association (2003) proposed DU_{LQ} rating system for golf systems by sprinkler type and system quality.

Sprinkler Type	Excellent (Achievable)	Good (Expected)	Poor
Rotor	80%	70%	< 55%
Spray	75%	65%	< 50%

Golf course D had the highest average (63 percent) DU_{LQ} of all the courses (Table 2). This result was influenced by the high fairway (66 percent) and green (65 percent) DU_{LQ}'s. There was very little pressure variation among sprinklers in the fairway. The pressures measured ranged between 50 psi and 60 psi and were within the recommended pressures of the manufacturer (RainBird, 2002). Sufficient sprinkler overlap was also achieved on the fairways at this course. The average ratio of sprinkler spacing to throws was 1.12. The sprinkler spacing on the fairways was 75 feet. Throws ranged between 74 feet and 90 feet. The greens at this course had pressure measurements ranging from 50 psi to 60 psi, with 88 percent operating at 60 psi. Greens also had sufficient (head-to-head) sprinkler overlap at this course. The average sprinkler spacing to throw ratio was 1.06. Sprinklers on the greens were spaced at 75 feet. The throws measured ranged from 65 feet to 84 feet. The high average DU_{LQ} at this course was the result of sprinklers installed and operating within the manufacturer's specifications.

Golf course E had an average (45 percent) DU_{LQ} lower than any other course (Table 2). This result was influenced by the low green DU_{LQ} (30 percent.). There were significant pressure variations on one of the greens tested and insufficient sprinkler overlap on both greens. The green with significant pressure variation had all four sprinklers operating at different pressures. The pressures measured ranged from 30 psi to 50 psi. Only one sprinkler was operating within the recommended pressures suggested by the manufacturer's sprinkler performance data (RainBird, 2002). The sprinkler spacing on the greens was 75 feet. Throws recorded during the catch-can tests for these greens ranged from 55 to 92 feet. The combination of variability in pressures and only one sprinkler operating within the manufacturer's specifications contributed to the poor distribution uniformity for the greens at this course.

Table 2. Lower quarter distribution uniformity (DU_{LQ}) statistics of five golf courses (GC) at three fairway, green, and tee locations within golf course. GC means represent the average of three holes measured in 2002.

			DU_{LQ}		
GC	GC Mean	Location	Location Mean †	Min	Max
A	57 ab	Fairway	40 a	28	58
		Green	73 b	69	77
		Tee	60 b	56	67
B	50 bc	Fairway	42 a	39	47
		Green	56 a	45	64
		Tee	52 a	43	59
C	56 ab	Fairway	53 a	43	63
		Green	61 a	56	67
		Tee	54 a	51	58
D	63 a	Fairway	66 a	65	67
		Green	65 a	54	73
		Tee	59 a	52	68
E	45 c	Fairway	46 a	41	54
		Green	30 c‡	30	31
		Tee	58 b	56	62

†Means within column followed by unlike letters are significantly different at the 5% level by Fisher's Least Significance-Difference test.
‡ Mean value represents an average of two greens due to irrigation system malfunction during the test.

DU_{LQ} locations within the three golf courses, B, C, and D, had similar measured values; whereas there were differences in locations within golf courses A and E. The average DU_{LQ} of the greens at golf course A was measured to be 85 percent greater than the fairway and 24 percent greater than the tee. The large difference between the green and fairway can be attributed to a 28 percent DU_{LQ} values on the fairway that had several malfunctioning heads, a number of sprinklers either not turning, not level, were broken (nozzles), or leaking. None of the sprinklers tested in this fairway had the recommended head to head coverage. The sprinkler spacing for this fairway varied between 80 to 90 feet. The throws measured during the tests varied between 60 to 70 feet. Eighty-three percent (5 of 6) of the sprinklers evaluated were operating below the minimum pressure requirement of 50 psi recommended by the manufacturer (RainBird, 2002). The IA auditing process Step 1 is to fix obvious broken heads before DU testing – this would eliminate the 28 percent DU for a ‘normal’ diagnosis of system design operating potential. The golf course managers were aware that their systems would be evaluated their systems, giving them a chance to diagnose and fix any problems before the tests. With some reasonable maintenance, it is often possible to increase DU before it is measured. On-site repairs were not authorized because the tests were conducted at night by non-golf course employees.

Golf course E had differences in DU_{LQ} among all three locations. The differences among the green and the other locations was the result of the greens operating below the manufacturer’s pressure recommendations. The researchers hypothesized that the differences among the tee and fairway were the result of worn or incorrect nozzles since both locations were operating within the manufacturer’s specification and achieving head to head coverage on the sprinklers tested.

In 2003 the golf course audits were completed using the IA methods without modification. This results in fewer catch containers than were used in 2002. All data was shared with the superintendents and in some cases corrective changes were made. There were substantial improvements in Golf Course A and B for the control hole (Table 3). Several other holes had a more modest improvement. Only two holes had a reduction in DU_{LQ}, one 2 percent and the other 4 percent. Precipitation rates remained fairly constant between the two years. Differences in both DU_{LQ} and PR may be influenced to some extent by fewer catch containers.

Table 3. Lower quarter distribution uniformity (DU_{LQ}) and precipitation rate (PR) data for the fairways from year one (2002) compared to year two (2003).

		DU_{LQ} (%)		PR (inches)	
		2002	2003†	2002	2003†
GC	Treatment				
A	Control Hole	28	60	0.46	0.39
	10% reduction	34	35	0.52	0.50
	20% reduction	58	56	0.70	0.64
B	Control Hole	39	73	0.71	0.78
	10% reduction	47	50	0.63	0.45
	20% reduction	40	60	0.61	0.54
C	Control Hole	63	68	0.63	0.74
	10% reduction	43	54	0.62	0.55
	20% reduction	54	54	0.55	0.55
D	Control Hole	65	75	0.84	1.14
	10% reduction	67	69	0.73	0.95
	20% reduction	66	62	0.76	0.74
E	Control Hole	41	56	0.54	0.32
	10% reduction	54	69	0.52	0.39
	20% reduction	44	60	0.52	0.41

†Audits preformed in 2003 were conducted using IA methods without modification. This method using fewer catch cans, therefore is less stringent and may slightly increase the DU_{LQ} and PR values.

Soil Moisture Uniformity

An understanding of the principles of water movement in the soil profile and an evaluation of the storage and balance of soil water are important for efficient soil and water management, and irrigation scheduling. Although DU_{LQ} is a good indicator to express the distribution of sprinkler water application on the ground surface, research has shown that it may under estimate the uniformity of irrigation water distribution below the ground surface (Li and Rao, 2000). The effects of nonuniformity of sprinkler water application and soil moisture research is limited in turfgrass irrigation evaluations. In agriculture, research on irrigation nonuniformity has been widespread. Li and Kawano (1996) reported sprinkler water is more uniformly distributed in the soil than that measured on the ground surface for an individual irrigation event. They attributed this to wheat canopy interception and redistribution of sprinkler water in the soil. The effect of irrigation uniformity and crop yield has also been investigated. Warrick and Gardner (1983) investigating crop yield as affected by spatial variations of soil and irrigation, concluded that irrigation uniformity was the most important factor. Other studies have disputed these findings, reporting that spatial variability in soil texture, elevation, and water redistribution in the soil are the main factors effecting crop yield (Hunsaker and Bucks, 1987; Li and Rao, 2000; Sousa et al., 1995). Individual factors may be dominant at a site or contribute equally making quantification difficult.

The average lower quarter distribution of soil moisture ($SMDU_{LQ}$) in the present study was greater than 65 percent for all golf courses, although the average catch-can lower quarter distribution uniformity (DU_{LQ}) of sprinkler water varied from 45 percent to 63 percent (Figure 1). These results support those of Li and Rao (2000) in a study evaluating the affect of sprinkler irrigation uniformity on wheat crop yields. They reported that irrigation uniformity coefficients of water in the soil were always greater than 90 percent although the uniformity coefficients of water application varied from 57 to 89 percent. They attributed these differences to winter wheat canopy interception and redistribution of sprinkler water in the soil.

Statistical analysis revealed that $SMDU_{LQ}$ was influenced by golf course and not by location within golf course. It was hypothesized that differences in $SMDU_{LQ}$ among golf courses would be the result of differences among DU_{LQ}. However, there was no correlation between $SMDU_{LQ}$ and DU_{LQ} for this study. In agricultural research, studies have shown that variability in soil texture may influence differences between irrigation uniformity and soil moisture uniformity (Warrick and Gardner, 1983). The spatial relationships of the two parameters were investigated individually to further evaluate responses.

Statistical estimates indicated that irrigation distribution had a strong spatial relationship. Spherical models were defined for irrigation distribution on the greens at all five golf courses. Beyond the 13 meters point, (± 2 meters) (i.e., 14.2 yards) the observations become independent or are no longer correlated with each other (Figures 2 and 3). The relationship among greens did not vary as much as expected. The relatedness within this distance may be a direct function of relatively consistent distance between irrigation heads. The analysis indicated low random variability and measurement error.

It was expected that the spatial structure of soil moisture was controlled primarily by irrigation delivery, with other soil factors (organic matter, texture, hydraulic properties, and management practices) also influencing soil moisture. For soil moisture, the linear relationship indicated the spatial autocorrelation occurs across the entire range. The data response indicated that soil moisture is strongly influenced by soil properties, and that irrigation delivery is not the most significant factor to soil moisture.

Figure 1. Mean lower quarter irrigation distribution uniformity (DU_{LQ}) and mean lower quarter soil moisture uniformity ($SMDU_{LQ}$) at five golf courses.

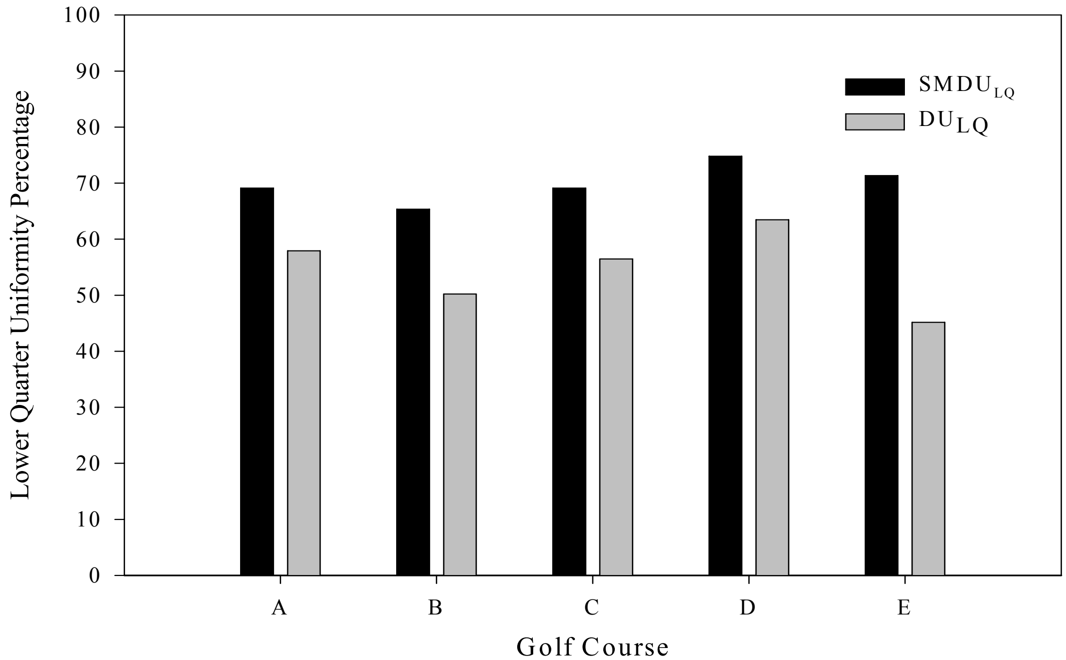


Figure 2. Semivariograms of irrigation delivery and corresponding soil moisture evaluations on three golf greens. Values for the fitted semivariogram sill c, and range a, fit with spherical models. Note that 1 meter equals 3.28 feet or 1.094 yards.

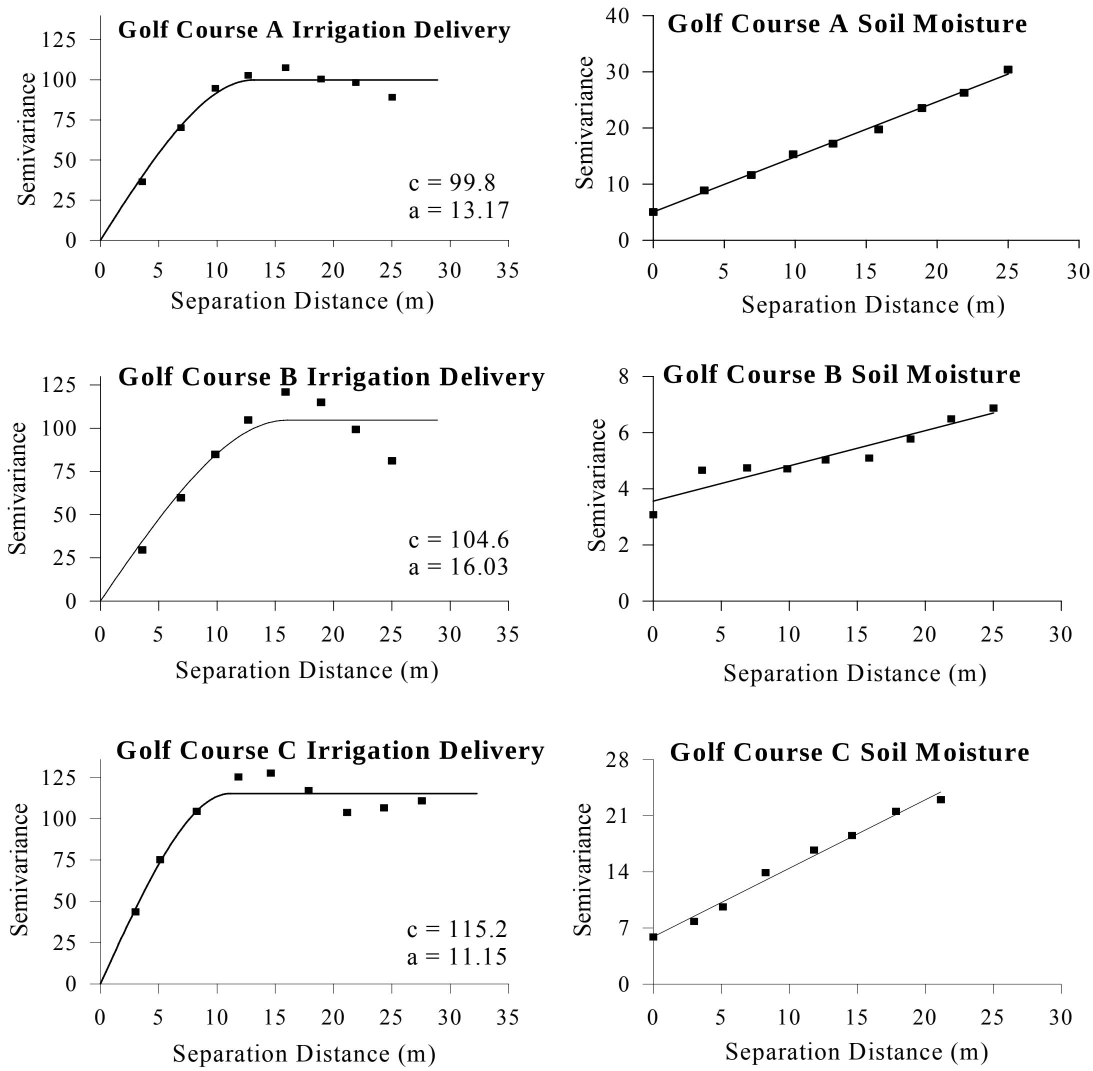
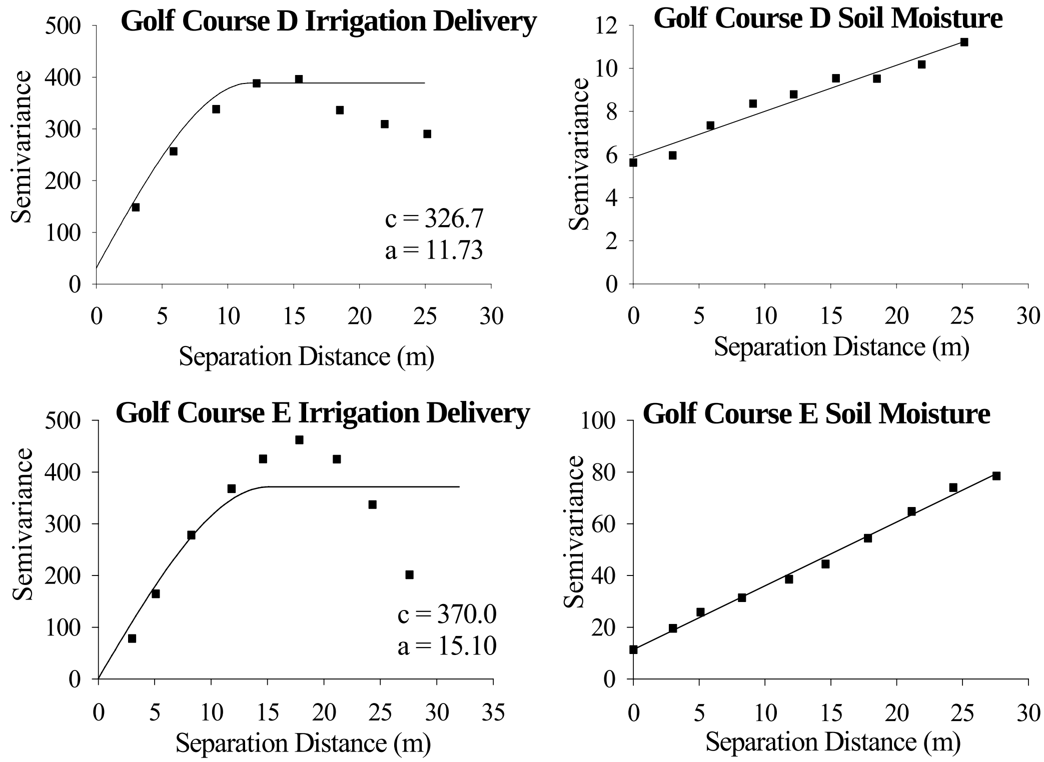


Figure 3. Semivariograms of irrigation delivery and corresponding soil moisture evaluations on two golf greens. Values for the fitted semivariogram sill c, and range a, fit with spherical models. Note that 1 meter equals 3.28 feet or 1.094 yards.



Particle analysis for this study revealed, that there were little differences among golf courses and their soil particle size distribution. All the courses had the soils with the majority of the particles in the coarse to medium sand range (Table 4). Therefore it cannot be concluded that soil particle size variability was the cause of differences in $SMDU_{LQ}$ among golf courses. Based on the results of this study, differences in $SMDU_{LQ}$ among golf courses was not influenced by DU_{LQ} or variability in soil particle size distribution. Therefore, it could only be speculated that these differences were influenced by elevation changes, infiltration rates, or the amount of water in the soil prior to irrigation at these five golf courses.

Table 4. Average particle size distribution of the rootzone mixtures of three locations (loc) on three holes at five golf courses (GC) using Standard USDA grading. One millimeter equals 0.0394 inches.

		% by weight					
		Particle size in millimeters					
GC	Loc	(1.0-2.0)	(0.5-1.0)	(0.25-0.50)	(0.1-0.25)	(0.05-0.1)	(<0)
A	Tee	2.8	23.9	59.0	9.6	3.5	1.3
A	Fairway	2.8	21.7	60.0	11.6	3.6	0.4
A	Green†	11.3	52.0	31.3	3.5	1.0	0.9
B	Tee	0.1	11.0	68.2	18.9	1.7	0.1
B	Fairway	0.0	10.6	68.8	18.3	2.2	0.1
B	Green†	2.5	23.2	60.6	11.9	1.6	0.2
C	Tee	2.8	27.3	44.8	18.2	6.7	0.2
C	Fairway	2.4	29.5	45.7	16.2	5.9	0.2
C	Green†	1.6	31.2	51.9	13.0	2.3	0.1
D	Tee	1.8	17.2	47.3	20.4	13.2	0.2
D	Fairway	0.3	21.2	44.4	24.7	9.2	0.3
D	Green†	7.1	27.4	39.8	19.5	5.9	0.4
E	Tee	4.6	25.1	52.9	11.9	5.4	0.0
E	Fairway	2.9	22.1	58.1	11.6	5.4	0.0
E	Green†	5.0	36.1	48.7	8.0	2.2	0.0
USGA†		<7	<45	> 35	≤ 20	≤ 5	

† United States Golf Association (USGA) suggested specifications for putting green turfgrass root zones.

Irrigation Practices and Turfgrass Quality

Research has shown that there is a relationship between irrigation practices and turfgrass water use (Hagan, 1955). How much water, when, and what rate to apply it are the primary considerations. Too often irrigation schedules are set up on a calendar basis rather than the turf's needs and then runtimes are increased to cover dry areas due to uneven distribution of irrigation system delivery on the golf course (Bowman et al., 2001). This method often results in water being applied excessively and more frequently than required. The objective of an effective irrigation schedule is to supply the correct amount of water before stress occurs without over watering.

In response to the demand for improved conditions, superintendents are employing more intensive maintenance practices. One of the key practices is an efficient irrigation system. Efficient water use on golf courses is dependent upon several factors, most notably the irrigation practices of the turf manager and performance of the irrigation system (Beard, 2001; IA, 2003; Meyer and Camenga, 1985).

Visual turfgrass quality was not influenced by reducing the current runtimes by ten and twenty percent over the ten month period of the present study (Table 5). Golf holes receiving reductions applied similar or higher irrigation amounts despite the reduced run times, due to the wide range of precipitation rates of the irrigation systems across locations (Table 6). In some cases this allowed reduction holes to have similar amount (gallons) of water applied per acre. However, reduction holes were still irrigated with less water than normal, based on previous run times. Therefore, based on the conditions of this study, reducing the current irrigation practices by ten and twenty percent did not have any adverse effects on turf quality over this ten-month study.

Table 5. Influence of irrigation treatments on average monthly visual turf quality ratings of control, 10% reduction, and 20% reduction treatments at five golf courses over a tenth month period; 1-9 with 1 being dead turf and 9 being superior quality, 6 was minimally acceptable.

	Golf Course				
Treatment	A	B	C	D	E
	----- Mean Quality Rating-----				
Control	6.5	7.0	7.7	7.7	6.5
10% reduction (10R)	6.6	7.0	7.7	7.8	6.5
20% reduction (20R)	6.5	7.0	7.7	7.7	6.4
Contrast 10R vs control	ns	ns	ns	ns	ns
Contrast 20R vs control	ns	ns	ns	ns	ns

ns,*,**,***, not significant, or significant at 0.05, 0.01,0.001 levels, respectively

Meyer et al (1985) in a study based on irrigation as a percentage of ET, reported that bermudagrass irrigated at 60% ET was better than acceptable and not significantly different than bermudagrass irrigated at 100% of ET. Although ET was not used to schedule irrigation in this study, irrigation amounts as a percentage of ET_p were evaluated. There was no significant difference among the five golf courses for irrigation amounts as a percentage of ET_p ($p = 0\ .06$). The mean irrigation percentage was 63 percent ET_p (±8).

Turf quality may have been influenced by the amount of rainfall during the ten-month study. Rainfall data is presented in Figures 4 through 8 for the five golf courses. Cumulative rainfall totals did not vary considerably from golf course to golf course with the exception of golf course A (69 inches). The average rainfall for the ten months (July – April) in central Florida is 37.2 inches (NOAA, 2003). All golf courses accumulated rainfall amounts well above the average rainfall. This leads to the conclusion that there were no significant differences in turf quality on the golf courses regardless of the water applied through irrigation.

