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Agricultural Water Management 80 (2006) 117–131
Agricultural water management
www.elsevier.com/locate/agwat

Can we maintain turf to customers' satisfaction with less water?

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Available online 15 August 2005

Abstract

Science-based, holistic, site-specific water conservation practices can reduce water use on turfgrass sites without adversely affecting turfgrass performance. However, when water use is decreased below a certain threshold, performance declines. Water conservation measures that reduce turfgrass performance essentially decrease its economic, environmental, recreational, and aesthetic values, which can in turn adversely impact many 'stakeholders', including the local economy and those affected by increased wind erosion, water erosion, or fire hazard. On larger turfgrass sites, considerable costs are associated with some water conservation strategies, especially when the quality of an alternative irrigation water source is poor or redesign of the landscape and/or irrigation system is involved.

Keywords: Turfgrass; Drought resistance; Water conservation; Best management practices for water conservation; Water management

1. The question

The question ''Can we maintain turf to customers' satisfaction with less water?'' suggests several points:

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0378-3774/$ – see front matter
doi:10.1016/j.agwat.2005.07.008

(a) That less water can be used on turf sites in many situations.
(b) That turf performance or quality could potentially be affected in a manner that would reduce its value to the customer.
(c) There are 'customers' who derive benefits from turfgrass.
(d) The issue of water conservation as a 'benefit' should be addressed in the context of other changes (environmental, economic, recreational, etc.) that may be 'costs' to customers.

In the midst of a water crisis, the general public, politicians, and water regulatory agencies may focus only on water savings that can be achieved by implementing immediate water saving measures without regard to potential short or long term consequences to all that may be affected. However, if water conservation measures are severe enough to compromise turf recreational use, economic impact, environmental/functional benefits, or aesthetics, then more than the perceived direct 'customer' may be adversely affected (Beard and Green, 1994; Gibeault, 2002; Cathy, 2003). The focus of this paper is to address the points posed by the question in the title.

2. Sound water conservation strategies can result in less water used on turf sites

In recent papers (Balogh and Watson, 1992; Ervin and Koski, 1998; Richie et al., 2002; Bastug and Buyuktas, 2003), the relationships between turfgrass evapotranspiration (ETc) and turf quality were explored along with the discussion of past research as reviewed by Kneebone et al. (1992) and Kenna and Horst (1993). Several conclusions can be reached based on the various studies relating ETc versus turf performance:

(1) In general, the landscape coefficients (K_L), for cool-season grasses (0.70–0.95) are higher than for warm-season turfgrasses (0.65–0.85) when the irrigation regime is at 3–7+ days between events, which would allow moisture stress within the surface zone. At these K_L values, the turf could maintain acceptable quality and growth, but as the K_L value was decreased below these general ranges using a similar irrigation schedule, turf performance rapidly declined (Meyer and Gibeault, 1987; Carrow, 1995).
(2) Irrigation scheduling can influence the K_L value versus turf performance. When a grass was irrigated more heavily (K_L 0.75–1.00 for tall fescue, *Festuca arundinacea* Shreb., 7 day schedule), the irrigation frequency could be extended; but with a 2–3 day schedule, a K_L of 0.50 maintained good quality (Richie et al., 2002). The concept of deep, infrequent irrigation scheduling is limited by the surface drying versus turf performance relationship, especially in arid regions. In arid regions, where most water addition is by irrigation, it is important to determine the deepest and least frequent irrigation schedule that will allow maximum water conservation without an unacceptable decline in turf quality resulting from too severe drying at the surface (Brede, 2000). Extending the irrigation interval too long will result in more water application to maintain the same turf quality level compared to a less frequent irrigation using less water. In a semi-arid or humid climate, deep rooting is important to take advantage of natural precipitation events. However, in an arid climate, rooting to a

depth that allows a reasonable interval between irrigation events without excessive surface drying is all that is needed and not the deepest rooted grass.