Table 6. Net irrigation precipitation rates (PR) of five golf courses (GC) at three fairway (fwy), green, and tee locations (loc) measured in 2002.

		PR inches per hour		
		Mean †	Min	Max
GC	Loc			
A	Fwy	0.55a	0.46	0.70
	Green	0.70a	0.65	0.74
	Tee	0.61a	0.35	0.78
B	Fwy	0.64a	0.61	0.71
	Green	1.70a	1.40	2.26
	Tee	0.85a	0.67	0.94
C	Fwy	0.60a	0.55	0.63
	Green	0.65a	0.61	0.73
	Tee	0.59a	0.48	0.74
D	Fwy	0.77a	0.72	0.83
	Green	1.73b	1.64	1.81
	Tee	0.76a	0.61	1.06
E	Fwy	0.52a	0.52	0.54
	Green	0.71a	0.55	0.87
	Tee	0.52a	0.41	0.74

Figure 4. Monthly Rainfall Amounts for Golf Course A.

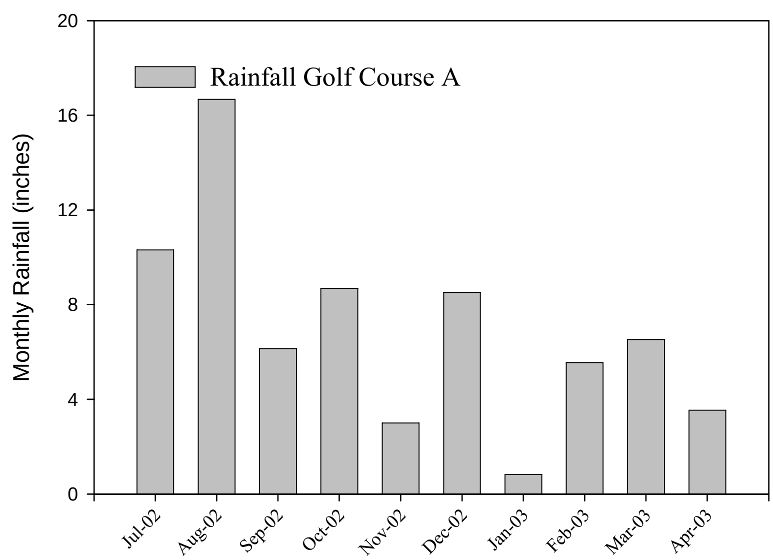


Figure 5. Monthly Rainfall Amounts for Golf Course B.

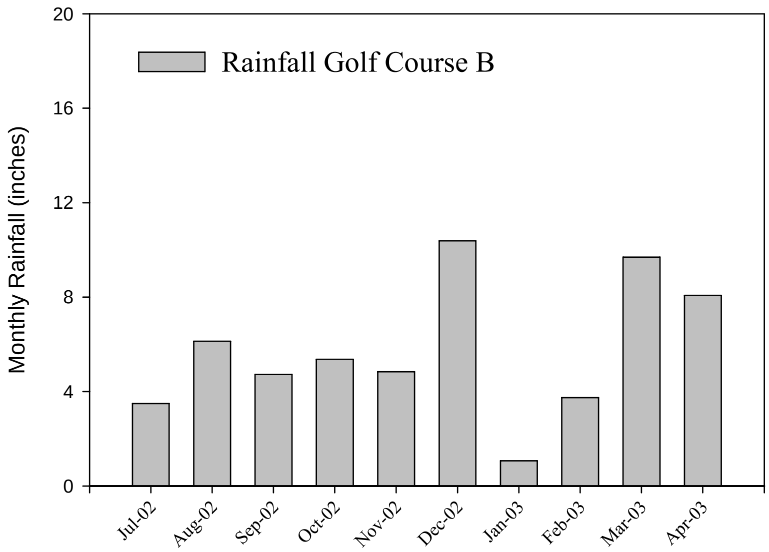


Figure 6. Monthly Rainfall Amounts for Golf Course C.

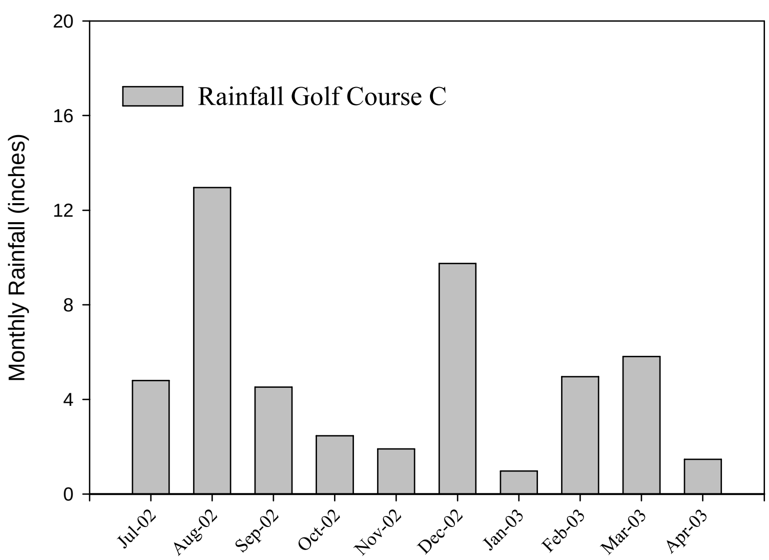


Figure 7. Monthly Rainfall Amounts for Golf Course D.

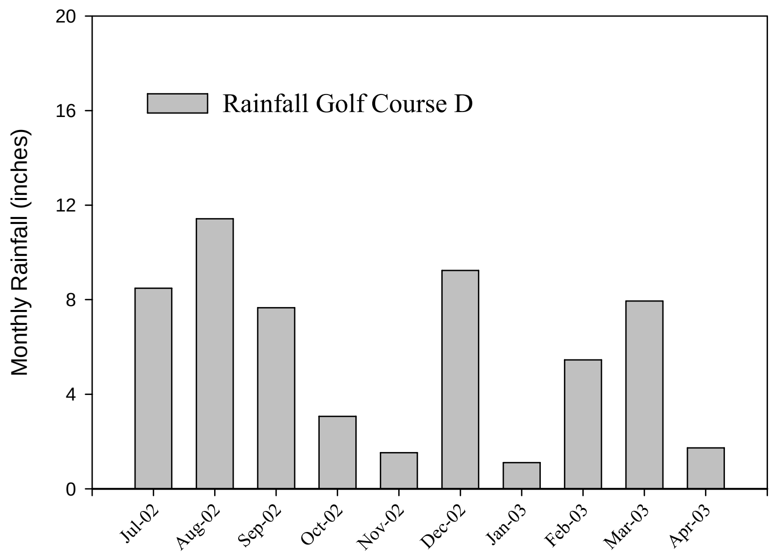
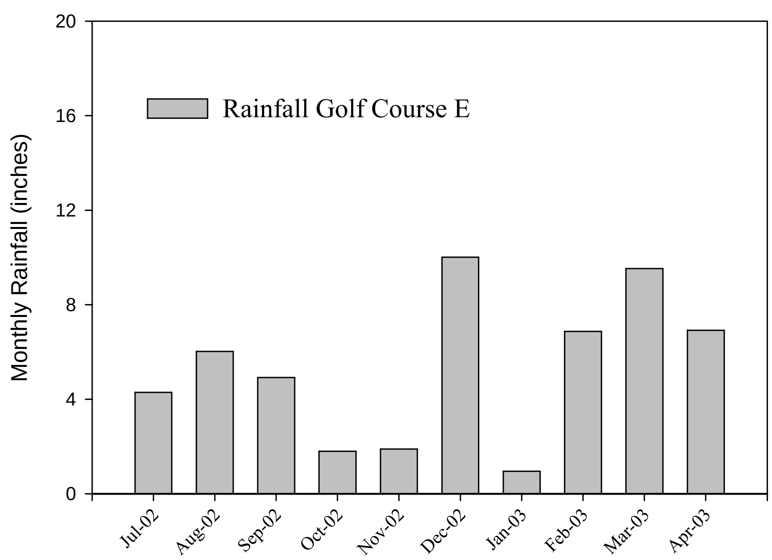


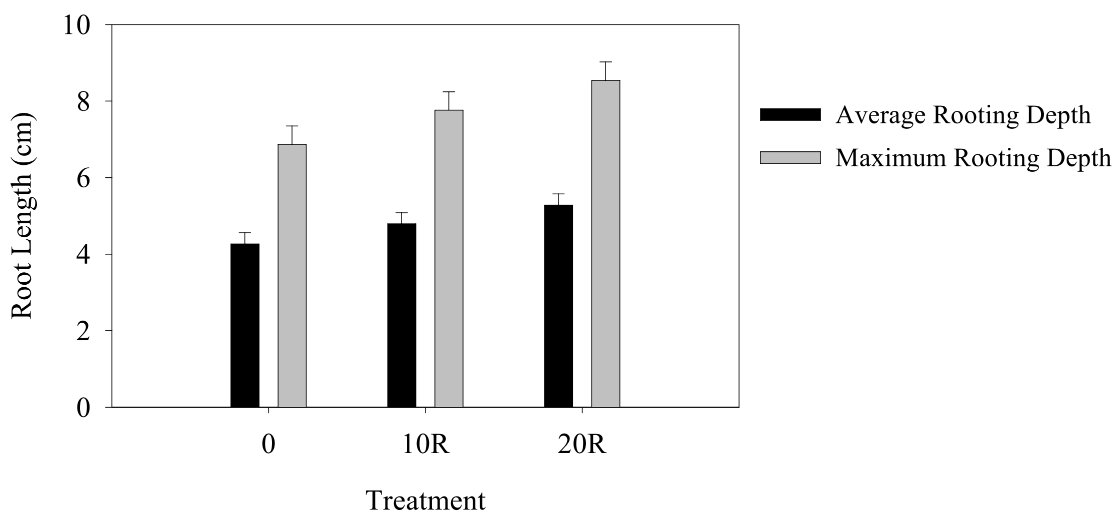
Figure 8. Monthly Rainfall Amounts for Golf Course E.



Infrequent irrigation has been reported to promote increases in root growth (Doss et al., 1960; Gerst and Wendt, 1983; Madison and Hagan, 1962). Fry and Qian (1996) reported that roots of 'Meyer' zoysiagrass irrigated less frequently (watered at first sign of leaf roll) had the ability to extract water from lower depths (22 to 30 inches) than if watered every day to replace ET. Researchers also reported that the turfgrasses with deeper roots had higher quality ratings late in the dry-down period. Huang (1997) showed that zoysiagrass had deeper roots (16 inches) when soil was allowed to dry between irrigation events than when it received irrigation daily. These studies have not been noted for high maintenance turf such as that found on golf courses. Although, deep and infrequent irrigation is a commonly accepted turfgrass recommendation, it provides no basis for determination of actual amounts and frequencies. An alternative recommendation that provides more exact irrigation control is to irrigate based on a percentage of ET. When implemented properly, this is a management recommendation that can contribute to increased turf quality and potentially reduce water consumption.

Rooting depth was influenced by irrigation treatments in both average and maximum rooting depth measurements averaged (four sampling dates) over the ten-month study. No differences in rooting depth were observe among golf courses. Due to higher than average rainfall and variable precipitation rates, differences in rooting depths (Figure 9) were hypothesized to be due to a conditional response. Based on the treatment implementation of this study, the ten and twenty percent reduction treatments were irrigated with less water than they would have normally been. This reduction in water over the ten-month study contributed to the differences in average and maximum rooting depths for the three irrigation treatments.

Figure 9. Mean and maximum rooting depth measurements for three irrigation treatments (0 = control, 10R = 10% irrigation reduction, 20R = 20% irrigation reduction) averaged over five golf courses, three locations, and four months. Error Bars were computed from the standard error around the mean.



Irrigation Scheduling

Scientific based irrigation scheduling, which computes irrigation water requirements on the basis of actual evapotranspiration (ET_{TURF}), has been used to accurately estimate turfgrass water requirements (Brown et al., 2001; Kneebone et al., 1992; Richie et al. 1997). The required values of ET_{TURF} are usually obtained by multiplying estimates of reference evapotranspiration (ET_o) computed from meteorological data by a correction factor know as a crop coefficient (K_C) (Brown et al., 2001; Carrow, 1995).

Reference evapotranspiration (ET_o) is defined as the rate of evapotranspiration from an extensive surface of 3- to 6-inch tall, green grass cover of uniform height, which is actively growing, completely shading the ground and not lacking water (Allen et al., 1998). A large number of empirical or semi-empirical equations have been developed for assessing crop or reference crop evapotranspiration from meteorological data (Allen et al., 1998). The modified Penman method is considered to offer the best results with minimum possible error in relation to a living grass reference crop (Allen et al., 1998). Reference crop evapotranspiration (ET_o) can be estimated using the modified Penman-Monteith equation (Allen et al., 1998).

The modified Penman equation is used in ET feedback systems, such as the California CIMIS (Snyder, 1986) and Arizona AZ-MET (Brown et al., 1988), to help agricultural growers and turf mangers develop water budgets for determining when to irrigate and how much water to apply (Brown et al., 2001). The California Irrigation Information Management System (CIMIS) (Snyder, 1986) is an integrated network of over 120 computerized weather stations located at key agricultural and municipal sites throughout California. They use the Penman-Monteith equation and a version of the Penman equation modified by Pruitt/Doorenbos. Arizona Meteorological Network (AZMET) provides meteorological data and weather-based information to agricultural and horticultural interests operating in southern and central Arizona. They use the Penman-Monteith equation.

A correction factor or crop coefficient (K_C) is required to convert ET_o to ET for a specific crop. The K_C for turfgrass depends on the type of grass (warm or cool season), cutting height and desired turf quality (Brown et al., 2001). Crop coefficients provide a means of adjusting ET_o data for different turfgrass species to aid in scheduling the irrigation system. (Brown et al., 2001). Devitt et al. (1992) installed drainage lysimeters on two golf courses and one park at Las Vegas, NV to examine the water requirements and K_C of common bermudagrass overseeded in the fall with perennial ryegrass. They found golf turf used 41% more water than park turf and attributed the difference in water use to differences in fertilizer management. Monthly K_C based on the modified Penman procedure ranged from 0.43 in February to 0.89 in June and July for fairway turf. Crop coefficients for the lower maintenance park turf ranged from 0.33 in February to 0.60 in August. Research has also shown that K_C values vary from region to region (Brown et al., 2001). Bermudagrass K_C values based on the modified Penman Equation (Allen et al., 1998) ranged from 0.83 during mid season to 0.72 during transition to winter dormancy in Arizona (Kopec et al., 1991). In Georgia, Carrow (1995) reported K_C values for Tifway bermudagrass ranging between 0.57 and 0.93 using the modified Penman Equation.

In this study, irrigation precipitation rate was influenced by golf course and location (tee, fairway, or green) within golf course. Analysis of PR by location within golf course resulted in similar measurements except for golf courses B and D. These differences can be attributed to the irrigation design of the green at these two courses. Both golf courses utilize part-circle sprinklers throwing into the green and part-circle heads throwing away from the green. The part circle heads will apply twice as much water as the full circle heads, used on the tees and fairways, when the nozzles of both sprinklers provide the same volume per minute under similar pressures.

It was hypothesized that the precipitation rates would not vary significantly, across locations on a golf course and therefore by reducing the runtimes by ten and twenty percent, comparisons could be made based on these reductions. The ten and twenty percent reduction holes received ten and twenty percent less irrigation water based on previous runtimes, however, irrigation amounts at some courses were similar or in some cases higher than the control treatments because of the range in irrigation precipitation rates across locations (Figures 10 to 14). For example using the tees for the three treatment holes in Golf Course A, if the controller allowed a series of valves on the "Normal treatment" to operate for 30 minutes and the heads that were controlled delivered water at a precipitation rate of 0.35 inches per hour, it would deliver 0.18 inches of water over the area , The irrigation controller was set to run all the golf course tees for the same period of time (30 minutes) for this example. The controller would correspondingly be reduced the run time of the "10 percent reduction" treatment by 3 minutes to 27 minutes. Since the irrigation heads delivered water at a rate of 0.78 inches per hour over this treatment area, it would actually receive 0.35 inches of water. If the controller for the "10 percent reduction" treatment was previously set to less than 30 minutes it would have been correspondingly reduced by 10% of its previous runtime. This illustrates the importance of understanding actual precipitation rates delivered on the golf course. Precipitation rates generally are assumed to be relatively uniform over a golf course depending on the head that was installed. Allowances by the person configuring the controller may not always be made for differences in nozzle, wear, pressure, etc in the controller set-up.

Figure 10. Golf Course A monthly irrigation amounts (dark columns), monthly rainfall amounts (white columns), and reference evapotranspiration (triangles). When irrigation amounts exceeded rainfall, a line within the dark column denotes rainfall amounts.

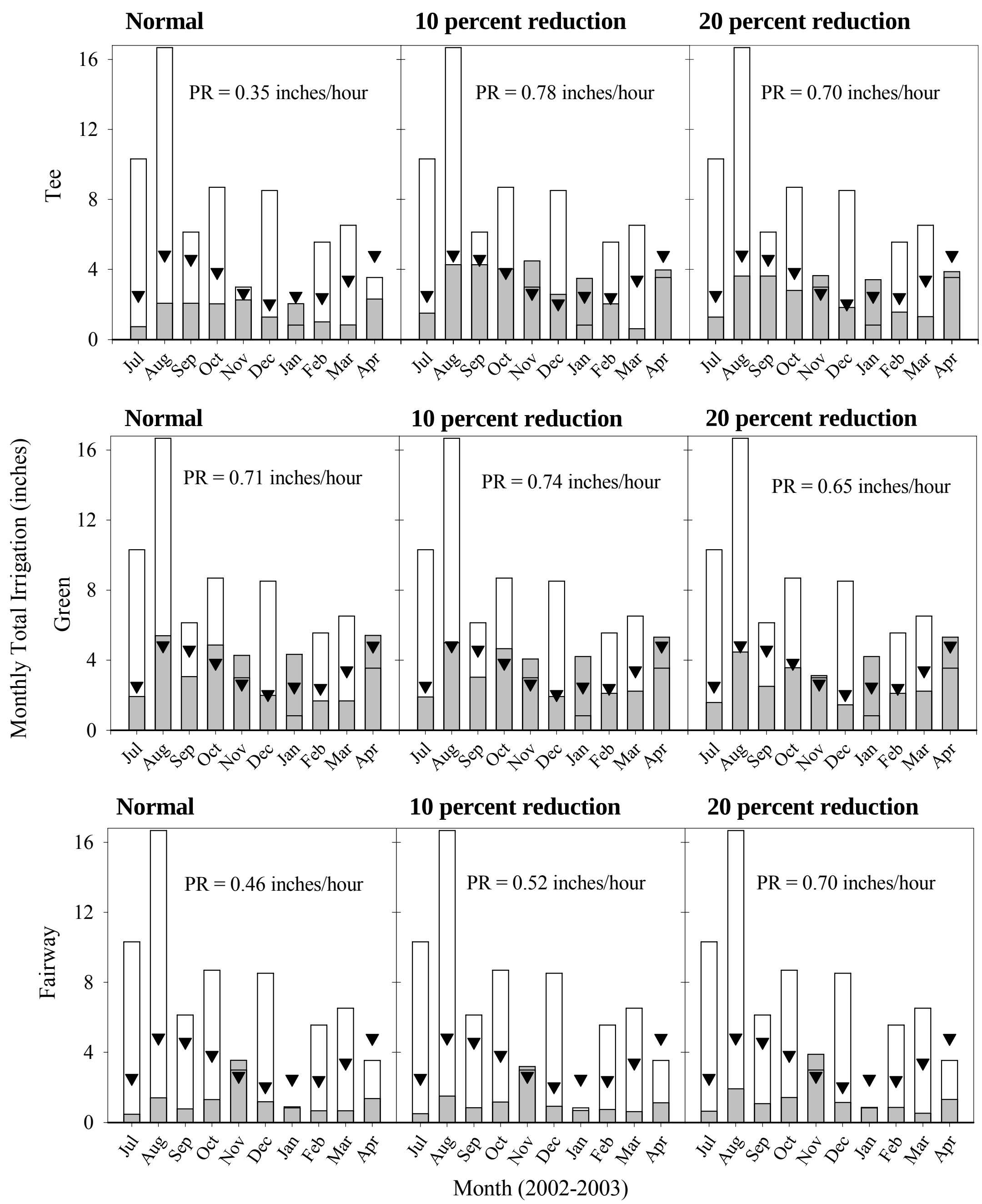


Figure 11. Golf Course B monthly irrigation amounts (dark columns), monthly rainfall amounts (white columns), and reference evapotranspiration (triangles). When irrigation amounts exceeded rainfall, a line within the dark column denotes rainfall amounts.

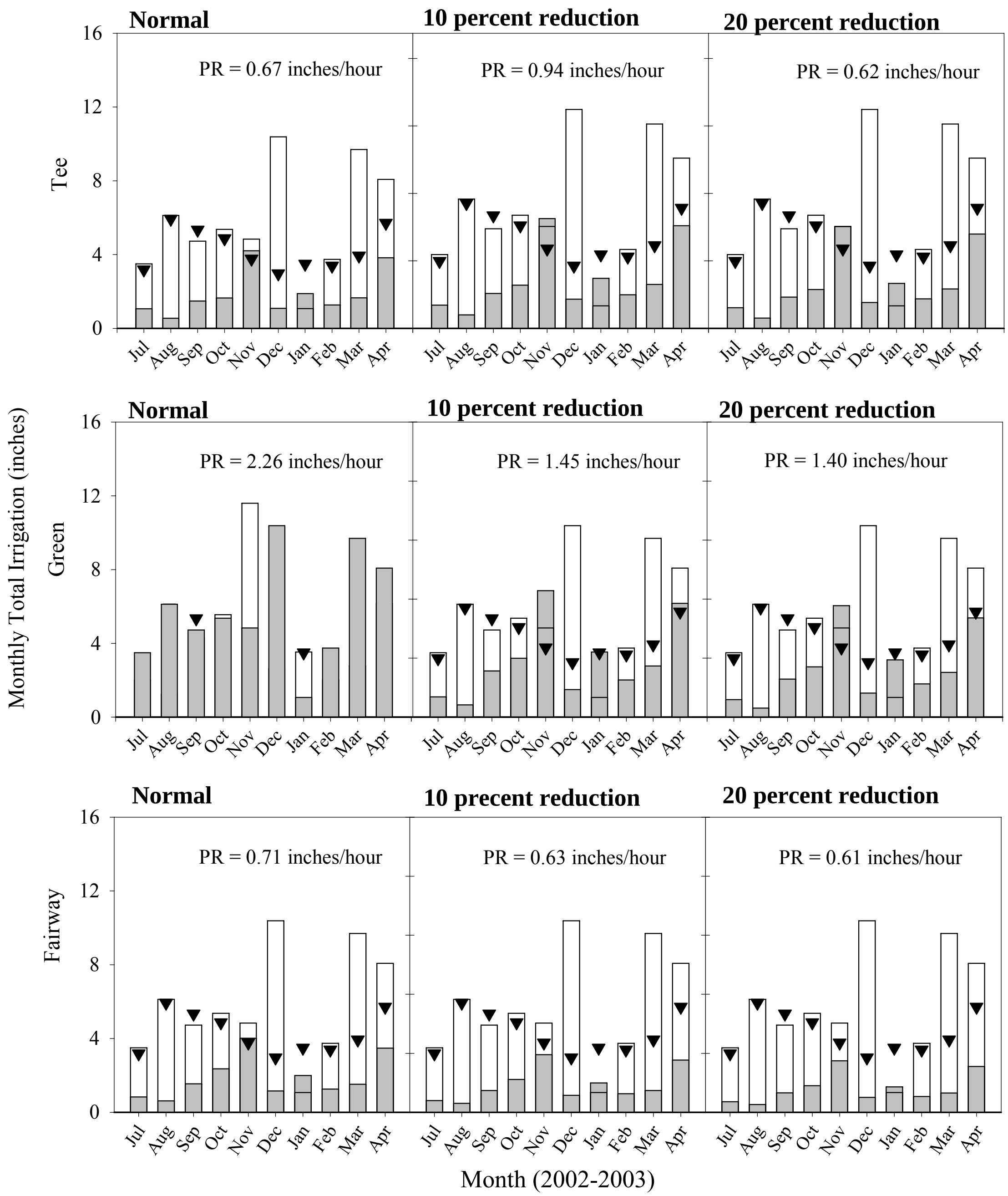


Figure 12. Golf Course C monthly irrigation amounts (dark columns), monthly rainfall amounts (white columns), and reference evapotranspiration (triangles). When irrigation amounts exceeded rainfall, a line within the dark column denotes rainfall amounts.