(3) Carrow (1995) reported turfgrass ETc was 40–60% less in a humid environment compared to the same cultivar grown in an arid environment, but similar K_L values were reported for both. ETo under the humid climate was less, accounting for the differences in observed ETc. Additionally, irrigation intervals in arid or semi-arid climates were normally within the range of 3–7 days, but Carrow (1996) reported irrigation frequencies of 5–20 days due to lower ETc, allowing more opportunity to capture natural precipitation rather than to irrigate.
(4) If a daily irrigation regime was followed, K_L for cool-season grasses is reported to be 0.88–1.09 (Aronson et al., 1987; Bastug and Buyuktas, 2003). Thus, allowing no drought stress on the turfgrass can result in high ETc. Dormant turf would be expected have only evaporation losses.
(5) Within the broad categories of cool and warm-season grasses, species differences are apparent.
(6) Within a species, there can be 20–60% range in ETc (Kjelgren et al., 2000).

Thus, controlled research studies confirm that water conservation can be achieved to a point before turfgrass quality starts to decline; thereafter, decreasing water results in reduced turf quality. The resulting reduction in turf quality or cover implies a potential for reduction in recreational use, environmental/functional capabilities, and economic use/value of the site, which in turn may adversely affect the direct customer, owners, local economy, and local environment (Beard and Green, 1994; Cathy, 2003). The real issue then becomes how to maximize water conservation on turfgrass areas while maintaining economic viability.

Be science-based: Water conservation measures are increasingly becoming incorporated into regulatory policy. However, it is essential that policy arising out of the political process be based on science and not political decision devoid of sound science. When incorporating science-based concepts into a water conservation program, it is important that it is true science and not pseudo-science where opinion is cloaked in scientific language. A science-based approach stimulates entrepreneurship to develop improved technology to enhance future water use-efficiency.

Holistic in terms of water conservation options: There is no ‘silver-bullet’ or single factor to achieve water conservation, rather a combination of water conservation strategies is needed to achieve high water-use efficiency in the whole system. The system includes soil, plant/landscape, atmosphere, turf manager, irrigation system, irrigation source, cultural practices, and any other aspect that may influence water-use.

Holistic in terms of consideration of the effects of water conservation measures on all stakeholders as a central component of all water conservation plans: Water conservation programs should include consideration of the effects on the economy, environment, jobs, and site use. The customer or user/manager/owner of a turf site is not the only stakeholder potentially affected by water conservation measures, but others include: the supply side (water authorities, suppliers); demand side (homeowner, turf manager, turf industry, etc.); and others affected by environmental and economic water conservation measures (society in general, local economy, health aspects, etc.).

3. Assessing the benefits and costs of water conservation programs

Vickers (2001) noted key steps to a successful water conservation program on a regional or state-wide basis as: (a) identify conservation goals; (b) develop a water-use profile and forecast; (c) evaluate planned facilities; (d) identify and evaluate conservation measures; (e) identify and assess conservation incentives; (f) analyze benefits and costs; (g) select conservation measures and incentives; (h) prepare and implement the conservation plan; (i) integrate conservation and supply plans, modify forecasts; and (j) monitor, evaluate, and revise program as needed. Specific best management practices (BMPs), however, that can be applied on a site-specific basis on a turfgrass facility are essential.

There are a number of components or strategies that should be integrated into an overall turfgrass BMPs water conservation plan, at the site-specific level (Gibeault and Cockerham, 1985; Carrow and Duncan, 2000a; Carrow et al., 2002a, 2002b). Within each broad strategy there are numerous options to consider when selecting the water conservation BMPs most appropriate for a particular site. However, except for the water audit approach, which deals only with the irrigation system, comprehensive, in-depth plans have not been available to turf managers (Irrigation Association, 2003a). Recently, Carrow et al. (2005), in conjunction with the Golf Course Superintendents Association of America, developed a comprehensive, water conservation BMPs document (template) for individual golf courses dealing with: the planning process; detailed options for different water conservation strategies; and information on benefit/cost assessment. Components of a site-specific water conservation program for golf courses are denoted in Table 1. Their BMP template model is currently being considered by two states in the USA as a model for state water conservation plans related to the golf course industry in contrast to rigid regulations, such as a set quantity of water or specific days and times of irrigation.