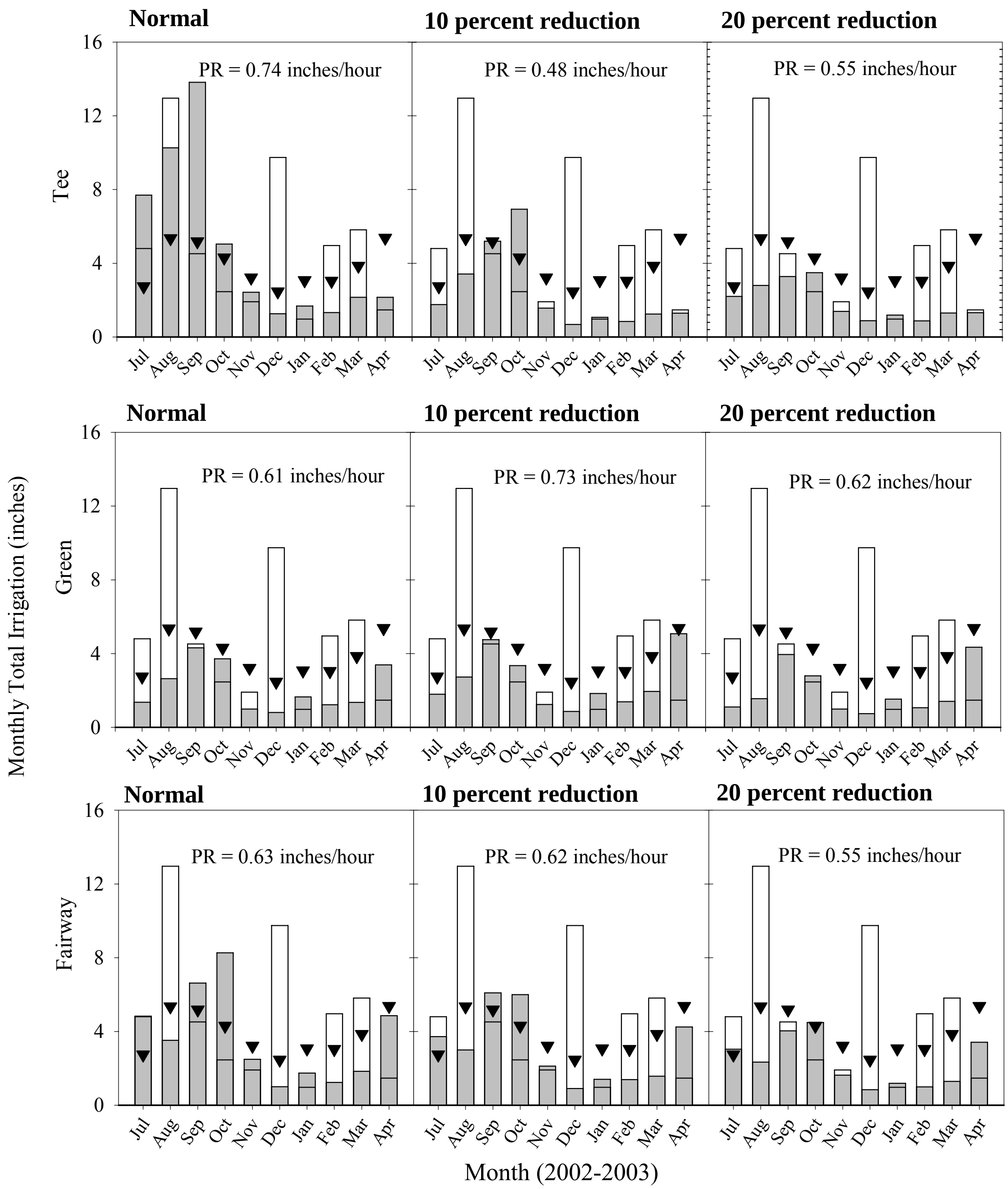


Figure 13. Golf Course D monthly irrigation amounts (dark columns), monthly rainfall amounts (white columns), and reference evapotranspiration (triangles). When irrigation amounts exceeded rainfall, a line within the dark column denotes rainfall amounts.

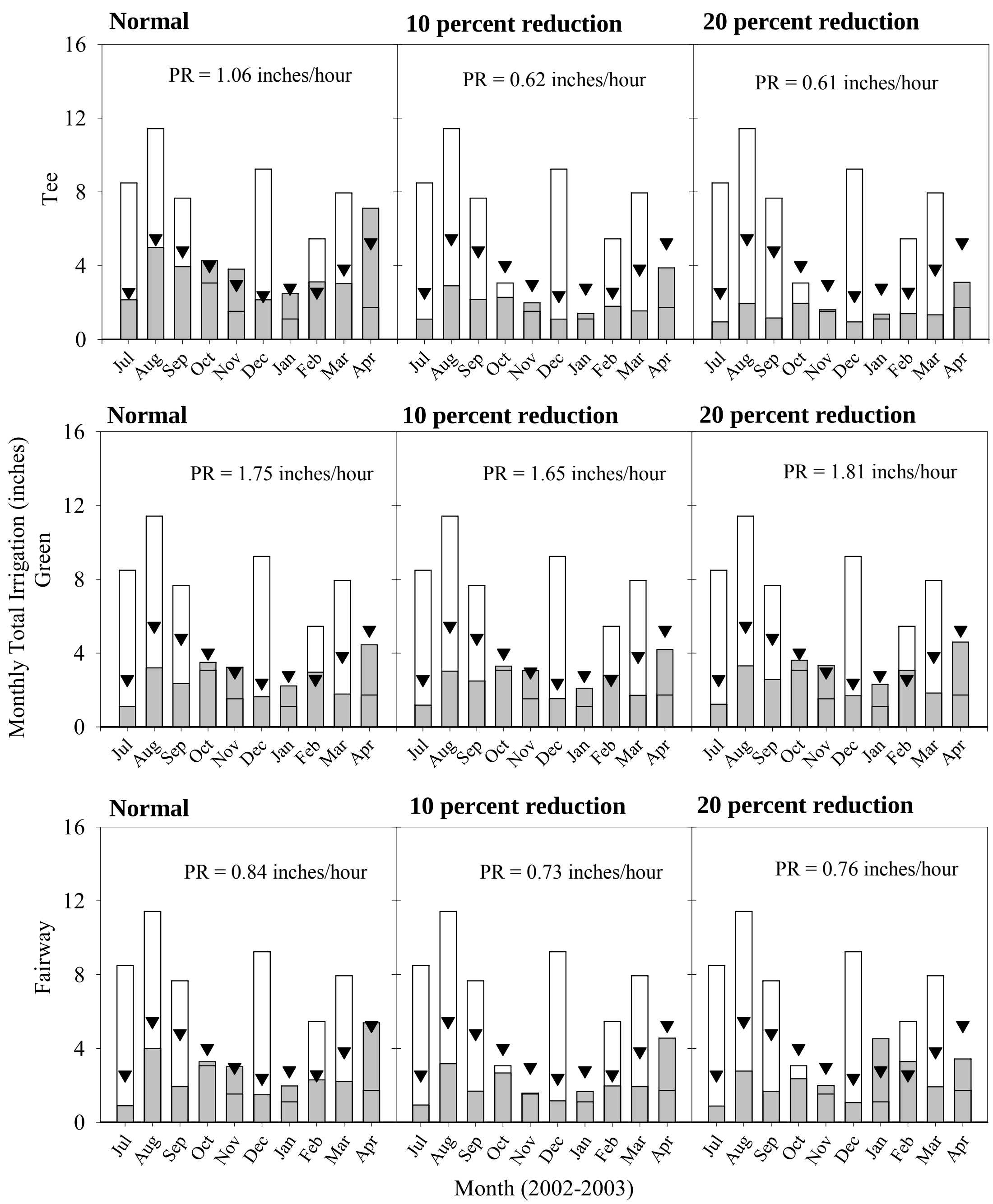
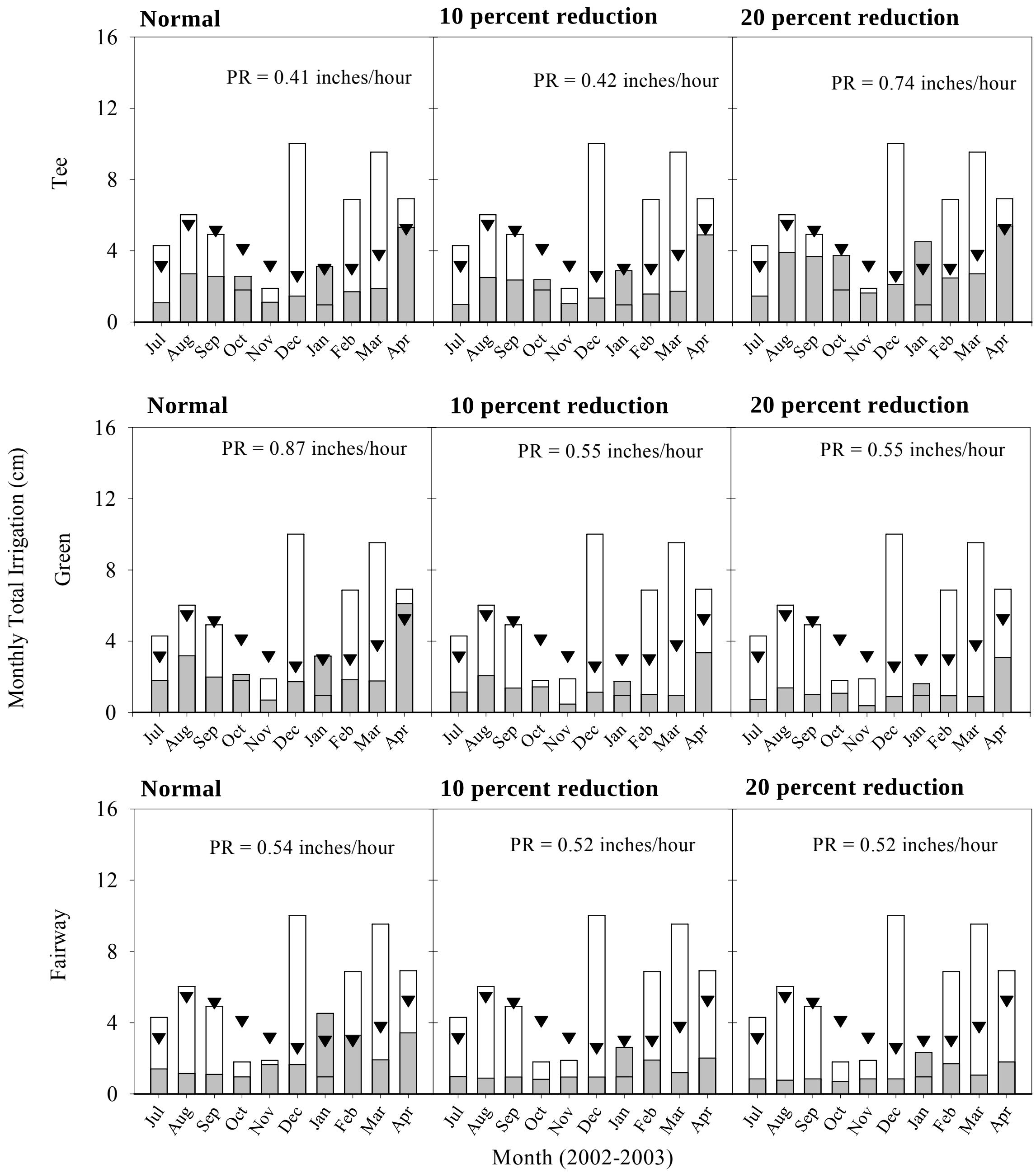


Figure 14. Golf Course E monthly irrigation amounts (dark columns), monthly rainfall amounts (white columns), and reference evapotranspiration (triangles). When irrigation amounts exceeded rainfall, a line within the dark column denotes rainfall amounts.



Greater irrigation amounts were recorded in the months of October and November at several courses. These increases were the result of additional applications of water during the fall for overseeding establishment. Although golf course E (Figure 14) was overseeded, there was not a large increase in irrigation amounts at this course during the overseeding process. Higher irrigation amounts were also recorded in the months of July, August, and September for the control tee and fairway at golf course C (Figure 12). These were the result of these locations receiving double run times. This was brought to the attention of the superintendent and corrected for the remainder of the study. Once the corrections were made there was a significant reduction in irrigation amounts at this golf course for these locations compared to the double runtime period.

The actual gallons of water used per acre on the control holes over the 10-month period is indicated in Table 7. The level of management and watering of the tees varied among the courses in relation to the fairway.

Table 7. Total gallons of irrigation water applied per acre on the control hole at each golf course over the 10-month period compared to reference evapotranspiration. Water applied data calculated from run times and measured precipitation rates.

Golf Course	Gallons per Acre			
	Tees	Fairways	Greens	ET_o
A	860,970	301,228	920,971	897,982
B	613,337	393,922	809,612	1,138,295
C	641,342	814,091	667,450	1,030,766
D	539,817	569,965	677,740	980,802
E	578,976	354,177	392,736	1,043,256

Although variations in irrigation precipitation rates across the locations of the golf courses prevented an optimum reduction in irrigation delivered, reducing the normal irrigation practices by ten and twenty percent did conserve a significant amount of water (Table 8). For example, golf course A has 60 irrigated acres. The water saved monthly at this course by reducing the runtimes by ten and twenty percent would be 364,469 and 631,492 gallons per month, respectively. Under more normal rainfall conditions and a correspondingly greater irrigation demand, the savings would have been greater since the percentage reduction would result in a larger amount proportional to that used.

Table 8. Average monthly water savings (gallons per acre) at five golf courses with ten and twenty percent reductions of normal runtimes. Values were calculated based on measured precipitation rate and run times and are corrected for area respective of the golf holes tested on each course.

	Ten Percent Reduction	Twenty Percent reduction
Golf Course	Gallons per acre	
A	6,167	10,686
B	4,969	8,749
C	7,174	11,102
D	3,753	7,000
E	3,696	5,924

Turfgrass Water Use

Beard (1973) defined turfgrass water use as the amount of water used for plant growth plus the water lost through evaporation from the soil surface and transpiration from the plant. The term evapotranspiration (ET) combines the evaporative processes that occur from the soil and by transpiration from the plants. For most practical purposes it is impossible to separate the evaporation and transpiration components of water loss from turf surfaces. Therefore, ET and water use are considered to be comparable terms (Augustin, 1983). ET data are usually presented as a depth of water loss over a particular period in a manner similar to that of precipitation. ET units are commonly expressed quantitatively as millimeters per day or inches per day. Beard (1985) stated that typical turfgrass water use rates in Texas vary from 2.5 to 7.5 mm per day with maximum values as high as 12 mm per day. Augustin (1983) reported that ET rates for warm season turfgrasses grown on research plots in Ft. Lauderdale, Florida ranged from 1.6 to 4.4 mm per day. Note 1 inch equals 25.4 mm. Augustine (1983) evaluated ET rates for a year and reported that bermudagrass sod used 43 inches of water per year in Ft. Lauderdale, Florida.

Research has shown variation among turf genotypes in rates of water use (Burton et al., 1957; Biran et al., 1981; Kneebone and Pepper, 1982; Carrow, 1995). Carrow (1995) measured ET rates of seven turfgrasses over a two-year period in Central Georgia . He reported that ET rates for cool season grasses ranged from 1.99 to 6.05 mm per day and the ET rates of warm season grasses varied from 1.40 to 6.22 mm per day. Among the warm season turgrasses, common bermudagrass had the lowest mean ET rate (3.03 mm per day) and Meyer zoysiagrass had the highest (3.54 mm per day). Kim et al. (1983) investigated the ET rates of twelve warm-season turfgrasses grown in College Station, Texas, under non-limiting water conditions. They reported that the range in ET rates was in the order of 45%. Variations in ET rates have been explained by differences in stomatal characteristics, growth rate and habit, canopy configuration, and rooting characteristics (Peacock and Dudek, 1984; Johns et al., 1983; Youngner, 1985; Beard, 1985; Kneebone et al., 1992).

Daily ET rates vary from region to region. Carrow (1995) reported that mean summer ET rates for ‘Tifway’ bermudagrass grown in Central Georgia were 3.11 mm per day. Beard et al. (1992) reported summer averages of 5.1 mm per day for the same genotype in the arid west. Kim and Beard (1988) reported that zoysiagrass consumed 8 to 14% more water than bermudagrass under humid conditions in Texas. These results differed from those of Kneebone and Pepper (1982) who observed no significant difference in ET between Tifway bermudagrass and Meyer zoysiagrass in Arizona.

Research also shows that ET rates vary from location to location within a golf course. Jiang et al. (1997) investigated the variability of water requirements across a Kansas golf course by comparing ET rates computed from an onsite weather station and actual ET rates at four tees on the golf course. Evaporation was measured using black Bellani plate atmometers placed on four golf tees and near the weather station at the Manhattan Country Club, Manhattan, KS in 1995 and 1996. Evaporation for each location on each measurement day was converted to an ET estimate for perennial ryegrass turf mowed at 0.5 inches using an empirical model developed previously by regressing plate evaporation vs. lysimeter ET under well-watered conditions. They reported that average ET rates on tees were 10 to 20 percent lower than the ET rates computed at the onsite weather station. In this study ET measurements were taken between the months of June and August for two years. Mean ET rates at the weather station were 9.6 mm per day for 1995 and 8.3 mm per day for 1996. Tees ranged between 7.4 to 9.6 mm per day for 1995 and 6.7 to 8.4 mm per day for 1996.

Turfgrass ET rates are also influenced by environmental conditions and cultural practices. (Kneebone et al., 1992; Beard, 2002; Cisar and Miller, 1999; Kim and Beard, 1983). Turf water requirements change frequently; influenced primarily by environmental conditions such as available soil water, solar radiation, relative humidity, wind velocity, and temperature (Allen et al., 1998; Skogley and Sawyer, 1992). Various studies have indicated that ET increases with water availability (Biran et al., 1981; Mantell, 1966; Marsh et al., 1980). Kneebone and Pepper (1982) investigated high irrigation levels (4.5, 9.6 and 14.3 inches per week) on ET of bermudagrass. They reported that ET levels increased with increased application rates and increased water–holding capacity of soils. Research has also shown that ET increases with increased light levels, increased temperatures, lowered humidity, moderate to high wind speeds, and long days (Carrow, 1995). Chow (1964) reported that a 2 meters per second wind will increase still-air ET by 20% and a 7 meters per second wind will increase still-air ET by 50%. Feldhake et al. (1984) reported that turfgrass ET rates increase linearly with solar radiation. Kneebone and Pepper (1982) reported that as air temperatures increased and humidity declined, turf water consumption increased. However, during times of frequent rain showers the air temperatures were reduced and water consumption decreased.

Mowing and fertilization are cultural practices that influence the water requirements of turfgrasses. Biran et al. (1981) investigated the effects of mowing heights on water use on various lawn grasses and reported that bermudagrass [cultivars 'Santa Ana' and 'Suwannee'] mowed at 1.2-inches had a rapid increase in water use compared to a 2.4-inch mowing height, but concluded that this increase was only temporary and water use rates between the 1.2- and 2.4-inch mowing heights began declining after six weeks. Burns (1976) similarly found no effect of cutting height on water consumption. However, a number of studies have reported a decreased ET rate as the cutting height of turf was lowered (Kim and Beard, 1984; Parr et al., 1984; Unruh et al., 1999).

Nitrogen (N) is the most frequently applied fertilizer in turfgrass systems (McCarty, 2001; Sartain et al., 1999). Nitrogen influences many aspects of turf including color, shoot and root growth, and water use (Beard, 1973; Bowman et al., 2001). High rates of N have been shown to increase shoot growth and reduce root growth (Beard, 1973; Goss and Law, 1967). Reduced root growth results in turf becoming less tolerant to environmental stresses, more susceptible to disease, and more dependent on frequent irrigation and fertilization to supply the needed nutrients and moisture for growth (Beard, 1973).

Deficit Irrigation

Deficit irrigation is some fractional level of irrigation made in response to some reference water use estimate, such as a Class A Pan (E_{pan}), Penman, or some other reference or determination (Kneebone et al., 1992). In recent years, there has been increasing interest in deficit irrigation as a water conservation technique. Meyer et al. (1985) irrigated several turfgrasses at 100, 80, and 60% of ET values estimated from modified Class A pan data. They reported that bermudagrass at 60% ET was better than acceptable and not significantly different than bermudagrass irrigated at 100% of ET. Qian and Engelke (1999) in a Texas study reported that turfgrass quality increased linearly as irrigation increased. However the researchers concluded that quality was not improved for bermudagrass, St. Augustinegrass, and buffalograss when watered at a rate greater than 55% of E_{pan}. Fry and Butler (1989) in a Kansas study reported that hard fescues exhibited acceptable to excellent quality when irrigated on a 2-, 4-, and 7-day interval at 75% E_{pan}.

Deficit irrigation has also been shown to increase root length. Fu et al. (2003) reported that compared to 100% ET_o and 0% ET_o irrigated tall fescue, irrigation treatments of 20% ET_o increased root length beginning 29 DAT (days after treatment). However, there were no differences in root length observed between 20% ET_o and 60% ET_o irrigation treatments.

Estimating Golf Course Water Demand Using AFSIRS

Water management districts use various water use models to determine irrigation requirements (IRR) for a crop. These irrigation requirements are used to help determine water amounts allocated in a consumptive use permit (CUP). A CUP allows water to be withdrawn from surface and groundwater supplies for reasonable-beneficial uses for public supply (drinking water), agricultural and landscape irrigation, industry, and power generation (SJRWMD, 2003). One of the models used by SJRWMD is the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS). AFSIRS is a numerical simulation model, which estimates IRR for Florida crops, soils, irrigation systems, growing seasons, climate conditions, and irrigation management practices (AFSIRS tech manual).

AFSIRS is based on a water budget of the crop root zone. This water budget includes inputs to the crop root zone from rain and irrigation, and losses from the root zone by drainage and evapotranspiration (ET). The water holding capacity in the crop root zone is the multiple of the water-holding capacity of the soil and the rooting depth of the crop being irrigated (AFSIRS tech manual).

The model is also based on the concept that the crop ET is being estimated from ET_p and crop water use coefficients. A crop coefficient is an adjustment factor, which is determined by different crop characteristics, i.e. turfgrass type, quality, and height (Brown and Kopec, 2000). Daily ET_p and rainfall can be ascertained from historical climate data available to the model. Records from nine Florida locations over approximately a 20-year period ending in the 1970s are part of the model database. The daily ET_p rates in the database were determined by using the IFAS Penman equation (AFSIRS tech manual).

Limitations to the operational use of the AFSIRS model specifically pertaining to use on golf courses were researched during a study at the University of Florida. The major problem with the simulation is that it does not have the ability to input actual rainfall and climate data from the site of interest. The climate databases available to the model are limited and may not give an accurate prediction of daily ET_p and rainfall. The ET rates used in the model were determined by using the IFAS Penman equation. Research indicated that this equation is not as consistent as the FAO Penman-Monteith equation for Florida conditions (Jacobs and Satti, 2001).

The default crop coefficient for golf course turf in the AFSIRS model is one, and the default irrigated and maximum rooting depths are 6 and 24 inches. The AFSIRS model does not have additional crop coefficients and rooting depths for turfgrasses. There has been more research conducted on crop coefficients since the model was designed, and rooting depths can vary from golf course to golf course (Jacobs and Satti, 2001).

Jacobs and Satti (2001) reported that there is a lack of irrigation systems to choose from in the simulation as well as irrigation efficiencies. A 75% efficiency value is assigned to a multiple sprinkler system in the model. Previous research indicates that there is a high variability between irrigation efficiencies of multiple sprinkler systems on golf courses due to several factors, such as head spacing, nozzle type, pressure, maintenance, etc. (Miller et al., 2003).

Irrigation requirements (IRR) for each golf course with default data and actual/updated data inputted into the model are illustrated in figure 14. Golf Courses A, B, C, and D each had an IRR of about 35 inches per acre and Golf Course E had an IRR at about 30 inches per acre (Table 9). Based on rainfall and ET_o, the net IRR was predicted to be about the same additional amount (depth) as the ET_o values. Calculating the depth of irrigation water applied to the fairway (largest irrigated area) of the control hole, the golf courses managers irrigated from 14 to 69% of what the model predicted was needed. Two golf courses irrigated approximately half of what the model predicted as the IRR. This was due to above normal rainfall, which is not accounted for by the model. Accounting for the actual rainfall received on each golf course, the turf managers irrigated from 28% to 66% more than they needed.

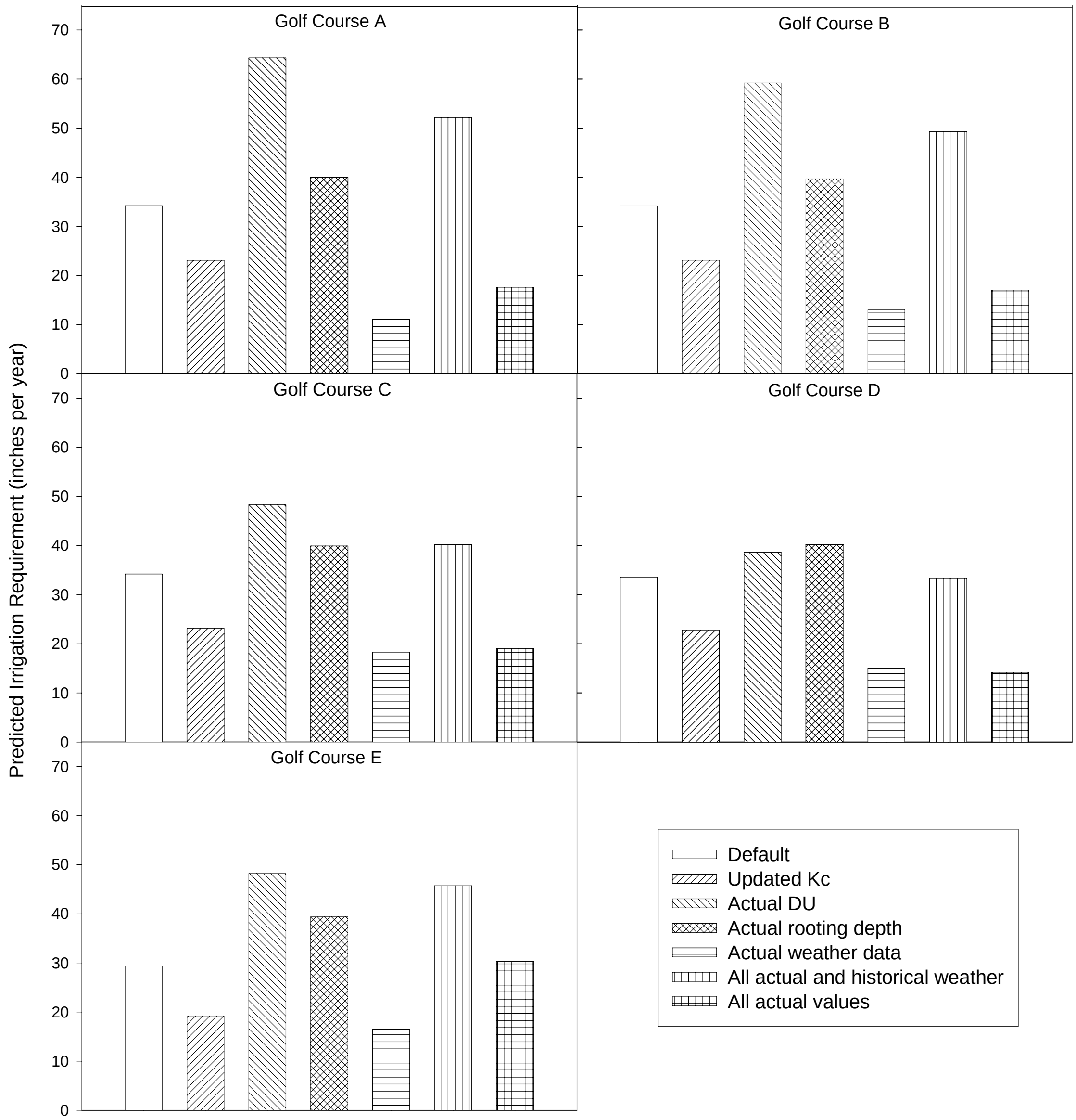
Table 9. Mean rainfall, potential evapotranspiration (ET_p), net irrigation requirement, irrigation in relation to predicted irrigation requirements.

Golf Course	Inches				
	Rainfall	ET_p	Net IRR†	Irrigation < IRR (default)	Irrigation > IRR (actual)‡
A	69	33.0	34	23	0
B	57	41.9	34	19	2
C	49	38.0	34	4	12
D	57	36.1	34	13	6
E	52	38.4	29	16	-4

†irrigation requirements predicted using AFSIRS with default values.
‡irrigation requirements predicted using actual on-site weather data.

Seven model estimates are graphed for each golf course (Figure 15). A bar illustrating the estimated water needs for each course using all default data is included for comparison. The only parameter that differs by golf course in the default runs is soil type. Because golf courses A, B, and C have the same soil type, they have the same IRR for the default run.

Figure 15. AFSIRS irrigation requirements (IRR) for five golf courses. Default: model run with all default data. All other were run with actual values collected on-site.



Predictions were made using the updated K_C monthly values. These K_C values were from the literature reported by researchers in Georgia and Arizona, the most appropriate K_C values available. The IRR for all five courses dropped approximately 10 inches per year from the default run. This is due to the updated monthly K_C values, which range from 0.53 to 0.97, being lower than the default K_C of 1 for turfgrass.

Additional model runs were conducted with actual weighted DU_{LQ} values for each course replacing the default irrigation system efficiency of 75%, for a multiple sprinkler system. Each course had three DU_{LQ} values, one for each hole, and therefore had three estimates with the actual DU_{LQ} model runs. But for graphing purposes, the three IRRs were averaged together for each golf course. The IRR for all five courses increased compared to the default run values. The IRR for courses B, C, and E went up about 15 to 25 inches per year when actual uniformities were used in the model. This is due to these courses having uniformities between 40% and 60%. The IRR for golf course A increased approximately 30 inches per acre per year from the default run values. The increase was a result of golf course A having two holes with low uniformities (32% and 37%). The IRR for golf course D increased by approximately 5 inches per year. This golf course had uniformities from 62% to 67%, much closer to the default value.

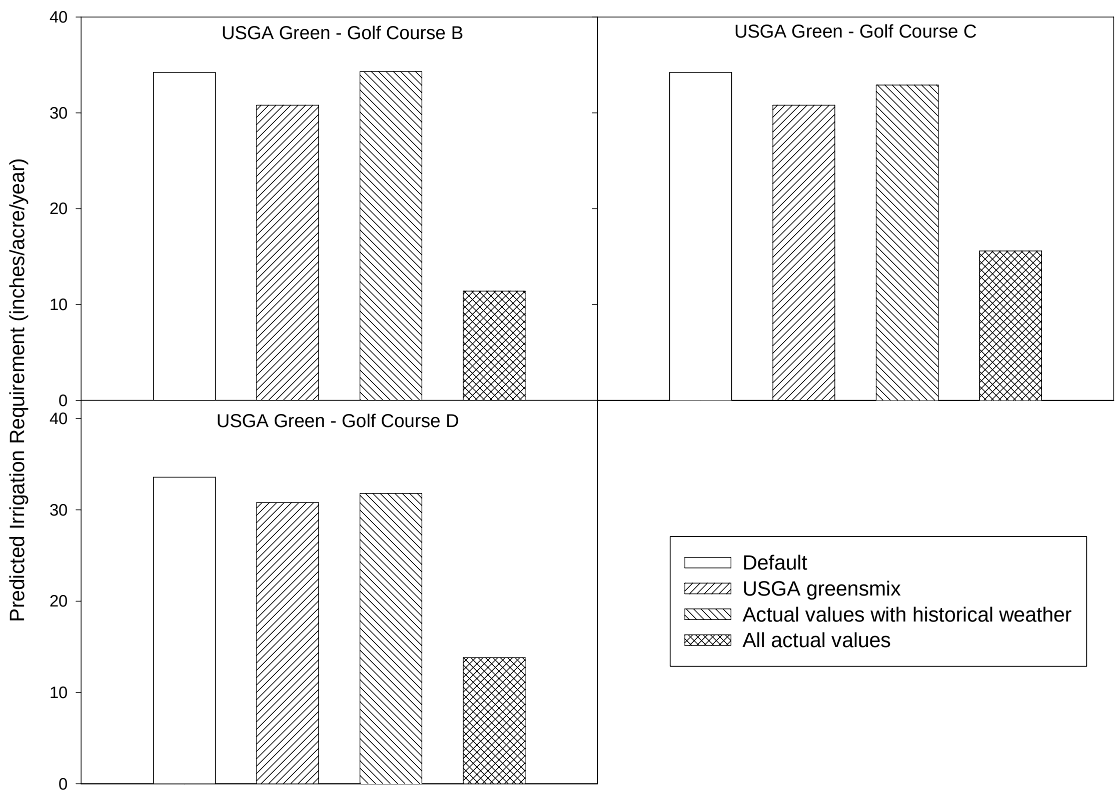
Actual root depths from each course were used for IRR estimations. All five IRRs increased about 7 inches per year with actual rooting depths replacing the default root depths. The actual average (irrigated) and maximum rooting depths were 1.7 and 2.7 inches, and the default irrigated and maximum rooting depths for golf course turf are 6 and 24 inches, respectively. This difference in actual and default root depths, led to the increase in IRR for each golf course.

Actual weather datasets for each course were difficult to input with the programming structure of the AFSIRS model. It was apparent from comparing the historical weather data to the year's weather data collected that short-term weather dataset represented a much wetter year than average. The weather dataset represented between 22 and 43 inches more than the average rainfall compared to the 20-year historical weather dataset. Using the actual weather data from the golf courses decreased the estimate of irrigation water needed by approximately 20 inches per year.

The model was also run for the five golf courses using all actual/updated data except for weather data, and all actual/updated data including weather data. Due to the wet year, it seemed appropriate to use the historical weather data rather than predict irrigation needs based on one year's data. Since the actual weather datasets are not historically typical for the Orlando area, a better comparison to the default data set is to estimate water needs with actual data combined with the historical weather dataset. That comparison shows that actual/updated data with typical weather data (historical weather database) increase IRR between 6 and 18 inches per year for golf courses A, B, C and E. This is primarily a direct result of these courses having low distribution uniformities. Golf course E's IRR increased approximately 6 inches per year with an average DU_{LQ} of 54%, and course A's IRR increased approximately 18 inches per year with an average DU_{LQ} of 43%. Golf course D with an average DU_{LQ} of 65% was predicted with no increase in IRR compared to running model with default data.

Figure 16 shows irrigation requirements for the three golf greens with USGA specifications. Default IRR was included for comparison purposes. DU_{LQ} of each green was used instead of the weighted DU_{LQ} for each golf course except for the default. The model was run with the USGA green average soil water content (13%) inputted in place of the average water content of the native soils. The IRR was decreased approximately 5 inches per year for all three courses due to the increase in the average soil water content value.

Figure 16. AFSIRS irrigation requirements (IRR) for three USGA golf greens. Default: model run with all default data. USGA Greens mix: model run with USGA average soil water content (13%).

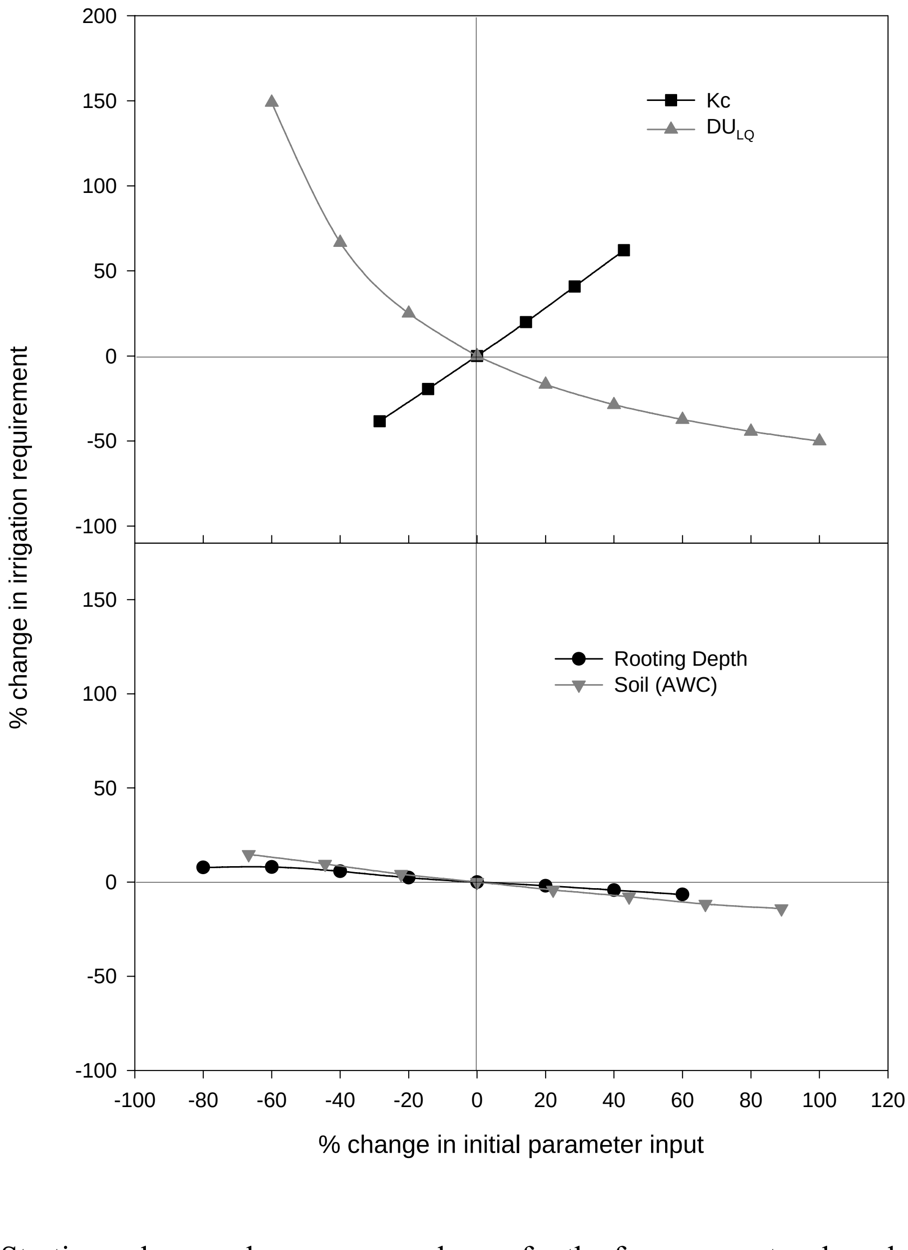


Predictions with all actual data, including USGA average soil water content, and historical weather data resulted in approximately the same IRR for all three courses when compared to the default IRR (Figure 16). This is because the average DU_{LQ} on the three greens at each course (ranged from 50% to 69%) was higher than the weighted DU_{LQ} of each golf course, and the higher average soil water content makes up for the DU_{LQ} being lower than the default 75%. All actual data, including USGA average soil water content, was used. Because actual weather datasets had high rainfall amounts, IRR was decreased about 20 inches per year for all three golf courses.

To provide a better picture for how AFSIRS model works and how the input parameters influence output (IRR), sensitivity analysis was utilized. Sensitivity analysis requires varying selected parameters individually through an expected range of values and then comparing the range of output values from each input variable (James and Burges, 1982).

K_C, DU_{LQ} (irrigation system efficiency), rooting depths, and average soil water content were the parameters that were analyzed for sensitivity on the AFSIRS model (Figure 17).

Figure 17. Sensitivity analysis of the AFSIRS model. Values were changed across a range of typical values.



Starting values, and ranges were chosen for the four parameters based on previous reported values. The K_C value starting point was 0.7. The values were changed in increments of 0.1 in both directions, and ranged from 0.5 to 1.0. The DU_{LQ} starting point value was 50%. The values were changed in increments of 10% in both directions, and ranged from 20% to 100%. Rooting depths had two starting points. The average depth starting point was 5 inches and maximum depth starting point was 20 inches. These depths were changed in increments of 1 and 4 inches in both directions, and ranged from 1 and 4 to 8 and 32 inches. Average soil water content starting point was 9%. It was changed in increments of 2% in both directions and ranged from 3% to 17%.

Changes in irrigation system efficiency (DU_{LQ}) resulted in the largest changes in IRR. IRR increases exponentially as DU_{LQ} decreases. Changing a DU_{LQ} from 50% to 20%, a 60% decrease of the starting point, results in a 150% increase in IRR. Changing a DU_{LQ} from 50% to 100%, a 100% increase of the starting point, results in a 50% decrease in IRR. Modifying K_C values had the second largest impact on IRR. IRR increases linearly as K_C values decrease. A 15% increase or decrease of the starting point results in a 20% change in IRR.

Changes in rooting depth and average soil water content had very little impact on IRR. As rooting depth and average soil water content increase, IRR decreases. Increasing and decreasing both inputs by 60% of the starting points resulted in less than 16% increases and decreases in IRR.

Summary of Findings

1. Understanding the performance of a golf course irrigation system is essential for conserving water on golf courses.

2. Knowledge of the actual precipitation rates on different areas of the golf course is vital to irrigation scheduling. Precipitation rates (as installed in the computer program that serves as the overall controller) varied dramatically across locations. The manufacture reported precipitation rates may be very different than actual precipitation rates. If the controllers are set based on these default rates, variable application that may result in under- or over-watering can occur.

3. The distribution uniformity at all five courses was below the recommended 70% DU_{LQ} suggested by the Irrigation Association as what is expected on golf course irrigation systems. Factors affecting irrigation uniformity were most often related to excessive pressure variations, and malfunctioning sprinkler heads. Sprinkler spacing and nozzle size can also significantly affect DU_{LQ}. The highest average DU_{LQ} for this study was 63 percent. The lowest average DU_{LQ} was 45 percent.

4. Based on this study, the low DU_{LQ} for the five golf courses can be attributed to the following factors: (listed in order of occurrence and frequency of occurrence) (1) pressure variations;(2) malfunctioning sprinkler heads (worn nozzles, leaks, heads not turning, heads not turning on); (3) improperly spaced sprinklers, and (4) interference by turf and other objects.

5. Soil moisture lower quarter distribution uniformity ($SMDU_{LQ}$) was 15 % ± 6 higher than catch-can lower quarter distribution uniformity in nearly all cases. On golf courses where the DU_{LQ} was higher, the differences in $SMDU_{LQ}$ and DU_{LQ} were not that great (11% ± 1), but as the irrigation uniformity decreased the differences were usually larger (20% ± 2). This observation warrants further study to determine the impact of irrigation distribution on watering efficiency.

6. No differences in turf quality existed between the irrigation treatments used in this study. The total amount of rainfall (52 to 69 inches at all five courses compared to normal cumulative rainfall of 37 inches for the ten months) that accumulated influenced irrigation amounts and reduced the likelihood that drought stress symptoms would appear. However, it is important to note that the holes receiving ten and twenty percent less water than they would normally still maintained acceptable quality ratings throughout the ten-month study, increased average and maximum rooting depth, and resulted in a significant reduction in water used.

7. Preliminary investigations of the AFSIRS model indicates that when actual data (crop coefficients, distribution uniformity, and rooting depth) was included in the model it predicted similar water needs to the default prediction for only 20 percent of the golf courses evaluated.

8. When actual data was used, rather than the default values normally used, the irrigation requirements predicted using the model increased between 6 and 18 inches per year for the golf courses. This was typically a direct result of those courses having low distribution uniformities. No allowances were made in this evaluation for why the distributions were lower. Courses should make necessary repairs to their irrigation systems before testing for distribution uniformities. This is standard for Irrigation Association accepted procedures.

9. Weather has significant potential to influence values but since AFSIRS is used primarily as a prediction equation, it is difficult to use current weather patterns to predict long-term future needs. It is difficult to utilize weather data outside the historical datasets already in place. More complete weather datasets may be beneficial for prediction.

10. More accurate crop (turf) coefficients can improve crop estimates. There is still limited research related to crop coefficients under Florida conditions.

Recommendations for Further Study

1. Long-term monitoring. In future studies of this type, water use on golf courses should be monitored for several years to remove the influence of one year's weather pattern.
2. Comparison of irrigation scheduling techniques on golf courses. Most of the ET based scheduling techniques on golf courses have only been tested under arid climates. Development of crop coefficients for Florida would also be beneficial. To complete this study, crop coefficients obtained in Georgia and Arizona were used.
3. The feasibility of altering an irrigation system to improve uniformity. Recent industry reports have indicated aftermarket nozzles may dramatically improve uniformity, but scientific tests are lacking.
4. The relationship between irrigation delivery and soil moisture. This was an unforeseen insight that may have significant implications for irrigation efficiency. It can be demonstrated that running the statistical analysis with simulation models of compressed scale data such as that taken with (Soil Moisture Distribution Uniformity, lower quarter) $SMDU_{LQ}$, should have a higher uniformity compared to the more open scale of the (irrigation system distribution uniformity, lower quarter) DU_{LQ}. This relationship is not well understood. It would be interesting to look at soil moisture distribution with deficit irrigation when rainfall is average or deficit.
5. The benefits of using compost as a soil amendment on golf courses. This amendment is the only one that has much promise from an economic perspective due to its low initial cost. In addition, soil amendment work on golf greens, while available, is still in its infancy in terms of knowledge and acceptance. In general, amending large turf areas is perceived as not cost effective.