Assessment of benefits and costs of implementing water conservation measures on all stakeholders is essential to understand implications. The immediate owner or manager of a turf site will naturally assess the direct costs involved to implement water conservation measures. For the homeowner, rebate or water cost incentives may help offset the cost of landscape design and plant material changes, irrigation system alterations, and rain sensors (WRA, 2003). For large scale facilities, such as a golf course, the implementation costs may be considerable for changes in landscape design/plant material, irrigation system design and operation, using alternative irrigation water resources (i.e., wastewater piping costs, water/soil amendments), more frequent cultivation, training, and monitoring. Vickers (2001) and WRA (2003) provide much discussion on direct and indirect benefits of reducing water consumption, but limited discussion concerning potential for adverse effects to: (a) facility costs to implement changes required by a plan, and (b) some potential adverse environmental impacts if overuse of water on turf resulted in adverse in-stream flow, over-pumping of groundwater, reduced wetland effects, and one mention of fire hazard from native grasses. In contrast, Cathy (2003), Beard and Green (1994), and Gibeault (2002) note a broad array of benefits that turfgrass and the turf industry contribute to society (Table 2), and present a good discussion with case studies of adverse effects when water conservation measures are taken to the extreme, especially without consideration of other environmental impacts.

Table 1
Components of site-specific turfgrass water conservation programs (Carrow et al., 2005)

Initial planning and site assessment		
	Determine the purposes and scope of the site assessment	
	Site assessment and information collection	
		Determine current water-use profile
		Identify water conservation measures that have already been implemented including costs or implementation
		Irrigation/water audit
		Additional site assessment information—assessment for alternative irrigation water sources; golf course design modifications; irrigation system design changes; microclimate soil/atmospheric/plant conditions affecting irrigation system design/zoning/scheduling; drainage needs for leaching of salts
	Determine future water needs and identify an initial water conservation goal	
Identify, evaluate, and select water conservation strategies and options		
	Use of non-potable water sources for irrigation—alternative water sources; water harvesting/reuse	
	Efficient irrigation system design and devices for water conservation	
	Efficient irrigation system scheduling/operation	
	Selection of turfgrasses and other landscape plants	
	Golf course design for water conservation	
	Altering management practices to enhance water-use efficiency—soil amendments; cultivation; mowing; fertilization; etc.	
	Additional water conservation strategies—landscape areas other than the golf course; indoor water conservation measures in facility buildings; development of conservation and contingency plans; monitor and revise plans; and education	
Assess benefits and costs of water conservation measures on all stakeholders		
	Benefits	
		Direct and indirect to the owner/manager and site customers
		Direct and indirect to other stakeholders, including water savings but also other benefits—society, economic, environmental
	Costs	
		Facilities costs for past and planned implementation of water conservation strategies, irrigation system changes; water storage; pumping; new maintenance equipment; water/soil treatments; course design alterations; etc.
		Labor needs/costs
		Costs associated with changes in maintenance practices; different irrigation water sources (water treatment, soil treatment, storage, etc.)
		Costs that may impact the community if water conservation strategies are implemented (especially mandated ones), such as revenue loss, job loss, etc.

As noted earlier, careful application of water conservation strategies can reduce turfgrass water use, but after a point turfgrass performance and associated benefits will start to decline. Therefore, as a part of an overall water conservation plan, actual water conservation/savings must be balanced by potential effects that may arise (i.e., economic, functional/environmental, recreational use of the site, and aesthetics) not just on the specific site, but also on the local and broad economy and environment. Two examples illustrate the effect when removal of turf is carried too far:

Table 2
Benefits that turfgrass sites contribute (after Beard and Green, 1994; Cathy, 2003; Gibeault, 2002)