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APPENDIX A
Water Use Manual to Promote Water Conservation Practices on Florida Golf Courses

Water use is among the most significant issues facing golf course managers today. In Florida, golf courses require large amounts of water to irrigate the golf course and surrounding landscape. Golf courses are highly visible features in many communities and are targets for criticism during periods of drought when golf courses, homeowners and others are restricted in their use of potable water.

The goal every turf manager should have is to achieve maximum water conservation on turfgrass sites while maintaining adequate turf quality and function. The golf industry must continue to achieve the goal of less water use. To accomplish this goal it must work toward 1) the development of new grass varieties that use less water, 2) the design of golf courses that minimize the area maintained under irrigation and maximize on-site collection of run-off and sub-surface drainage water, 3) the development of new irrigation systems that provide better efficiency and control, 4) finding alternative water sources that reduce or eliminate the use of potable water, and 5) the development of best management practices that result in less water use.

Changes in resources, design, and management can be implemented to aid in maximizing water conservation. Specific subject areas that should be addressed include:

1. Water Sources
2. Irrigation System Design
3. Irrigation System Performance Evaluation
4. Irrigation Scheduling
5. Golf Course Design
6. Best Turfgrass Management Practices
7. Water Conservation
8. Golf Course Water Conservation Plan

No single strategy will achieve sufficient benefits in water conservation. The industry must always encourage a scientific approach to water conservation. A political approach without science will not work in terms of maintaining quality and functioning systems which are sustainable. To obtain that goal the industry must 1) inform the general public about conservation practices, and 2) educate those that directly utilize the golf course about the importance of on-site conservation and any potential consequences on turf quality.

Water Sources

Alternative Sources

- Reclaimed water or reuse water (not to be confused with wastewater or effluent water) effectively utilizes water that may otherwise be wasted. Reclaimed water may be less expensive than potable water. Reclaimed water should be used to irrigate turfgrass areas if available.
- Some reclaimed water sources contain nutrients that can be used by the turfgrass plant. The nutrients applied through irrigation should be accounted for in your overall nutrient budget.
- Potential turf growth problems with reclaimed water include 1) total soluble salts, 2) sodium permeability hazard, 3) specific salt toxicities (Na, Cl, B, HCO_3, SO_4), 4) high N, P, heavy metal concentrations, and 5) pH balance. The water may cause equipment problems due to salts (corrosion) or high bicarbonates (scale). Irrigation application rates may need to be adjusted (increased) to account for salts. additional water treatment may be necessary to prevent accumulation of bicarbonates in the soil and/or to adjust pH.
- Brackish water may be utilized in some instances to supplement other water sources. Bermudagrass is somewhat tolerant and seashore paspalum is very tolerant of high salt content water. Using water with a high salt content requires precise applications to prevent damage to susceptible plant material.
- Water obtained from reverse osmosis (RO) desalinization plants on-site may be used to supplement other sources. While these systems are expensive to install and maintain, in recent years they have become popular for island courses and a few coastal courses in Florida.

Collection and Storage

- Storage ponds to collect storm runoff water can maximize on-site available water. These should be implemented if feasible during the design phase of a new golf course construction or during renovation.
- Horizontal wells may provide an alternative water source.
- In some cases, golf course design may be changed to enhance runoff on an area for collection.

Irrigation System Design

- Irrigation systems should be designed by trained professionals, considering location, topography, soils, vegetation, water supply, and water quality.
- Irrigation systems need to be designed with varying control devices and rain shut-off devices. Central computer control provides greater flexibility and regulation than what can be achieved from using only field satellite control systems. If the current system does not use central computer control, it should be considered as a necessary upgrade with future irrigation system improvements.

- Current irrigation systems if properly configured and software options maximized, can 1) monitor rainfall and adjust schedules accordingly, 2) utilize weather stations to adjust scheduling, 3) set minimum ET levels that must be met before irrigation will take place, and 4) monitor system performance including flow and pump performance.
- Irrigation systems should be designed for efficiency and flexibility from the pump station to the heads. Variable frequency drive (VFD) pumps (phased pump system) are more efficient at water delivery and minimize wear on the other parts of the irrigation system. A VFD pump should be considered a necessary upgrade with future pumping station improvements.
- Pipe size, sprinkler heads, nozzles, and head spacing should be appropriate for the irrigated area, water pressure, expected wind, and the zoning. Tree, shrubs, and non-turf areas should be considered when designing the irrigation system. Modifications may be necessary to older systems for increased delivery uniformity and to minimize overspray in areas that do not require irrigation.

Golf Engineering Associates (www.geogolf.com) estimated the average cost of installing irrigation on a golf course at about $675 per head, which would include design, installation, controllers, parts, and wiring. A pump station costs about $100,000 more. Using 63 foot triangular spacing (odd spacing to install considering 20 foot pipe length) it will require approximately 15 heads per acre. If the course is 100 irrigated acres, the cost will be about $1,000,000. Decrease the acreage to 90 acres and the cost will be around $910,000.

Wesco Turf Supply Inc of Florida (Toro Representatives) indicated that the number of heads on Florida golf courses has increased dramatically since the 1980s. At that time 500 to 750 heads per course was more typical; whereas 1000 to 2000 heads per course is currently more typical. Cost estimates (for contractor planning purposes) for 2004 were $1,000 per head installed (including a pump station).

- Having fewer the heads per zone with the corresponding increase in number of zonesallows greater control. Greens should have dual zones to allow separate watering of the green surface and the surrounds. Dual zoning should be considered as a necessary upgrade with future irrigation system improvements.
- Irrigation installation should be completed by qualified specialists following the designer's plan and using existing standards and criteria. Any deviation from the plan should have the designer's approval and be noted in the as-built plan.
- Installation procedures should include 1) written installation procedures, 2) installation details, 3) material list identifying head types with proper nozzle identification and indicating flow and operating pressures, 4) direction to the contractor to provide "as built" drawings, 5) direction to the contractor to provide product information manuals, and 6) suggested maintenance procedures.

Irrigation System Performance Evaluation

- Irrigation performance evaluation should be conducted after installation and every few years to determine Distribution Uniformity (DU), precipitation rate, and identify necessary system adjustments. Although no direct water savings are associated with an irrigation audit, the characterization of the system's performance can indicate areas of needed improvement. Improvements may not be feasible depending upon irrigation design.

> A 1998 Georgia Department of Natural Resources Report recommended that irrigation audits be performed by individuals certified by the Irrigation Association, or other irrigation specialists who can competently address all aspects of irrigation system design and management (dealers, consultants, etc.). The rigorous requirements for becoming a certified auditors reduces the potential for poor quality audits. The Irrigation Association has developed two auditor certifications: *Certified Landscape Irrigation Auditor (CLIA) and Certified Golf Irrigation Auditor (CGIA).*

- An irrigation audit can reveal inefficiencies such as 1) quantity of water exceeding the plant needs, 2) non-uniformity of water application, 3) precipitation rate exceeding soil infiltration rate, 4) incorrect heads/nozzles, 5) improper application pressure, and 6) malfunctioning and/or misdirected sprinklers.
- Irrigation system performance evaluation should be required information for Consumptive Use Permits (CUP). The manufacturer reported precipitation rates and design distribution uniformity may not be accurate. The fact that the course has low DU may be a function of design, installation, and maintenance. Corrections/modifications should be made as appropriate before evaluating for DU.
- Golf course personnel may need training from irrigation manufacturer's factory personnel to optimize the computerized irrigation system.
- An annual irrigation system review can be beneficial. This review can include a certified irrigation auditor or appropriately qualified irrigation consultant review scheduling and maintenance procedures in order to make recommendations for improvement, annual check of pressure, flows, or diameters of throws on a representative sample of heads, and catch container tests.
- Catch-container tests are most often utilized to determine delivery uniformity. Distribution Uniformity (DU) is usually used to evaluate turf and landscape irrigation distribution. It compares the average of the lowest 25% of the readings in catch-containers to the overall average. A DU of 100% is perfect, but not attainable.

Table A-1. The Irrigation Association (2003) suggested Distribution Uniformity (DU_{LQ}) rating values for different sprinklers. This DU_{LQ} are after the irrigation system has been checked and modifications and repairs have been completed.

Type of Sprinkler	Excellent	Very Good	Good	Fair	Poor
	- - - - - - - - - - - - - - - % - - - - - - - - - - - - - - -				
Rotor	80	70	65	60	50
Impact	80	70	65	60	50
Fixed Spray	75	65	55	50	40

- The Christiansen Coefficient of Uniformity (CU) is sometimes used to evaluate irrigation system uniformity. It determines how much each catch-container amount varies from the average reading. A CU of 100% is perfect, but not attainable. A CU value is typically higher than a DU value for the same catch-container test.

General Catch-can Auditing Information

Catch-can auditing is the best method to determine actual system performance. A series of collection containers are spaced uniformly in a specified area. Spacing of about 30 feet on center is sufficient for a golf course, but closer spacing on a green (10 feet on center) would be more appropriate. If container number is limited, you can pour out and re-use the same containers as you test zone by zone. Another method sometimes used is to place a can at each head and halfway between heads. This is a simple placement pattern that requires a minimum number of containers. When placing catch-cans at each head, make sure the cans are far enough away form the heads so as not to interfere with the spray pattern. Each irrigation zone should be run for 10 to 30 minutes during a period of minimum wind (less than 10 mph). A minimum depth in the collection can of 0.5 inches is suggested. The run time should allow for five to ten rotations of a geared rotor or impact sprinkler head. Running the system longer will lead to more accurate results. Use a pressure gauge to check and record the water pressure at each sprinkler head while the system is running if possible. Volume in each collection container can then be measured and recorded.

Distribution Uniformity Calculation

Distribution uniformity is typically calculated as the *Low Quarter Distribution Uniformity* or DU. Catch-can data are summarized into one value using the DU equation.

$$DU = \frac{Avg.LQ}{V_{avg}} X100$$

Where: DU = Lower Quarter Distribution
Avg. LQ = Average volume of lower 25% of sample
V_{avg} = Average catch can volume

Irrigation Scheduling

- When to irrigate may be based on signs of plant stress (leaf firing or browning of the leaf edges), calendar methods (for example every 3 days), by historical evapotranspiration (ET) data, soil moisture levels, water balance procedures, or some combination of these procedures. Historical ET data will require access to local weather data. A water balance approach will require judicious irrigation and rainfall data documentation.
- In order to maximize irrigation water, a thorough knowledge of the turf water requirements, effective root-zone, soil water-holding capacity, daily water use, and irrigation system capabilities are needed.
- The most effective scheduling for golf course managers would be to utilize a multi-tiered approach. Historical data could be utilized to predict gross irrigation control settings. If available, on-site weather stations could provide refined settings based on ET and rainfall. ET_p levels can be used by obtaining values at http://fawn.ifas.ufl.edu. These values should be used only as a general guideline for irrigation scheduling or for monthly controller adjustments when local information is not available. The final scheduling adjustments could be made by monitoring 1) soil moisture status of "indicator spots" and 2) plant water status using visual observation of "indicator spots". These indicator spots are areas that have historically low soil moisture or areas where plants show early drought stress symptoms. Monitoring plant indicator areas alone is not as effective since they provide limited information on how much water to add.
- AFSIRS model may be used to predict water needs. In one study conducted in central Florida, when using actual weather data collected on-site, AFSIRS predicted water use by five golf courses over a 10-month period within 22% (average) of actual water use for five golf courses.
- Deficit irrigation (replacing less than full ET) is a suggested management philosophy that may be used. Deficit irrigation manages irrigation quantities so that there is always soil storage to take advantage of any possible rainfall. In humid Florida, a large part of the water requirement can be provided by rainfall.

Effective rainfall, rainfall that is stored in the root zone and available for turf use, directly reduced the amount of water which must be pumped for irrigation.

- Current irrigation systems can interface with weather stations to calculate ET amounts and control the irrigation based on these amounts.

> In one study turfgrasses were irrigated at 100, 80, and 60% of ET values estimated from modified Class A pan data. They reported that bermudagrass at 60% ET was better than acceptable and not significantly different than bermudagrass irrigated at 100% of ET (Meyer et al., 1985). In a Texas study it was reported that turfgrass quality increased linearly as irrigation increased (up to 55% ET). However the researchers concluded that quality was not improved for bermudagrass or St. Augustinegrass when watered at a rate greater than 55% of E_{pan} (Qian and Engelke, 1999). Deficit irrigation has also been shown to increase root length. It was reported in one study that irrigation treatments of 20% ET_o increased tall fescue root length beginning 29 days after treatment. There were no differences in root length observed between 20% ET_o and 60% ET_o irrigation treatments. (Fu et al., 2003). It should be noted that tall fescue is not adapted to Florida conditions due to lack of heat and drought tolerance.

- Irrigation scheduling should be site specific to maximize water conservation while considering system limitations. Allowing for distribution differences may be necessary to maintain uniform turf. It was reported in one study that turfgrass plots irrigated twice a week had significantly higher quality ratings than turfgrasses with four irrigations per week Richie et al. (2002)
- The current irrigation philosophy is to irrigate to a depth just below the root zone. Watering deeper than that does not benefit the plant, unless you are trying to displace salts from the rootzone. In the case of salt affected sites, irrigation scheduling will have to be adjusted (increased) to allow for salt leaching.
- Sandy soils coupled with the constant traffic from golfers and maintenance equipment, increase the water requirements of a golf course. This issue is exacerbated on the golf greens due to the shallow rooting of the closely mowed turf and increased traffic. Consideration must be given for compacted areas and areas with increased traffic stress.
- Sloped areas, compacted soils, and sandy soils will need to be irrigated in short, frequent intervals due to water infiltration and retention dynamics.

Golf Course Design

- The most important consideration is to minimize irrigated turf area where the highest quality is expected. Reduced irrigation frequency and amount may be necessary to conserve water in roughs. System design for separate control of rough irrigation is helpful for conservation practices since the height of cut in the rough also may allow the turf to be more drought tolerant due to increased rooting. This may be more important conservation tool in secondary roughs.

- Higher mowed turf or unmowed drought resistant turf may be used in low-use areas.
- Turf alternatives either in the form of more drought resistant landscape plants, mulches, rocks, and sand should be used as appropriate. This type of design is only useful if the area falls within a non-irrigated area or an area that utilizes micro-irrigation. If the area is renovated to reduce turf, the irrigation design should be altered. Heads will need to be relocated, new zoning/piping may be necessary, and alternative heads may be required. The new irrigation system should be designed and installed to improve irrigation distribution uniformity.
- Improve soils during construction or renovation for improved water retention. In Florida this usually involves adding (either a "cap" or incorporation) a finer textured soil with organic matter or by adding organic matter into the existing soil. Unless a supply of organic matter material is nearby, this will be an expensive undertaking. Since a significant cost of using organic matter is shipping, it becomes more cost prohibitive as the land area that is amended increases
- Select low water-use and/or drought tolerant turfgrasses, groundcovers, shrubs, and trees for use on the course. Realize that water-use and drought tolerant plants may not coincide. For instance, bahiagrass can be classified as a high water-use turf, but it is very drought tolerant. For selecting water conserving landscape plants, consult the book *Waterwise: Florida Landscapes* available from Florida's Water Management Districts.

Best Turfgrass Management Practices

- Increase turf mowing heights if feasible, especially on greens. This promotes deeper rooting for more effective use of available water and increases carbohydrate assimilation for healthier plants. Education of the golfing community is key to acceptance of higher mowing heights. Rolling, grooming, and regular sand topdressing may be necessary to maintain green speeds favored by golfers.
- Provide adequate levels of nutrients to the turf, especially nitrogen and potassium. Avoid excessive levels of nitrogen, since it promotes water-use and reduced drought tolerance. High rates of N have been shown to increase shoot growth and reduce root growth (Goss and Law, 1967). Reduced root growth results in turf becoming less tolerant to environmental stresses, more susceptible to disease, and more dependent on frequent irrigation and fertilization to supply the needed nutrients and moisture for growth (Beard, 1973).

In a study at two golf courses and one park in Las Vegas, NV growing common bermudagrass overseeded in the fall with perennial ryegrass it was shown that golf turf used 41% more water than park turf. The difference in water use was attributed to differences in fertilizer management Devitt et al. (1992).

- Fertilizer recommendations for golf course turfgrasses can be found at http://edis.ifas.ufl.edu/ss404.
- Use soil cultivation techniques such as spiking, slicing, and core aerification to improve water infiltration/wetting and minimize runoff during irrigation or rainfall events.
- Soil additives may be used to promote infiltration and retention. This may include sand topdress or sand cap fine-textured soils, add organic matter to fine-textured soils, add organic matter to coarse-textured soils, wetting agents to hydrophobic sands.
- Alleviation of excess total salts or toxic ions in the soil may be necessary. This is most commonly accomplished with a leaching program (requiring water amounts above that used by the plant).
- It may be necessary to alleviate sodic soil conditions, most commonly with gypsum additions.
- Biostimulants that promote root growth under non-ideal situations may become more common. The current research on many of these products is limited.
- Amelioration of soil pH with liming agents or acidifying agents as appropriate.
- Insect control, particularly soil inhabiting insects (e.g., mole crickets and grubs) should be done on an as needed basis. Root feeding insects result in less efficient plants for taking up water.
- Plant growth regulators (PGR) such as trinexapac ethyl (Primo) reduce the need for mowing and may be useful in reducing the need for irrigation. Research has shown that some PGRs lower ET, which may extend the available water supply. Growth regulators may also improve the carbohydrate reserves of the turf plants thus improving stress tolerance.
- Improve drainage where needed to produce a healthier turf.
- Irrigate at rate less than infiltration rate.
- Limit cart traffic to minimize turf wear and soil compaction.
- Use an appropriate mulch [http://edis.ifas.ufl.edu/mg251] in shrub and flower beds to reduce water evaporation losses. Heavily landscaped areas, particularly with annual plants may be water-demanding, so should be held to a minimum.
- Plant shrubs and small trees in groups rather than individual plantings to reduce areas of tree and turf competition for moisture and nutrients.

Water Conservation

- Have a water conservation plan (see below). Decide which areas require the least water if you need to cut back on water use. In some cases the golf course may elect to replace some turf areas with more drought-tolerant plant materials.
- Superintendents need to determine irrigation amounts and application timings. These amounts should consider ET rates, soil type, grass management factors (fertilization and location), and expected weather conditions.
- Computerized irrigation systems can be beneficial if properly set up. Computerized control systems, portable hand-held controllers, and variable frequency drive (VFD) pumping systems can be used to apply water in the most efficient means to reduce water and energy consumption.
- A rain shut-off device is very beneficial when watering after working hours. Watering at night or in the early morning is beneficial due to less wind and lower evaporation rates. Use of weather reports and on-site weather stations can be beneficial to reducing the chance that the course is watered immediately preceding rain.
- Improve irrigation uniformity through careful evaluation of sprinkler head design, nozzle selection, head spacing, and pressure selection.

Golf Course Water Conservation Plan

- Each course should develop an overall strategy to conserve water on the entire golf course property over a period of time. The turf manager can concentrate on turfgrass and landscape areas and provide input to others that develop conservation practices for non-outdoor areas. This plan must be specific, on paper, presented to the club (owner/manager/governing committees) for adoption, accepted by the club, and have provisions for regular monitoring.
- Each golf course should develop a water contingency plan. This plan should outline the steps the club will take to deal with emergency water shortages (usually due to prolonged drought events). This contingency plan should be included as part of the "Water Conservation Plan" and have acceptance by the club.
- The Audubon Cooperative Sanctuary Program for Golf Courses includes a segment that educates course personnel about water conservation and protection and recognizes courses that take significant steps to conserve water.

APPENDIX B
Irrigation Scheduling Methods and Tools

Method	Tools or parameters used	Advantages/Disadvantages
Soil Moisture Monitoring		
Hand feel and appearance	Hand probe (screw driver)	Variable accuracy, requires experience
Soil moisture tension	Tensiometer	Good accuracy in most conditions, easy to read but narrow range
Electrical resistance tester	Gypsum block	Limited accuracy
Indirect moisture content	TDR	Highly mobile, expensive
Gravimetric analysis	Oven and scale	Labor intensive, results in 24-48 hours
Crop Canopy Index		
Visual appearance	Field observation	Variable accuracy
Water stress index	Infrared thermometer	Expensive & requires experience
Water Budget Approach		
Checkbook method	Computer	Indicates when and how much water to apply, requires experience and persistent record keeping
Reference ET	Weather station data	Requires appropriate crop coefficient, weather instruments expensive and require regular maintenance

APPENDIX C
Materials and Methods for
Irrigation System Evaluation, Turf Performance and AFSIRS Testing

The Materials & Methods reported here contain standard metric units that are accepted by the scientific community. In most cases, conversions have been made in the preceding text to reflect a request by the District.

Course Selection

A field investigation on golf course water use was conducted on five golf courses in the Central Florida ridge area from January 2002 to April 2003. They were selected based on three general criteria.

1. Course must be permitted for water use in the St. Johns River Water Management District of Florida
2. The irrigation system had to be computerized and less than five years old
3. The superintendent having a willingness to cooperate.

Course selection was finalized in January of 2002 and surveys were sent to the participating golf course superintendents. The surveys were used to ascertain the golf course's layout, irrigation practices, irrigation system components, and turf cultural practices.

Hole Selection

Three holes at each course were chosen by the superintendent and considered to be a fair representation of the entire course. Global Positioning System (GPS) technology was used to map each of the three holes at each golf course. These maps included sprinkler head location, brand and model of sprinklers, layout of the tees, fairways, greens, and their representative area. Maps were used to determine the spacing of sprinklers, and for data entry during the study. All sprinklers evaluated in this study were rotor heads.

Weather stations were installed in June of 2002 to monitor environmental parameters. The weather stations were located in flat-grassed areas so that the nearest obstruction was at least ten times its height away from the station. Weather stations were placed in irrigated areas on the golf course property. The golf holes were located within 300 m of the weather stations. The stations recorded the date, time, temperature, soil heat flux (HFT3, Radiation Energy Balance Systems, Bellevue, WA), solar radiation (LI-200SZ, Licor Inc. Lincoln, NE), wind speed and direction (WAS425, Vaisala, Inc. Sunnyvale, CA.), relative humidity (HMP 45C, Vaisala, Inc.,Woburn, MA), and precipitation (TE525 Tipping Bucket, Texas Electronics, Inc., Dallas TX) at 15 minute intervals via a CR10X datalogger (Campbell Scientific, Inc., Logan, Utah).

Irrigation Audits

Irrigation audits were performed on three golf holes at each of the five courses from March through May of 2002, . The audits were conducted using the agricultural methods of *ANSI/ASAE S436.1 MAR 01* Standards (ASAE, 2001), and using the evaluation methodology described in the Irrigation Association of America's Certified Golf Course Irrigation Auditor training manual (IA, 2003) . Procedures in this study differed from the ASAE standards for agricultural systems due to the specialized design of golf course irrigation systems. Procedures described by the Irrigation Association were modified by increasing the number of catch-cans placed in the testing areas.

The catch-cans used in this study had an opening diameter of 7.6 cm (3.0 in) and a depth of 10.8 cm (4.25 in.). For tee complexes (all tees) and greens, catch-cans were placed in a grid pattern on 3-m centers over the entire surface. The number of catch-cans used to determine uniformity on tee complexes varied between 48 to 205, depending on surface area measured. The number of tees in a tee complex ranged from 1 to 5 for golf courses in this study. Individual tees were evaluated separately, unless they were close together. The DU_{LQ} for each tee was then calculated to determine the uniformity of the tee for that hole. The number of catch-cans used to determine uniformity of the greens varied between 44 to 138. For fairways, catch-cans were placed in a grid pattern on 9-m centers throughout the entire fairway and the primary rough if irrigated. The number of catch cans used to determine the uniformity of fairways varied between 63 and 147. Once it was determined that all zones had run for a certain location, the collected water in each can was measured using a 500 ml graduated cylinder and recorded for further analysis.

ASAE standards (ASAE, 2001) were followed for wind speed measurements. Wind speed during the tests was measured using a Skywatch meteos handheld anemometer with an accuracy of ± 5 % (JDC Electronics, South Africa). Wind speeds were taken prior to the catch-can test and thereafter at 20 minute intervals. If the wind speed exceeded 5 m s^{-1} prior to the test, the test was delayed until the wind speeds were within the recommended limit. If wind speeds exceeded 5 m s^{-1} during the tests, it was noted and the wind speeds throughout the test time were averaged to see if the average wind speed exceeded the limit. To limit the effects of wind and other confounding variables the tests were conducted at night. An entire hole (tees, fairway, green) could be completed in one night. The test run time on fairways and tees of the five courses ranged between twenty and thirty minutes. The test time for greens ranged between ten and thirty minutes.

Soil Moisture

Once the catch-cans were laid out, soil moisture measurements over a 20-cm depth were taken at each catch-can using the Spectrum Field Scout TDR 300 Soil Moisture Probe (Spectrum Technologies Inc., 2002). The measurements have 1.0% resolution and ± 3.0% volumetric water content accuracy. Immediately following soil moisture measurements, each irrigation station was turned on for its entire testing runtime. Tees generally ran first followed by the fairways and then the greens. The number of sprinklers operating at one time was representative of the normal operating conditions of that particular system. Irrigation runtimes varied from golf course to golf course, however each location within individual courses received the same amount of time. The test runtime on fairways and tees of the five courses ranged between 20 and 30 minutes per zone. The test time for greens ranged between 10 and 30 minutes per zone. Post irrigation soil moisture readings were taken at each catch-can.

Irrigation Pressure at Head

During the catch-can test, irrigation pressures were tested on random rotor sprinklers at each location with a pressure gauge and pitot tube. The tube was placed directly in the stream of the main nozzle at a distance approximately 0.6 cm away. The number of sprinklers tested on tee locations ranged between two and six depending on the size of the tee complex (all tees). Fairway pressures were checked at the beginning, middle, and end of the fairway. Pressures on greens were checked at each sprinkler.

Sprinkler Throw Distances

Sprinkler throw distances were measured during the catch-can test on the same sprinklers evaluated for pressure. The throw distance of the water was measured upwind from the sprinkler and downwind from the sprinkler if the wind was measured greater than 2 m s^{-1}. If wind was measured below 2 m s^{-1} only one throw measurement was taken.

Irrigation Precipitation Rates

The net precipitation rate (PR) is the rate that sprinklers apply water to a given area per unit time and can be calculated as follows:

$$PR_{net} = \frac{V_{avg} \times 60}{TR \times CDA} \qquad \text{Eq. [1]}$$

Where:

PR_{net} = Net Precipitation Rate, (cm h^{-1})
V_{avg} = Average catch can volume (mL)
TR = Testing run time (min)
CDA = Catch can opening (cm^2)

Precipitation rates (PR) were calculated for each location on the golf course. At each course, three locations (tee, fairway, and green) on three holes were evaluated. The PR for each tee in the tee complex was calculated using and then averaged to determine the mean precipitation rate for the tee complex. Irrigation test run times varied from golf course to golf course, however each location within individual courses received the same amount of time.

Particle size analysis

Soil core samples (10 cm-wide and 15 cm-deep) were taken from tees, fairways, and greens on three holes at the five golf courses in Central Florida in June of 2002. Samples were oven dried at 105° C for 24 h. Samples were then passed through a 2 mm sieve to remove stones and plant debris. After sieving, 100 g. of soil was then weighed for each location. Separation of particle sizes was performed using United States Department of Agriculture (USDA) standard sieve numbers between 270 (0.05-0.10 mm) and 10 (>2mm). Sieves were placed in order of decreasing size. Samples were then inserted into the top sieve and shaken for three minutes. Soil fractions remaining in each sieve were then weighed and recorded.

Reference Crop Evapotranspiration

For these studies reference crop evapotranspiration (ET_o) was made using the modified Penman-Monteith equation (Allen et al., 1998).

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma \dfrac{37}{T + 273.2}\mu_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \qquad \text{Eq. [2]}$$

where:

ET_o	Reference evapotranspiration (mm h^{-1})
R_n	Net Radiation (MJ m^{-2} h^{-1})
G	Soil heat flux (MJ m^{-2} h^{-1})
e_s	saturation vapor pressure at air temperature (kPa C^{-1})
e_a	vapor pressure of air (kPa)
u_2	Wind speed at 2 m (m s^{-1})
Δ	slope of saturation vapor pressure curve at air temperature (kPa C^{-1})
γ	psychrometer constant (kPa C^{-1})

Soil Moisture Uniformity

Lower quarter distribution uniformity (DU_{LQ}), was the primary measure of irrigation system performance. Soil moisture lower quarter uniformity ($SMDU_{LQ}$) was used to quantify the uniformity of soil moisture in the turfgrass rootzone. $SMDU_{LQ}$ was defined as:

$$SMDU_{LQ} = \frac{AVG.\mathrm{SM}LQ}{AVERAGE} \times 100 \qquad \text{Eq. [3]}$$

$SMDU_{LQ}$ = Lower quarter soil moisture distribution uniformity (percentage)
Avg. SMLQ = Average soil moisture of the lower 25% of the sample
Average = Average soil moisture of the total sample

Irrigation Reductions Treatments

Three irrigation treatments were compared. The first treatment consisted of irrigating using the normal runtimes set by the golf course superintendent. Treatment two and three were ten and twenty percent reductions of normal runtimes used for treatment one. Normal runtimes were historic runtimes used by the turf manager under those conditions. Treatments were assigned to golf holes by the superintendent at each golf course. In this study each golf course superintendent controlled the irrigation program for treatment one based on their experience. The superintendent could change irrigation settings for treatment one based on rainfall, humidity, wind, and temperature, with corresponding reductions for treatments two and three. The reductions were set up on the main irrigation controller and irrigation runtimes were monitored monthly. Any adjustments to irrigation treatments were documented by the superintendent or irrigation technician into an irrigation log. Reasons for adjustments included seasonal change, watering in product, irrigation systems tests, localized dry spots, and syringing. Water reductions began on 17 July 2002 and ended on 20 April 2003.

Irrigation amounts per period (inches $month^{-1}$ or cm $month^{-1}$) were calculated on a monthly basis by using the runtimes set up by the superintendent and the net precipitation rates calculated. It was hypothesized that the precipitation rates would not vary significantly between locations on a golf course and therefore by reducing the runtimes on locations at two holes by ten and twenty percent, comparisons among the amounts of water going out on the three holes could be made.

Turfgrass Quality Assessment

Visual ratings for quality were taken on a monthly basis, beginning in August 2002 and ending in May 2003. Global Positioning System (GPS) maps were used to record quality ratings and document any problem areas, primarily drought stress or thin areas. Quality ratings were assigned on a 1-9 scale, where 9 represents superior quality turfgrass and 1 represents brown or dead turf. A quality rating of 6 was considered to be the minimal acceptable quality for turfgrass on golf course turfgrasses. Quality ratings for the months of November to March were based on overseeded grasses. The grasses on the golf course were perennial ryegrass (*Lolium perenne* L.) on tees and fairways and rough bluegrass (*Poa trivialis* L.) on greens. At each course, three locations (tee, fairway, and green) on three holes were evaluated. Each tee was assessed individually and then averaged to calculate the mean quality rating for the tee complex (all tees on that hole). Fairways were divided in relatively equal sized sections, either four or five, depending on the length of the fairway. These sections were drawn on the GPS map to ensure the same sections were monitored monthly. These sections were assessed individually and then averaged to calculate the mean quality rating for the fairway. Greens were subdivided into four quadrants. Each quadrant was assessed individually. Quadrant ratings were then averaged to calculate the mean quality rating for the green.

Rooting Depth Measurement

Maximum and average rooting depths were measured on three locations (tees, fairways, and greens) at each golf course. Measurements were taken in September and November 2002 and February and May 2003. Three random samples were taken at a 15 cm depth from each location using a Mascaro soil profiler (Turf-Tec International, Coral Springs, FL). The maximum rooting depth was determined by physically measuring the longest root in each of the three samples. Measurements were taken from the top of the thatch layer to the tip of the root. These values were then averaged and the mean maximum rooting depth of the three samples was recorded as the maximum rooting depth for that location. Average rooting depth was determined by visually assessing the samples where the majority of the roots were present. A ruler was then used to measure distance to the top of the thatch layer. These measurements were then averaged and a mean rooting depth was calculated. This was determined to be the average rooting depth for the location being tested.

Data Analysis

Normally distributed data was analyzed using Statistical Analysis System General Linear model procedure (SAS Institute, 1987). In this study, golf courses were considered random effects and locations were fixed effects. Mean separation was accomplished using Fisher's least significance-difference (LSD) test for the determination of statistical differences in the analysis for effects of golf course, location, and their interactions. Turf quality and rooting depth data were analyzed by analysis of variance procedures using the mixed model procedure (Littell et al., 1996) and single degree of freedom contrasts.

Geostatiscal Analysis

Geostatistical software (GS+, Gamma Design Software, St. Plainwell, MI) was used to analyze the spatial structure of the data and to define the semivariograms. Semivariance analysis was used to estimate the range over which irrigation delivery and soil moisture on the greens were related. Selection of the models for semivariograms was made principally on visual fit and r^2 of the regression. Semivariance, $\gamma(h)$, of all samples can be defined as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[z(x_i) - z(x_i + h) \right]^2 \qquad \text{Eq. [4]}$$

where $N(h)$ is the number of samples separated by lag distance h and $z(x_i)$ and $z(x_i + h)$ are experimental measures of any two points (separated by the lag distance h). Semivariance is evaluated by calculating $\gamma(h)$ for all possible pairs of points in the data set and assigning each pair to an interval class h. The semivariogram is the graph of the semivariance statistic between spatially separate data points as a function of the distance.

Semivariance analysis expresses the variation between data points as a function of the distance separating them. Semivariance ideally increases with distance between sample locations, or lag distance (h), to a more or less constant value (sill). Samples separated by distances closer than the range (a) are related spatially, and those separated by distances greater than the range are not spatially related.

Modeling Data Characterization

The data collected during the study that was used for modeling were weather data, irrigation distribution uniformity, and rooting depths. Each golf course had an on-site weather station that collected daily climatic data including temperature, relative humidity, soil heat flux, wind speed, and rainfall. This data was used to develop site specific weather datasets, containing daily ET_p rates and rainfall, to be used with the AFSIRS model. The average amount of rainfall in historical weather datasets used in the model for the Orlando area is 50.7 inches per year; whereas, the average rainfall recorded at the five courses from June, 2002 to May, 2003 was 78.4 inches. The AFSIRS model was run for each golf course using updated K_C values, actual irrigation efficiency (DU_{LQ}) values, measured rooting depths, with or without USGA green medium, and actual local weather datasets. The K_C values were from the literature reported by researchers in Georgia and Arizona, the most appropriate K_C values available. Model runs were initially made with only one parameter change at a time. Combinations of default and actual data were run in the model, as well as all actual data from each golf course.

ET_p rates

ET_p rates were calculated using the program REF-ET (University of Idaho). REF-ET was developed as a stand-alone computer program to calculate ET_p from meteorological data made available by the user (Allen, 2002).

System Efficiency

Because it is extremely difficult to determine irrigation system efficiency in a field setting, distribution uniformity (DU_{LQ}) values were collected and used in the model to replace the default efficiency value (75%) for a multiple sprinkler system. For modeling purposes, an average DU_{LQ} for each of the three holes on the five courses was determined by weighting the DU_{LQ} for each location (tee, fairway, green) based on their total areas. Because the fairway occupies the most area, the DU_{LQ} for a hole was similar to the DU_{LQ} of the fairway on that hole. The weighted average DU_{LQ} for the three holes on the five courses were calculated as follows: golf course A = 32, 37, and 59%, golf course B = 40, 49, and 42%, golf course C = 62, 45, and 55%, golf course D = 62, 67, and 67%, and golf course E = 41, 54, and 44%.

Irrigated Rooting Depth

Because two of the holes on each course had reduced run times for the conservation treatments, only the rooting depths from the control holes (typical irrigation practices) were used for modeling. Analysis of variance indicated that there were no differences in rooting depths by month or by location (tees, fairways, greens) at a 95% probability level. Therefore rooting depths from each month, at each location, were averaged together to get an average and maximum rooting depth for each golf course. The measured average rooting depth was used to replace the AFSIRS default irrigated rooting depth of 6 inches, and the measured maximum rooting depth replaced the default maximum rooting depth of 24 inches. The average and maximum rooting depths from the five golf courses, used for modeling, were (avg. and max. in inches): golf course A = 1.7 and 2.6, golf course B = 1.7 and 2.8, golf course C = 1.8 and 2.9, golf course D = 1.8 and 2.6, and golf course E = 1.7 and 2.7, respectively.

Crop Coefficient

Because the climate in Florida is predominantly sub-tropical, most golf courses grow the warm-season grass bermudagrass (*Cynodon dactylon x C. transvaalensis*). The predominant bermudagrass cultivar used for fairway and rough turf areas is 'Tifway'. It is common for a golf course manager to overseed with a cool-season grasses, such as perennial ryegrass (*Lolium perenne*) or rough bluegrass (*Poa trivialis*), in late fall for winter and spring playability. A literature search suggested alternative crop coefficient (K_C) values were available to replace the default value of 1 in the model. In a Georgia study, Carrow (1995) reported actual Tifway bermudagrass K_C values 0.62 in May, 0.54 in June, 0.53 in July, 0.65 in August, 0.97 in September, and 0.73 in October. Brown and Kopec (2000) reported K_C values for ryegrass are 0.83 in November, 0.80 in December, 0.78 in January, 0.79 in February, 0.86 in March, 0.89 in April. These reported K_C values were used in the corresponding months in the model.

Soil Type

Soil types for tees and fairways were determined from soil survey maps. Two courses, A and E, have push up greens and therefore have the same soil type on the green as the tee and fairway. Three of the golf courses in the study have greens built to United States Golf Association (USGA) specifications (USGA Green Section Staff, 1993). These greens have a 12- to 14-inch rootzone medium, made up of a 80% sand and 20% peat covering a 4-inch gravel layer. This allows for a higher water holding capacity (WHC) than most native sandy soils. The average soil water content of a USGA green is 13%, and the average soil water content of the native soils on the 5 golf courses is 7% (Hummel, 1993). Due to the difference in soil water content, these greens were run separately when soil type influences were being analyzed. The soil type used for the golf courses in the model (except USGA greens) were: golf course A, B, C = Astatula sand, golf course D = Candler sand, and golf course E = Blanton fine sand.

APPENDIX D
Golf Course Descriptions and Data

Course A

GPS Coordinates: Latitude 28.9301
Longitude -81.8590

Water Sources:

- Ground

Water used for other purposes

- Non golf course areas (specify) common areas

Irrigation controller/computer:

Location of controller Maintenance Facility
Make and Model Rain Bird Nimbus II
Age of system? ____________ or upgrade? 3.0 years
Is it possible to monitor the water used on a specific hole? Yes

Irrigation components:

Types of heads on:

	Make	Model#
Greens	Hunter	G90
Fairways	RB	900 / 950
Tees	RB	900 / 950
Approaches	RB	900 / 950
Rough	RB	900 / 950

Number of heads on:

- Greens 4 per green
- Fairways 2/station
- Tees 1 or 2
- Approaches 2
- Rough 2/station

Turf Information:

Acreage of:

- Greens 4.0
- Fairways 30.0
- Tees 6.0
- Approaches 4.0
- Rough 80
- Total Irrigated Acreage? 50+/-

Grass types:

- Greens Tifdwarf
- Fairways 419 bermudagrass
- Tees 419 bermudagrass
- Approaches 419 bermudagrass
- Rough 419 bermudagrass

Soil types:

- Greens sand –push-up
- Fairways clay/sandy loam
- Tees sand
- Approaches sand
- Rough sand

Pump Station:

Type of pumps _2 800 gpm / each + _30 hp jockey
Rating of pumps (capacity, HP, GPM) 125 HP, 1200 gal/min
Age of pumps 8 years

Evapotranspiration weather Data:

Weather Station:

- On site (location) Yes ** installed prior to study by researchers.**
- Can data be accessed from site? yes, CR 10 measurement and control system (Cambell Scientific, Inc., Logan, UT).
- What type of data can be evaluated? ET_o parameters (solar radiation, wind speed, humidity, and temperature) precipitation.
- What sensors are on system? **solar radiation** (LI-200SZ Pyranometer Sensor. Licor Inc. Lincoln, NE) **wind speed** (WAS425 Ultrasonic Wind Sensor. Vaisala, Inc. Sunnyvale, CA.) **temp & relative Humidity** (HMP 45C temp and rel. humidity probe. Campbell Scientific, Inc. Logan, Utah) **precipitation** (TE525 Tipping Bucket. Campbell Scientific, Inc. Logan, Utah).

General Questions:
What is your current irrigation schedule? Varies with weather
Do you have flow meters on your system? Yes at main pump
How old is your course? 10years old
Has course been renovated? No
Do you overseed? Yes If so when? Oct/ Nov

Course B

GPS Coordinates: Latitude 28.5108
Longitude -81.7117

Water Sources:

- Ground

Water used for other purposes

- fertigation

Irrigation controller/computer:

Location of controller Pump House
Make and Model Rain Bird Nimbus II
Age of system? __2yrs__________ or upgrade?______
Is it possible to monitor the water used on a specific hole? Yes

Irrigation components:

Types of heads on:	Make	Model#
• Greens	RB	950
• Fairways	RB	900
• Tees	RB	900
• Approaches	RB	900
• Rough	RB	950

Number of heads on:

- Greens 4 per green
- Fairways double row triangular
- Tees 1 – 3
- Approaches included in fairway program
- Rough varies

Turf Information:

Acreage of:

- Greens 2.75
- Fairways 12.0
- Tees 4.0
- Approaches 1.0
- Rough 30.25
- Total Irrigated Acreage? 50+/-

Grass types:

- Greens Tifdwarf
- Fairways 419 bermudagrass
- Tees 419 bermudagrass
- Approaches 419 bermudagrass
- Rough 419 bermudagrass/bahia

Soil types:

- Greens 70 -30 sand peat mix
- Fairways sand
- Tees sand
- Approaches sand
- Rough sand

Pump Station:

Type of pumps _Watertronex; VFD
Rating of pumps (capacity, HP, GPM) VTS-75/75/255 TV
Age of pumps 1 years

Evapotranspiration weather Data:

Weather Station:

- On site (location) Yes ** installed prior to study by researchers.**
- Can data be accessed from site? yes, CR 10 measurement and control system (Cambell Scientific, Inc., Logan, UT).
- What type of data can be evaluated? ET_o parameters (solar radiation, wind speed, humidity, and temperature) precipitation.
- What sensors are on system? **solar radiation** (LI-200SZ Pyranometer Sensor. Licor Inc. Lincoln, NE) **wind speed** (WAS425 Ultrasonic Wind Sensor. Vaisala, Inc. Sunnyvale, CA.) **temp & relative Humidity** (HMP 45C temp and rel. humidity probe. Campbell Scientific, Inc. Logan, Utah) **precipitation** (TE525 Tipping Bucket. Campbell Scientific, Inc. Logan, Utah).

General Questions:
What is your current irrigation schedule? Front 9 WED&SAT Back THU& SUN
Do you have flow meters on your system? Yes at main pump
How old is your course? 1years old
Has course been renovated? No_
Do you overseed? Yes If so when? Nov
Has Irrigation system ever been audited (Efficiency, DU)? NO

Course C

GPS Coordinates: Latitude 28.7012
Longitude -81.8681

Water Sources:

- Surficial

Water used for other purposes

- Fertigation

Irrigation controller/computer:

Location of controller Maintenance Facility
Make and Model Toro Osmac SitePro
Age of system? ___6years_ __ or upgrade?_3.0 years
Is it possible to monitor the water used on a specific hole? Yes_

Irrigation components:

Types of heads on:

	Make	Model#
Greens	Toro	780
Fairways	Toro	780
Tees	Toro	780
Approaches	Toro	780
Rough	Toro	780 or 2001

Number of heads on:

- Greens 4 per green
- Fairways 3 row square
- Tees 1 or 4
- Approaches included in fwy
- Rough varies

Turf Information:

Acreage of:

- Greens 3.0
- Fairways 20.0
- Tees 4.0
- Approaches 4.0
- Rough 70_
- Total Irrigated Acreage? 140+/-

Grass types:

- Greens Tifdwarf
- Fairways 419 bermudagrass
- Tees 419 bermudagrass
- Approaches 419 bermudagrass
- Rough 419 bermudagrass/ bahia

Soil types:

- Greens sand
- Fairways sand
- Tees sand
- Approaches sand
- Rough sand

Pump Station:

Type of pumps Flowtronex; Newman VFD
Rating of pumps (capacity, HP, GPM) 1500 GPM capacity, 60 HP, 750/GPM
Age of pumps 6 years

Evapotranspiration weather Data:

Weather Station:

- On site (location) Yes ** installed prior to study by researchers.**
- Can data be accessed from site? yes, CR 10 measurement and control system (Cambell Scientific, Inc., Logan, UT).
- What type of data can be evaluated? ET_o parameters (solar radiation, wind speed, humidity, and temperature) precipitation.
- What sensors are on system? **solar radiation** (LI-200SZ Pyranometer Sensor. Licor Inc. Lincoln, NE) **wind speed** (WAS425 Ultrasonic Wind Sensor. Vaisala, Inc. Sunnyvale, CA.) **temp & relative Humidity** (HMP 45C temp and rel. humidity probe. Campbell Scientific, Inc. Logan, Utah) **precipitation** (TE525 Tipping Bucket. Campbell Scientific, Inc. Logan, Utah).

General Questions:
What is your current irrigation schedule? As needed and visual inspection
Do you have flow meters on your system? Yes at main pump
How old is your course? 6 years old
Has course been renovated? No
Do you overseed? Yes If so when? Oct/ Nov
Has Irrigation system ever been audited (Efficiency, DU)? NO

Course D

GPS Coordinates: Latitude 28.7012
Longitude -81.9994

Water Sources:

- Ground
- Reclaimed
    - Ponds
    - Is there a minimum amount delivered per night? _____________
      Current reclaimed use. _40-50 mil/yr___
      Amount Dumped 100-150,000 gal/night (depends on time of year)

Water used for other purposes

- Non golf course areas (specify) common areas
- Fertigation

Irrigation controller/computer:

Location of controller Pro shop
Make and Model Rain Bird Cirrus
Age of system? __4 yrs__ or upgrade?____

Is it possible to monitor the water used on a specific hole? YesIrrigation components:

Types of heads on:	Make	Model#
• Greens	RB	950
• Fairways	RB	900
• Tees	RB	900
• Approaches	RB	950
• Rough	RB	900

Number of heads on:

- Greens 8 per green (Inner/outer)
- Fairways 3 row triangular
- Tees 1 or 2
- Approaches varies
- Rough varies

Turf Information:

Acreage of:

- Greens 6.0
- Fairways 45.0
- Tees 6.0
- Approaches --_
- Rough 142
- Total Irrigated Acreage? 200+/-

Grass types:

- Greens Tifdwarf
- Fairways 419 bermudagrass
- Tees 419 bermudagrass
- Approaches 419 bermudagrass
- Rough 419 bermudagrass

Soil types:

- Greens 85 – 15 sand-peat mix
- Fairways sandy loam
- Tees sandy loam
- Approaches sandy loam
- Rough sandy loam

Pump Station:

Type of pumps Newman;VFD
Rating of pumps (capacity, HP, GPM) 75 HP, 700 gal/min
Age of pumps 5 years
Evapotranspiration weather Data:

Weather Station:

- On site (location) Yes ** installed prior to study by researchers.**
- Can data be accessed from site? yes, CR 10 measurement and control system (Cambell Scientific, Inc., Logan, UT).
- What type of data can be evaluated? ET_o parameters (solar radiation, wind speed, humidity, and temperature) precipitation.
- What sensors are on system? **solar radiation** (LI-200SZ Pyranometer Sensor. Licor Inc. Lincoln, NE) **wind speed** (WAS425 Ultrasonic Wind Sensor. Vaisala, Inc. Sunnyvale, CA.) **temp & relative Humidity** (HMP 45C temp and rel. humidity probe. Campbell Scientific, Inc. Logan, Utah) **precipitation** (TE525 Tipping Bucket. Campbell Scientific, Inc. Logan, Utah).

General Questions:
What is your current irrigation schedule? Varies with weather
Do you have flow meters on your system? Yes at main pump
How old is your course? 5 years old
Has course been renovated? No
Do you overseed? Yes If so when? Oct/ Nov
Has Irrigation system ever been audited (Efficiency, DU)? NO

Course E

GPS Coordinates: Latitude 28.7239
Longitude -81.5720

Water Sources:

- Ground

Water used for other purposes

- Fertigation

Irrigation controller/computer:

Location of controller Maintenance Facility
Make and Model Rain Bird Stratus
Age of system? ____________ or upgrade? 3.5 years
Is it possible to monitor the water used on a specific hole? Yes

Irrigation components:

Types of heads on:

	Make	Model#
Greens	RB	950
Fairways	RB	900
Tees	RB	900
Approaches	RB	900
Rough	RB	900

Number of heads on:

- Greens 4 per green
- Fairways double row 80 ft. spacing
- Tees 1 or 2
- Approaches varies
- Rough varies

Turf Information:

Acreage of:

- Greens 2.5
- Fairways 25.0
- Tees 2.0
- Approaches 1.5
- Rough 60
- Total Irrigated Acreage? 100+/-

Grass types:

- Greens 328 bermudagrass
- Fairways 419 bermudagrass
- Tees 419 bermudagrass
- Approaches 419 bermudagrass
- Rough 419 bermudagrass/bahia

Soil types:

- Greens sand – push-up
- Fairways sand- clay
- Tees sand – push-up
- Approaches sand- clay
- Rough sand- clay

Pump Station:

Type of pumps _Turbin Goulds (Model 12RJHO)
Rating of pumps (capacity, HP, GPM) 125 HP, 1200 gal/min
Age of pumps 10 years
Evapotranspiration weather Data:

Weather Station:

- On site (location) Yes ** installed prior to study by researchers.**
- Can data be accessed from site? yes, CR 10 measurement and control system (Cambell Scientific, Inc., Logan, UT).
- What type of data can be evaluated? ET_o parameters (solar radiation, wind speed, humidity, and temperature) precipitation.
- What sensors are on system? **solar radiation** (LI-200SZ Pyranometer Sensor. Licor Inc. Lincoln, NE) **wind speed** (WAS425 Ultrasonic Wind Sensor. Vaisala, Inc. Sunnyvale, CA.) **temp & relative Humidity** (HMP 45C temp and rel. humidity probe. Campbell Scientific, Inc. Logan, Utah) **precipitation** (TE525 Tipping Bucket. Campbell Scientific, Inc. Logan, Utah).

General Questions:
What is your current irrigation schedule? Varies with weather
Do you have flow meters on your system? Yes at main pump
How old is your course? 28 Years old
Has course been renovated? No
Do you overseed? Yes If so when? Oct/ Nov
Has Irrigation system ever been audited (Efficiency, DU)? No

APPENDIX E
Soil Amendments for Golf Course Use

The basics of soil quality relates to early and ongoing attempts at classifying soil suitability or land capability (Carter, 2002). In a series of discussion papers published in 1991, soil scientists identified soil pH, salinity, sodicity, soil organic matter, soil erosion and compaction as key parameters that can be used to measure soil quality (Carter, 2002). Ketcheson (1980) noted that intensive agriculture had resulted in a deterioration of soil organic levels and soil physical properties. Scientists noted that conversion of forest soils into agricultural soils was accompanied by a loss in both soil organic matter and structural stability and, under some conditions, an increase in soil compaction (Martel and MacKenzie, 1980). Use of continuous grass, however, tended to reverse the decline in soil quality. Soil organic matter is often related to soil quality because of its relation to soil structure, water retention, nutrient availability, and other functions.

In many cases it is not possible to make a perfect match between the soil and its intended use. Under these circumstances, the soil may be amended to better meet its intended quality. Research and experience has shown that to a certain extent soils resources can be manipulated, engineered and/or managed for specific end results. This is often the case with Florida soils, which contain on the average in excess of 95% sand (Sartain, 1995).

In general soil amendments can be classified as either organic – derived from plant or animal products, or inorganic – mineral based ("earthy") products. In general, organic amendments are relatively inexpensive, improve soil structure through increased aggregation, promote microbial growth that is important for nutrient availability, and have moderate nutrient holding capacities. Types of organic amendments include peat, humus/humates, muck soils, composts, sludges, manure based products, and organic biostimulants (e.g. sea kelp). Inorganic amendments may include a wide variety of materials that may have a wide range in cost. They typically have a minor influence on soil structure but may still improve aeration. Inorganic amendments have little influence on microbial growth and have a low to high nutrient holding capacities. Types of inorganic amendments include porous ceramics/calcined clays, diatomaceous earths, zeolites or clinoptilolite zeolites, expanded shale, and starch-based hydrogels.

Organic matter is commonly mixed with sand in golf green construction. According to United States Golf Association (USGA) guidelines a typical golf green mixture will contain between 80 to 90% sand and 10 and 20% peat by volume. Peat is added to sand to reduce the soil's bulk density and improve aeration. The sand + peat mix allows the media to retain more plant-available water and allows for a gradual release of available water. Irrigation management is still critical, since the surface can become excessively wet if over-watered.

It is suggested that the peat have a minimum organic matter content (as determined by loss on ignition) of 85 percent ASTM D 2974-87 Method D). The specific purpose of adding this organic matter is to increase the water and nutrient retention properties of the rootzone. A desirable USGA greens mix has a saturated hydraulic conductivity of 12 to

24 inches per hour and a porosity of 25 to 55 percent (at 40-cm tension). USGA guidelines do not specify the exact type of organic matter that should be used in a greens mix, but the greens mix should fit within a set of criteria for sand size, hydraulic conductivity, porosity, bulk density, and silt and clay content. General sand size specifications are listed in Table E-1. In the high temperature and rainfall environment of Florida this organic matter oxidizes very rapidly so that a relatively small percentage of the organic matter remains after the first year. The rootzone typically will not become void of organic matter due to the organic matter contribution from plant roots.

Table E-1. The sand used in a USGA root zone particle size distribution of the final root zone mixture (adapted from 1993 USGA specifications).

PARTICLE SIZE DISTRIBUTION OF USGA ROOT ZONE MIX

Constituent	Particle Diameter	Recommendation (by weight)
Fine gravel	2.0 - 3.4 mm	Not more than 10% of the total particles in this range, including a maximum of 3% fine gravel (preferably none)
Very coarse sand	1.0 -2.0 mm	
Coarse sand	0.5 - 1.0 mm	Minimum of 60% of the particles must fall in this range
Medium sand	0.25 - 0.50 mm	
Fine sand	0.15 - 0.25 mm	Not more than 20% of the particles may fall within this range
Very fine sand	0.05 - 0.15 mm	Not more than 5%
Silt	0.002 - 0.05 mm	Not more than 5%
Clay	less than 0.002 mm	Not more than 3%

While soil organic matter has been shown to contribute physical and biological properties to soil that results in improved soil quality, inorganic amendments may also contribute some of the same properties to soil. Inorganic amendments have been suggested for use in sandy soils to increase plant available water and to improve CEC, while maintaining high drainage and aeration properties. Several organic polymers and inorganic materials have been tested over the last 30 years, with a few proven to absorb water and nutrients that can be released for plant use.

Several soil amendments, including calcined clay, diatomite, expanded shale, perlite, pumice, sintered fly ash, slag, and vermiculate have been suggested for use in sand-based turf growing media (Carrow, 1993). Many of these alternative amendments impart desirable physical and chemical properties to the soil, but they are high in cost and their duration in the soil is sometimes limited. In addition, some amendments perform better than organic matter (e.g. peat) in a mixture with sand with some characteristics, but fail miserably compared to organic matter in other comparisons.

Increases in CEC can increase the soil's capability to retain cationic nutrients, such as NH_4^+, K^+, Ca^{2+}, and Mg^{2+}. Organic soils can have CEC values of 50 to 100 cmol kg^{-1}, while values for sands can be as low as 3 to 5 cmol kg^{-1} (Tisdale et al., 1985). The CEC of golf putting greens is usually quite low (0 – 6 cmol kg^{-1}) due to the textural properties of the materials used in their construction (USGA Green Section staff, 1993).

Incorporation of amendments in sandy soils also affects the structure of the soil. The structure in turn is influenced by the degree of compaction, management practices, texture, and organic matter-clay interactions (Balogh and Watson, 1992). Turfgrass roots, microbial activity, and wetting and drying of the soil enhance the development of soil structure. Beard (1973) stated that improved soil structure created favorable conditions, including good water retention, for turfgrass growth and development on unmodified soils having a low intensity of traffic. Unfortunately, most of the turf areas on golf courses are under intense traffic that is often detrimental to soil structure.

Most modern golf courses construct or renovate their golf greens using rootzone materials that either comply or nearly comply with current (1993) USGA specifications. At this time, USGA specifications only apply to the greens, which comprise approximately 3% of the turf area on a golf course. This provides greens with somewhat similar performance characteristics (moisture and nutrient retention) across the nation, and in many foreign countries. Due to the overwhelming attention given to this localized feature of the golf course, most of the research focus on soil amendments to sands has been focused on construction materials suitable for greens. Because the total space occupied by greens is relatively small compared to the surface area of the entire golf course, the added expense of amending the soil for the green is viewed as cost effective. Since the most concentrated wear from direct human contact on the golf course is on the golf green, it also typically sees the most intensive management. When necessary, golf course superintendents (agronomic specialists) will sacrifice quality in other areas of the golf course while maintaining good turf cover on the greens.

Soil Amendment Products

Inorganic Products

Porous Ceramics/Calcined Clays: Porous ceramics are made by heating clays, usually montmorillinite or illite, to 1,500 to 1,800 degrees F and screened for size distribution. They are hard and resistant to breakdown, but can be abrasive. Similar to ceramic clays, calcined clays are made from the same clay materials, but heated at lower temperatures for a shorter duration, reducing production cost. These clay products retain water and increase air porosity, moisture retention, and permeability. Some may have a capacity to retain K^+ and NH_4^+. Commercially available examples include Profile, Permapore, and Isolite.

Diatomaceous earth: Diatomaceous earth amendments are made from hydrated silica material (diatom shells produced by certain algae). They may or may not be heat-treated. They are stable, lightweight granules that can increase air porosity, but have low nutrient retention. They retain water but much may be unavailable. Early work suggested that the particles might be brittle and subject to breakdown with cultivation practices. Commercially available examples include PSA and Axis. The Axis product is a calcined product, making it more resistant to breakdown.

Zeolite/Clinoptilolite Zeolite: Zeolites are mostly made of SiO_2, but also contain elements that may or may not have nutritive value to plants. They have a porous crystalline structure with low bulk density. Zeolites comprise a group of about 50 mineral types, but few are used at present in turfgrass culture. Clinoptilolite is the most abundant and commonly used zeolite mineral and is particular interest to the golf industry due to its high CEC and affinity for nutrients. They increase water retention less than the porous ceramics but have a significantly higher CEC. Examples of commercially available products include: Clinolite, EcoSand, Ecolite, Zeoponix, ZeoPro and ZeoSand.

Polymers (a.k.a., polyacrylamide gels): These gels are typically applied as dry crystals that expand upon hydration. Their component ingredients vary by product. Polymer types include (a) starch-polyacrylonitrile graft copolymers, (b) vinyl alcohol-acid copolymers, and (c) acrylamide-sodium acrylate copolymers. There is some debate related to their extent of water release to plants as well as their degradation rate. Several may also release nutrients, depending upon their make-up. Examples of commercially available products include: Agrosoke, Aqua-Lox, Sta-wet, Stocksorb, Superasorb C, Terrasorb, Terracottem, Water-Lock. Previous studies have shown that these polymers can increase pore space in soil, increase soil permeability and water infiltration and drainage, decrease water runoff, result in soil drying faster after rain or irrigation, and result in warmer soil temperature in the springtime (Sartain, 1995). One disadvantage sometimes noted was excessively soft playing surfaces when the polymers were applied at high rates. There are confirmed reports that swelling of polymers in sand greens after irrigation resulted in puddling and heaving of the green surface. In general many of the polymers have not been thoroughly studied with turfgrasses.

Phosphogypsum: This is a by-product of phosphate mining. The Florida Institute of Phosphate Research (2003) stated that there are currently about 1 billion tons of phosphogypsum stacked in 24 stacks in Florida and about 30 million new tons are generated each year. In 1989, stacking of phosphogypsum became a legal necessity when the U.S. Environmental Protection Agency (EPA) banned the use of phosphogypsum. In 1992, this rule was modified to allow the use of phosphogypsum with an average radium-226 concentration of less than 10 picocuries per gram (pCi g^{-1}) for agricultural application as a soil amendment. Central Florida phosphogypsum ranges from 20-35 pCi g^{-1}. Phosphogypsum formed during the chemical processing of north Florida rock, however, has only 5 to 10 pCi g^{-1} and is sold to peanut farmers who use it to provide the calcium needed to form strong peanut shells. No mention if it can be sold to turf managers.

Colloidal phosphate: This is a soft, untreated clay material with the main ingredients as phosphorus (≈22% P_2O_5) and calcium (≈19%). In addition, it may supply a wide variety of minor elements.

Pumice: The origin of pumice is volcanic rock. The porous material has been shown to increase water retention, air porosity, and permeability of sand in laboratory studies. No work could be located on use of pumice as a turf soil amendment.

Vermiculite: Vermiculite is a very porous material with a high moisture-holding capacity and low bulk density. It has a tendency to compress under pressure, so it may prove to be unsuitable in a rootzone receiving traffic.

Perlite: Perlite is a very light, porous material commonly used for greenhouse and nursery media and a stabilizing substrate for hydroponics. It is resistant to weathering but may be brittle and subject to breakage with compaction and cultivation.

Organic Products (Table E-2)

Sphagnum moss peat: Most of these peats originate in Canada, but some suppliers are also located in Minnesota, Michigan, Maine and Washington. This type of peat is a young peat with high organic matter content (>95%). They are very fibrous so they have a high water holding capacity and a low density (more needed on a v/v basis). It also tends to have a low pH and high C:N ratio. Sphagnum has been used the longest as an organic amendment.

Reed sedge peat: The major suppliers of this type of peat are found in North Dakota and Minnesota. This type of peat is older than moss peat so they are more stable. The organic matter content ranges from 85 to 92%. It tends to have a fine texture, making it easier than some organic products to mix with sand. Generally characterized by a low C:N ratio, and a pH level that varies from 5.5 to 7.0

Peat humus: These are very decomposed form of organic mater and they generally fall below 85% organic matter content (as recommended by USGA). It is a fine texture product that is easily mixed with sand. These peats are characterized by low C:N ratios and are most frequently used for topdressing.

High organic (muck) soils: These soils are well distributed in the regions of the USA, with some deposits found in Florida. The organic matter content of this product ranges from 20 to 60%. A silt loam or similar soil is typically a significant component. It is generally not considered a desirable component in greens mixes due to the soil component characteristics do not meet USGA specifications.

Composts: These products vary in quality, especially texture. The organic sources most common are products such as rice hulls, finely ground bark, or sawdust. They may break down very quickly depending upon their organic source and stage of maturity. They may also include biosolids (sludge) as part of their feedstock. While historically composts have been derived from plant and vegetable products, more recently, some compost are being derived from animal manures, human waste, and animal parts (see below).

Compost type is often due to regional availability of feedstocks. They are more likely to be the best alternative soil amendment for large areas (e.g. golf course fairways) due to their cost-to-benefit ratio. Yard waste compost use is discouraged by USGA due to variability. Biosolid compost are rich in nutrients, especially nitrogen and phosphorus. Composts may also suppress diseases such as *Pythium* root rot, brown patch (*Rhizoctonia solani*) and dollar spot (*Sclerotinia homoeocarpa*).

Kelp and manure products: These products are generally not used as much for their organic matter source as for their nutritive value. They may or may not be a part of a composted product. If they are not part of a composted product, then they are usually added in smaller quantities than the other organic products. Their benefits are usually short term.

Humic substances: Humic substances or humates, may be partitioned into functional groups such as humic acid, fulvic acid, and humin. Iron humate contains both humic and fulvic acid constituents and iron. Many of the humate have low solubility with a fraction that may be insoluble, therefore best results have been obtained when it is incorporated into a sandy or porous media instead of being surface applied.

Table E-2. Characteristics of selected organic matter amendments (adapted from Hummel, 2000).

Amendment	OM %	Fiber %	Water retained	Bulk Density	pH
Moss peat	>95	47	52	0.13	4.0
Reed sedge peat	85-92	21	60	0.21	6.2
Peat humus	80-90	2	44	0.29	5.5
Biosolid compost	60-75	--	40	0.35	vary
Rice hulls	79	53	66	0.23	4.9

Review of Research Related to Amendments

Inorganic Amendments

Due to the overlap among amendments evaluated in the studies, the results reported are generally based on individual report rather than categorized by the amendment.

Bigelow et al. (2001) evaluated the effects of peat moss and several inorganic amendments on bentgrass establishment and growth. Amendments had a significant effect on establishment and turf quality in the following order: peat moss>Ecolite= Profile>Greenschoice>unamended sand. The amendments were mixed at 10% by volume. Low water retention in sand was sited as a reason for reduced establishment without an amendment. Their study suggested that Profile or Ecolite plus peat moss may provide the best of nutrient and moisture retention.

Early work with calcined clays indicated that a significant portion of the water is held at high tensions and may be unavailable for plant use (Hansen, 1962; Smalley et al., 1962; Letey et al., 1966; Morgan et al., 1966; and Ralston et al., 1973). More recent research discussed in other sections of this review indicates that the porous ceramic products may provide beneficial water relations, although their greatest strength may be in exchange capacity.

Waltz and McCarty (2000) compared creeping bentgrass establishment on sand, and sand plus peat or porous ceramic or diatomaceous earth (15% v/v of each amendment). They reported the quickest establishment in sand + peat (3 months sooner then other treatments) due to increased water retention at the soil surface improving early seed germination. After three months all treatments except the sand only treatment had cover and acceptable color. A delayed establishment and unacceptable color was observed with sand only treatments due to low fertility. The sand + diatomaceous earth plots sustained a period of drought better than the other plots. The researchers reported that the greatest strengths of the inorganic amendments are their resistance to degradation and breakdown.

Robinson and Neylan (2001) evaluated three sand sources and various sand-and-amendment combinations for infiltration rate, capillary porosity, and noncapillary porosity in relation to minimum USGA criteria for green construction. Incorporated into the sand were sterilized fowl manure (2.5% v/v), Canadian sphagnum peat moss (10 %), composted pine bark (10%), clinoptilolite zeolite (5%) or porous ceramic (10%). The amendments were incorporated through the entire profile and seeded to bentgrass (*Agrostis stolonifera*). None of the amendments had a significant effect on emergence, but did outperform the unamended sands. The unamended control and porous ceramic and zeolite treatments had increased soil strength with depth, whereas the organic amendments had consistent soil strength with depth. Peat moss, pine bark, and porous ceramic treatments provided a significant increase in capillary porosity, therefore resulting in the best improvement in moisture retention. No amendment provided a substantial increase in nutrients except for increased potassium retention for the zeolite treatments. Turf quality was generally similar for the amendment treatments.

Bowman (1999) summarized a 5-year study to determine the response of turf to the various mixes in golf greens, as well as the soil physical and chemical properties. The amendments tested were Irish sphagnum peat, Profile, Geenschoice, Isolite, and Ecolite. The results indicated that inorganic amendments improved the soil moisture holding capacity, but much less so than did the peat. Moisture retention curves indicated that a considerable portion of the amendment-held water is unavailable to roots. None of the amendments reduced nitrate leaching, but Ecolite and Profile were very efficient at reducing ammonium leaching (note: ammonium leaching is not a significant leaching issue in warm moist soils of Florida due to the rapid conversion to nitrate-nitrogen).

Murphy's (1999) soil amendment research indicated that inorganic amendments ZeoPro and Profile did not produce a performance advantage over organic amendments. His data indicated these amendments had lower turf quality than peat or compost amendment.

Li et al. (2000) evaluated porous ceramic, calcined diatomaceous earth, and polymer coated clay added to sand at 10%. Data collected included saturated hydraulic conductivity, water retention, water release curves, bulk density, and total porosity at construction and 1 and 2 years after establishment. The porous ceramic treatment had on average a 7.5% greater CEC than the control plots. The diatomaceous earth increased water retention by 20% and porous ceramic by 13%, compared to the control. The porous ceramic actually increased both the saturated hydraulic conductivity and the amount of available water in the sand-peat media. The saturated hydraulic conductivity of plots receiving all inorganic amendments was reduced by 75%.

Miller (1996) reported that a porous ceramic soil amendment could be utilized to backfill core aerification holes to reduce surface temperatures and localized dry spots. Research found that porous ceramic amendment increased tissue concentration of K, but no changes in Ca, Mg, or P concentrations were noted. In another reported study, Miller (2000) evaluated Axis, Ecolite, EcoSand, EcosandX, Greenschoice, Isolite, Native fine-sand soil, Profile, PSA, medium sand, medium sand + peat, and ZeoPro following a single filling of aerification holes in a medium sand media growing Tifdwarf bermudagrass. Data indicated that ZeoPro and Profile had the highest quality turf. Axis, Greenschoice, Isolite, PSA, medium sand, and medium sand + peat treatments were poorest in quality. Axis and Isolite-amended sand had the best water relations with 0.4 to 1.4 days longer to drought stress.

McCoy and Stehouwer (1998) compared porous ceramics to diatomaceous earth products and found that diatomaceous earth materials contained a larger proportion of internal porosity than the porous ceramics tested. The diatomaceous earth products also released water from the internal pore space at slightly less negative pressure heads than porous ceramics. Yet, all the products released water from the internal pore space at relatively low soil water suction. They further reported that the porous ceramics contained had selectivity for K on exchange sites. To summarize their findings, they indicated that diatomaceous earth amendments are better suited to addressing root zone water retention issues whereas porous ceramic is better suited to addressing nutrient retention concerns.

Richardson and Karcher (2001) also conducted an evaluation of inorganic amendments and their influence on recover of bentgrass following aerification. In their study, they evaluated the zeolites: Clinolite, Ecosand, ZeoSand, Zeoponix, ZeoPro; porous ceramic Profile; and calcined clay: Red Plus and Red Plus 25 DR. Their data indicated that compared to sand alone, none of the inorganic amendments enhanced the recovery of creeping bentgrass following aerification despite the fact that all the amendments had a higher CEC than sand. Their focus was primarily on properties related to particle size and cation exchange.

Comer (1999) evaluated moisture and nutrient retention of several inorganic amendments including some of the gel materials. Products evaluated included ZeoPro, TerraCottem, PAM, and Agrosoke, each mixed with sand. ZeoPro provided the greatest turf growth and N, P, K uptake, even after two years. Best water use efficiency was measured with zeolite-amended treatments. The ZeoPro increased performance of fertilizers. The hydrogels actually lowered turf's water use efficiency.

Some early work concentrated on the rate of application of gels is crucial to obtain proper water infiltration and nutrient uptake by the plant. Wallace and Wallace (1986) determined that a mixture of two polymers (PAM and polysaccharide incorporated at a rate of 0.0005% of the soils weight, would produce a major improvement in water infiltration rate. Rates as low as 0.00025% could still cause some effect. It was determined that if the rate were increased to 5%, yields would only be equivalent to the control. Therefore, it was concluded in their study that incorporation of PAM into the soil should be at a rate that exceeds 0.0005%, while remaining less than 1% of the dry weight of soil. In practice, economics relates that rates be on the order of only 0.0005% to 0.001%, dry weight basis.

It has been reported that PAM (gels) degrade in the soil at a rate of about 10% per year (Azzam et al., 1983; Barvenik, 1994) due to mechanical degradation, chemical and biological hydrolysis, sunlight, salt, and temperature effects. Seybold (1994) indicated that acrylamide residual from PAM is a neurotoxin to humans, which raises some question to its safety in the environment.

Pathan et al. (2001) studied fly ash amendment, which is comprised primarily of fine sand and silt-sized particles, when incorporated to a depth of 12-15 cm (0 to 20% on a weight basis) had significant effects on soil water holding capacity, hydraulic conductivity, plant nutrition, and turf growth during establishment. Plant available water increased progressively with increasing rates of fly ash, whereas hydraulic conductivity decreased.

Phosphogypsum applied at the rate of 2 Mg ha^{-1} increased the water infiltration rate on a Cecil and Wedowee soil by two-fold (Miller, 1987). Soil loss was reduced by 50%. Smith et al. (1989) incorporated Phosphogypsum and peat to a depth of 3.5 feet in a citrus soil. At one location citrus tree growth was unaffected after eighteen months. At another location, growth on the phosphogypsum soil was inferior to the growth on the peat-amended soil.

G.C. Horn (1966) reported results of a 6-year study on various soil amendments. He found that colloidal phosphate applied at the rate of 5% imparted better soil properties than did the 10% rate. The 10% rate of colloidal phosphate resulted in reductions in water infiltration rate. Application of 20% by volume of expanded vermiculate was better than 10 or 5%. The expanded vermiculate did not retain its expanded form when added to the soil. He summarized his studies by indicating the combined soil amendment of 20% vermiculate + 5% colloidal phosphate + 10% calcined clay and 10% peat produced the best turfgrass growth and imparted the most desirable physical and chemical properties to a putting green soil.

Vermiculite was reported to improve turfgrass yield and quality when compared to unamended sand or sandy loam soil (Smalley et al., 1962; Horn, 1970). Vermiculite has been reported to decrease permeability (Smalley et al., 1962; Paul et al., 1970), increase available water (Hagan and Stockton, 1952; Horn, 1970) and increase CEC (Horn, 1970). One study noted a sharp decrease in permeability in vermiculite amended plots after the second year and suggested it was due to compression of the particles (Smalley et al., 1962).

Studies with perlite added to sand are contradictory. In studies reported by Paul et al. (1970), perlite decreased permeability on a medium sand. Moore (1985) reported that 10% perlite added to a medium sand increased total porosity by 10% to 15% and moisture retention by 5%. In 1985, Crawley and Zabcik reported Perlite additions of 20% were required to give an increase in moisture retention and in total porosity. Earlier studies by Hagan and Stockton (1952) reported no increase in available water with perlite additions.

Clinoptilolite zeolites have received a lot of attention as an amendment due to their high CEC values. Mumpton and Fishman (1977) reported their exchange capacity to be about 230 cmol kg^{-1}. At least one company is now reporting their zeolite product to have CEC values greater than 300 cmol kg^{-1} (personal communications). In addition to increasing nutrient retention, several studies (Ferguson et al., 1986; Ferguson and Pepper, 1987; Huang, 1992) have indicated that clinoptilolite will increase moisture retention and improve turfgrass quality when compared to sand alone.

Review of Research Related to Compost as a Soil Amendment

Composting is a popular means of turning waste into a useful soil amendment. Composts have several beneficial effects on soil properties such as plant available nitrogen (N), pH, and organic matter content (Bugbee and Elliot, 1999; Roe et al., 1997; He et al., 1992). Since yard trash can no longer be put in class A landfills in many states, large quantities of material have been diverted to composting facilities. The composting facility of Palm Beach County, FL, produced approximately 200,000 tons of yard waste (wood chips, grass clippings, and leaves from homeowners and landscaping firms) in 2000 (Oshins and Block, 2000). Composting provides a means of reducing the amount of material entering landfills while producing a useful end product. Research has indicated the usefulness of various composts as soil amendments (Duggan, 1973; McSorley and Gallaher, 1996; Kostewitcz, 1993). Compost has also been used successfully for turfgrass sod production (Cisar and Snyder, 1992). If available locally so that shipping cost do not make the compost product cost prohibitive, it may provide the best alternative to peat or inorganic amendments for a influencing soil water retention and nutrient availability over large turf areas.

Guertal (2002) reported that a composted biosolid as the organic matter source for greens mix was a suitable alternative to reed-sedge peat. The biosolid contributed phosphorus to the system, whereas the reed-sedge peat required supplemental phosphorus fertilization for optimum turf growth. The biosolid amendment and sand mix required dolomitic lime to raise the soil pH and to supply needed calcium and magnesium. Infiltration rates were faster in the greens built with biosolids compared to those built with peat, but still within the range suggested by USGA. Guertal felt that the faster infiltration resulted in lower color and quality ratings due to dryer conditions.

Compost Characterization and its Influence on Soil Chemical Properties

Typically, the carbon to nitrogen (C/N) ratio decreases during the composting process until it becomes stable in the range of 14:1 to 20:1(Brady and Weil, 1999). For composted biosolids, this ratio can vary substantially depending on the percentage of woody materials added during the composting process. Dissanayake and Hoy (1999) determined a C/N ratio of 7:1 for composted biosolids (no additional materials) used in a soil amendment study, while Bugbee (1999) and Shiralipour and Chrowstowski (1996) determined a ratio of 26:1 and 10:1 for co-composted hardwood chips and biosolids, respectively. Analysis of the chemical composition of several composts has shown that composted biosolids have a substantially greater N content than composts from other feedstocks (Dissanayake and Hoy, 1999). The increased N levels result in the lower C/N ratio desirable for crop production.

Compost contains macro and micronutrients necessary for plant growth in varying amounts depending on the feedstock source used (Sims and Kline, 1991). Compost applied as an amendment can increase soil concentrations of nutrients. Jackson (1997) found that compost application increased extractable zinc (Zn), copper (Cu), manganese (Mn), and iron (Fe) in the soil 3 and 6 months after application. Epstein et al. (1976) found increased levels of calcium (Ca) and magnesium (Mg) after treatment application in plots amended with sludge compost. Increasing soil concentrations of nutrients can affect plant uptake. Roe et al. (1997) found that compost applied to a sandy field soil increased concentrations of P, K, Ca, and Mg in leaf tissue. Jokela et al. (1990) found elevated levels of N and P in slash pine (*Pinus elliottii* Engelm.) grown in soils amended with municipal garbage composted with sewage sludge.

The feedstock used to produce the compost can have a significant effect on the final pH, thus affecting the rate of pH change in the soil. Roe et al. (1997) determined pH values ranging from 5.9 to 7.7 for several composts. Compost amendments can increase the pH of the soil. Tester and Parr (1983) found an increase in soil pH of about 2.5 units with the addition of sewage sludge-woodchip compost. This is a result of alkaline pH and abundance of $CaCO_3$ in compost (Shiralipour and Chrowstowski, 1996).

Compost amendments do not always increase the pH of the soil and effects can vary with compost source and rates. Jackson (1997) found that the addition of composted municipal solid waste with biosolids decreased the pH of the soil over the control initially, while composted yardwaste had the opposite effect. However, after 6 months compost addition of any source did not significantly affect soil pH. Avnimelech et al. (1994) found the addition of some compost to be as effective as or superior to gypsum applications for reclaiming alkaline soils.

Compost applications have been shown to reduce salinity of soils (Avnimelech et al., 1994) by replacing the sodium with calcium. However, compost applications can increase the salinity of soils. Epstein et al. (1976) found that salinity of the soil increased with increasing sludge compost application rates. However, due to leaching over time, salinity levels tend to decrease to normal levels in the soil.

Compost Effects on Soil Physical Properties

Many types of compost contain mixed feedstocks often from plant materials. This addition of organic matter can have an effect on soil properties including, aggregate stability, decreased bulk density, and increased pore space and water retention (Brady and Weil, 1999; Jackson, 1997; Shiralipour and Chrowstowski et al., 1996; Khaleel et al., 1981). Giusquiani et al. (1995) found that the addition of urban waste compost increased soil porosity and decreased bulk density when applied to a calcareous soil.

One of the primary causes of poor turfgrass cover on roadsides is the droughty nature of the road shoulder. Good drainage is required to protect the roadbed. During periods of high rainfall roadside turf can thrive, but drought conditions can take a toll on turfgrass quality and density. Water holding capacity of soils may be increased with the addition of compost. Epstein et al. (1976) found higher soil moisture content and retention in test plots treated with dry sludge compost than the control throughout most of the measuring period. Shiralipour and Chrowstowski et al. (1996) applied co-composted biosolids and yard waste at a rate of 134 Mg ha^{-1}. Water holding capacity (weight basis) increased 15 percent in sandy loam, 14 percent in loam, and 5 percent in clay loam. This was attributed to the increase in soil organic matter provided by the compost. Giusquiani et al. (1995) found that compost addition linearly increased water retention of the soil and increased plant available water correspondingly. This shows that compost additions may have a positive effect in areas susceptible to drought stress. However, plant available water may not be increased. The addition of compost can decrease bulk density, which can negate the effects of the increased available water on a volume basis (Khaleel et al., 1981).

Compost Effects on Plant Growth

Compost as a soil amendment can have substantial effects on seed germination, plant growth, and yield. Ozores-Hampton et al. (1999) found that a high salt concentration in co-composted yard trimmings and biosolids delayed tomato germination by 14 and 21 days. There were no differences from the control 30 days after seeding which was attributed to leaching of soluble salts.

Since the nutrient content of composts varies with feedstock composition, application rates should be adjusted when used as an N source. Pure composted biosolids can contain about 2.5 to 3.5 percent N (Garling and Boehm, 2001). However, some compost sources require an additional source of N to avoid immobilized N from a poor C/N ratio. Sims and Kline (1991) found that dry matter production of wheat (*Triticum aestivum* L.) decreased with increasing co-composted sewage sludge applications due to immobilization of N as a result of the high C/N ratio of the compost. Effects on soybean (*Glycine max* L.) growth where N is not a limiting factor were either equal to or greater than the control. Additional sources of N can be obtained from either an inorganic source, organic source, or can be blended with a feedstock having a high N content (Stevens and Kostewitcz, 1992; Kostewitcz, 1993; Stevens and Kostewicz, 1994).

Garling and Boehm (2001) found that compost applied to a mixed sward of creeping bentgrass [*Agrostis stolonifera* var. *palustris* (Huds.) Farw.] and annual bluegrass (*Poa annua* L.) improved color, increased growth, and increased foliar N. Composted biosolids and biosolids co-composted with yard waste increased foliar N by 50% and 30%, respectively over a 3-yr period when compared to the control. However, results were not always positive and can vary depending on rates, compost maturity, and available N. Cisar and Snyder (1992) found that St. Augustine (*Stenotaphrum secundatum (*Walt.) Kuntze.) and bahiagrass (*Paspalum notatum* Flugge.) grown in solid waste compost had discolored leaves and poor growth after 6 weeks. However, at 5 months, sod produced in fertilized compost over plastic had higher quality, offered better tear resistance, and exhibited enhanced rooting when compared to non-fertilized sod grown in soil.

Maturity of compost amendments can have a substantial effect on plant responses. Chanyasak et al. (1983) found that yields of komatsuna (*Brassica rapa* var *Pervidis*) were reduced substantially by immature compost treatments regardless of rate. It was also determined that well-matured composts gave greater yields than the control at 10 dry tons ha^{-1} but gave diminished yields at 20 dry Mg ha^{-1}. Compost has been shown to have positive effects on plant yield regardless of application method. McSorley and Gallaher (1996) found increased yield of maize (*Zea mays* L.) with applications of yard waste compost applied as mulch or incorporated into the soil.

Some compost can contain high levels of heavy metals that can limit their use in agricultural applications. Research has shown that elevated levels of some heavy metals can produce increased levels in plant tissues (Sims and Kline, 1991). However, a maximum concentration in plant tissues (plateau effect) can exist for several elements, regardless of available concentrations in the soil (Barbarick et al., 1995).

Composts Influence on Soil Microbial Activity

Dissanayake and Hoy (1999) found that soil amendment with composted biosolids reduced root-rot symptom severity caused by *Pythium arrhenomanes* in sugarcane (interspecific-hybrids of *Saccharum*) in a steam-treated soil infested with the causal pathogen. The highest microbial activity was recorded for composted biosolids when compared to several other feedstock sources (Dissanayake and Hoy, 1999). High levels of microbial activity can result in a general suppression of soilborne pathogens (Brady and Weil, 1999). These results suggest that soil amendments with organic materials may provide an effective biological disease control option for soilborne plant diseases. In addition, microbial populations in the soil are responsible for the breakdown of plant tissues, converting organically held nutrients into plant available forms (Brady and Weil, 1999). By adding composted biosolids with high microbial activity, an increase in plant available nutrients can be expected.

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APPENDIX F
Alternative Turfgrass for Salt-Affected Sites*

Seashore paspalum (*Paspalum vaginatum* Swartz) is a warm-season grass that is native to tropical and sub-tropical regions world-wide. Seashore paspalum grows naturally in coastal environments and is often found in brackish marsh water or in close proximity to ocean waters. It is currently the only southern turfgrass with greater salt tolerance than bermudagrass that has shown potential to be used in high maintenance situations such as those found on golf courses. It also grows in areas that receive extended periods of heavy rains and low light intensity. Its best growth occurs in response to warm temperatures and long daylengths.

Seashore paspalum was introduced into the United States from around the world through maritime travel. It was reputedly used as bedding in the hulls of slave ships. As the ships came into southern US ports, bedding would be discarded on the shore, leaving the grass to re-grow and establish on the banks in these coastal towns. It has since spread along coastal areas of the southeastern US, thriving in the salt-affected waters and environments of these areas.

Seashore paspalum does not produce viable seed and therefore must be planted as sod or sprigs. The fine-textured types are similar in appearance to hybrid bermudagrass (*Cynodon* spp.). They produce a dense, dark green turf. Although the species has been in existence for hundreds of years, selection of cultivars for commercial, residential, and sports turf use has been limited to the mid and late 1990s. The largest collection of seashore paspalum can be found at the University of Georgia's turfgrass breeding program in Griffin, GA, which has gathered and tested more than 300 ecotypes of this species.

Seashore paspalum produces a high quality turfgrass with relatively low fertility inputs. While it has initially been marketed for golf course and athletic field use, it has good potential for use in the home lawn market as well. Although you may see it touted as being extremely drought tolerant, it still requires water to remain green, just like any other turfgrass. It does have characteristics that make it tolerant to a wide range of stresses, but for best growth and performance, it should be grown under optimal conditions. Some of the advantages for use of seashore paspalum include:

- Excellent tolerance to saline or reclaimed water
- Excellent wear tolerance
- Good tolerance to reduced water input, but does require water to remain green
- Relatively low fertility inputs needed to produce a dense, dark green lawn
- Few insect and disease problems in most environments
- Tolerates a wide pH range
- Can grow well with potable (drinking) water as well as poor quality water
- Produces a dense root system, which is important in giving turfgrass good tolerance to most stresses

Some of the disadvantages include:

- Poor shade tolerance.
- Mowing requirements. This grass performs best when mowed at one to two inches. Mowing frequency also becomes more important at the lower mowing heights, as missed mowings will result in scalping of the grass.
- Weed control. Seashore paspalum is sensitive to many common herbicides and may be injured or killed by their use. In addition, most herbicides currently on the market are not labeled for use on this species yet, although the chemical companies will be expanding those labels to comply with increased use of seashore paspalum.
- Seashore paspalum tends to become thatchy, particularly when over-fertilized and over-irrigated.
- Recent data suggest seashore paspalum may be susceptible to several common nematodes.

The species *Paspalum vaginatum* is quite large and much diversity may be found within the species. For example, seashore paspalum types may be fine-textured, with small, narrow leaf blades, or they may be coarse-textured types that grow in a less dense, more open style. Generally, these coarser types are preferred for roadside utility or soil stabilization uses, while the finer-textured types are better suited for landscape, golf course, or athletic use. Limited research has been conducted on seashore paspalum, therefore, not all information is available at this time to answer all questions on best management of this grass in Florida.

Salam is a proprietary cultivar grown by Southern Turf Nurseries. It was released in the 1990s and is suited for athletic, golf course, and landscape use. It has many qualities similar to Sea Isle 1. Sea Isle 1 is the cultivar with the most university testing. This cultivar was released by the University of Georgia in 1999. It is a fine-leaved, dense-growing selection from Argentina, intended for use in commercial or residential landscapes or athletic use in fairways or sports fields. It produces a dark green, dense grass with excellent salinity tolerance and good tolerance to drought and wear. It performs well with relatively low fertility inputs. Seaway is another proprietary cultivar produced in Florida by Environmental Turf Solutions.

Seashore paspalum must be established vegetatively by sod or sprigs. Sprigging rates should range from 5-10 bushels per 1000 square feet. Plugs should be spaced 12 inches on center. The best time for establishment is during periods of most active growth, when temperatures exceed 70°F. When you first plant seashore paspalum, you generally won't see any shoot growth for the first 10-14 days. This is typical of seashore paspalum--it initially concentrates on root establishment and then, once it has a root system capable of supporting it, it will divert growth to the shoot system. This is when it will start to spread and fill in rapidly.

Frequently during establishment is important. Newly sprigged areas should be irrigated several times a day to keep the soil most. Avoid allowing the soil surface to dry out for the first seven to ten days. After the sprigs are rooted and runners (stolons and rhizomes) start to form, irrigation frequency can be decreased. Newly laid sod should be irrigated at least once a day for brief periods for the first 10 days and every other day for another seven to ten days. At this time the grass should have an established root system and can withstand irrigation twice weekly.

While establishing a seashore paspalum lawn, small amounts of fertilizer should be applied on a regular basis to hasten growth and ground cover. "Spoon-feeding" ¼ to ½ lb. of nitrogen per 1000 square feet in two applications during a three to four week period will stimulate growth. To encourage root development, phosphorous should be applied during establishment at rates equal to or greater than the nitrogen. Potassium needs of seashore paspalum are also greater during establishment. An application of a 1:2:3 fertilizer ratio of $N:P_2O_5:K_2O$ made each week for two or three weeks will provide a good fertility program for establishing seashore paspalum. If sodding seashore paspalum, ground cover will be immediate, but at least two weeks will be needed to insure that the root system is functional and capable of supporting the shoot system. If sprigging, coverage will take longer and establishment fertility requirements will need to be in place until both root and shoot systems have grown in.

Once established, the fertility regime should be reduced. In north Florida, it is estimated that two to three pounds of nitrogen per 1000 square feet per year will produce a good quality seashore paspalum lawn. It is best to apply fertilizer in small increments (at least two to three applications) from late March or early April through August. In south Florida, additional nitrogen (up to one pound) will be required to keep a nice lawn. Phosphorous application should be made depending upon results of soil tests. As some Florida soils contain ample amounts of phosphorous, little or none may be required. Apply equal amounts of potassium to nitrogen for best performance of seashore paspalum. A 1:0:1 fertilizer blend or something similar would be a good choice.

Seashore paspalum may be mowed with a rotary mower. Strict attention must be paid to mowing frequency, particularly in the summer. If seashore paspalum is left unmowed for more than a week, it will typically be scalped when mowed, which will provide opportunity for fungal and insect problems.

Due to the tolerance of seashore paspalum to periods of drought, irrigation is recommended on an as-needed basis. Signs of water needs include rolling of leaf blades, wilting, and foot imprints that remain on the turf after walking on it. At these signs of water deficit, apply ¾ inch of irrigation to the entire lawn. This will supply water to a depth of approximately nine to twelve inches in most Florida soils and should provide adequate water. Do not apply smaller volumes of water more frequently, as this will not encourage root growth. To avoid over watering when rainfall is adequate, reduce the frequency of irrigation. Over watering not only wastes water but may result in weakened root systems, nutrient leaching through the soil, and poor stress tolerance. How frequently the turf is irrigated will vary depending on time of year, your soil type, how much shade you have, etc. Because seashore paspalum is very tolerant of poor water quality, it can be irrigated with reclaimed water or water subjected to saltwater intrusion. It is important to realize, however, that even this grass can develop salt toxicity problems with repeated use of saline water over extended periods, particularly in areas receiving little rainfall. Where rainfall is ample, this will flush out accumulated salts in the soil and minimize salt toxicities.

Thatch may occur due to excessive nitrogen application, over-watering, or poor mowing practices. Vertical mowing is the most efficient remedy for excessive (longer than an inch) thatch. Vertical mowing uses vertical knife-like blades to thin out the thatch by slicing into it. While this process can alleviate build-up by removing thatch, it also removes portions of the grass and will cause temporary damage to the turf. For seashore paspalum, vertical blades should be spaced two to three inches apart for successful verticutting. It is important to perform this procedure only during times of active grass growth, and only on healthy, non-stressed grass (i.e., no drought, shade, insect, or disease problems).

Seashore paspalum does not have good shade tolerance, particularly when the shade is due to trees or vegetative canopies rather than to buildings. It can tolerate a few hours of shade daily, but would not be a good choice for a heavily-treed area.

Current herbicides available are generally not labeled for seashore paspalum, which means that it is not legal to use them on this species. Furthermore, many of the herbicides commonly used on lawn grasses will injure seashore paspalum and should not be used. Pre-emergence herbicides for homeowner use that do not injure seashore paspalum include pendimethalin (Pre-M and other trade names) and oryzalin (Surflan). Post-emergence herbicides that are safe on seashore paspalum are three-way mixtures of 2,4-D + MCPP + dicamba (Trimec® Southern, Weed-B-Gone®, etc.), halosulfuron (Manage®), and dicamba (Vanquish®).

Seashore paspalum has a few problems with insects, but chemical requirements for their control are minor. It is subject to occasional problems from mole crickets, sod webworms, spittlebugs, white grubs, billbugs, cutworms, and fall army worms. It generally has no problems with chinch bugs.

Organisms which may cause problems include fusarium blight, which may be found under hot, humid conditions, or when the grass is under drought stress. When infected, the entire turfgrass plant will change color from green to reddish brown to dark brown. Helminthosporium disease may also occur under conditions of high humidity or soil compaction. This disease is seen as small purple leaf spots with brown centers and light tan halos. There are also reports of take-all root rot in some locations in Florida.

*This review adapted from CIR 1244 by L.E. Trenholm and J.B. Unruh, UF-IFAS University of Florida.

Post-review note: confidential studies conducted by a golf course architectural firm (personal communication) indicated that seashore paspalum has had some miserable failures when irrigated with half-strength to full-strength seawater. Their studies suggest that significant data needs to be generated relating to how often a seashore paspalum turf profile needs to be flushed with fresh water for it to be successful in the market.