Functional/environmental
Prevent soil loss from wind erosion—a primary reason turf is used as a groundcover.
Reduce air borne dust
Protect for soil loss by water erosion—a primary reason turf is used as a groundcover.
Reduce sediment movement into water features—a primary reason turf is used as a groundcover.
Capture water from runoff for soil moisture recharge
Reduces climatic temperature
Reduces sod/soil surface temperatures on sports fields and turf areas used for enjoyment
Entrapment of organic chemical pollutants and enhances degradation
Contributes soil organic matter and enhance of soil quality
Fire protection by providing a green zone that is not combustible
Glare reduction
Air pollution control
Many turfgrass sites incorporate wetlands, surface water capture, trees, shrubs, natural areas
Recreational
Integral part of many sports—soccer, golf, football, etc.
Enhances participation in outdoor activities and sports
Contributes to a safe playing environment for athletes—cushioning and surface stability, smoothness
Contributes to spectator enjoyment
Low cost, living surface that can be self-repairing
Aesthetic
Beauty contributes to quality of life
Feeling of mental well-being—horticulture therapy
Community pride
Ornamental compliment to trees, shrubs, and flowers
Allows individuals to express themselves and influence their surroundings through individualized landscape
Economic
Direct revenues, taxes, jobs from sports events and golfing in the local economy
Enhancement of tourism—in some cases tourism is build around golfing
Parks, sports venues, golf courses, and landscape industry contribute jobs, money and taxes
Suppliers of turfgrass equipment, supplies, and services contribute jobs, money, and taxes in the economy
Enhanced home and properties values and, therefore, greater tax revenues
Contributes to purchase of non-turf items goods and services in the community—restaurants, dry cleaners, service stations, etc.

- When China removed all turf and many trees from Beijing public spaces during the Cultural Revolution in the 1960s, the result was major air pollution from dust storms, related health problems, and higher air temperatures within the city (Cathy, 2003). Revegetation with trees alone did not resolve the problem but required turfgrass cover. Recently, the People's Daily (2000) reported ''Beijing will take drastic moves to eliminate the sources of dust so as to reduce the amount of dust people breathe in everyday . . . worksites that refuse to plant trees shall be taken back . . . and shall be turned into lawns put under the management of gardening departments''.
- Mowed turfgrass can be an effective fire buffer and replacement near homes can result in fire hazard and higher homeowner insurance. 'Firewise' landscaping for the

wildland-urban interface suggests that zone 1 (9 m ring around home); and zone 2 be well-irrigated, low growing, and low flammability species; zone 3 to low-growing plants and well-spaced trees in this area, with low volume of vegetation for fuel (Firewise, 2004).

4. Site-specific turfgrass water conservation strategies

Several potential water conservation strategies with options can be used in BMPs for a turfgrass site (Table 1) (Carrow et al., 2005):

4.1. Use of non-potable water sources for irrigation-alternative water sources, water harvesting/reuse

An important strategy for water conservation is to use alternative non-potable water sources, such as runoff collected in ponds, effluent (wastewater), poor quality ground water, seawater or seawater/blends (Carrow and Duncan, 2000b). As recreational areas shift to poorer water quality, more salt-induced problems are anticipated that will require extra alternative irrigation water beyond the normal irrigation rate for salt leaching. Monitoring of soil moisture and salt levels at multiple depths will become more commonplace by mobile and/or installed moisture and salt sensors. The necessity of using grasses with higher salt tolerance will alter management not only because the grass is new, but because salt-induced problems must be managed (Carrow and Duncan, 1998).

The environmentally friendly term ‘water harvesting’ is not often used in relation to golf courses or other turf sites, yet it is a common practice (Florkowski and Landry, 2002). Many golf course irrigation lakes also serve as landscaping features and catch excess runoff, preventing the loss of substantial amounts of water from the site and preventing sediment into streams or rivers. Catchment features are usually part of an overall stormwater control and reuse plan mandated by governmental policies. A recent survey of Georgia golf courses indicated that as much as 67% of irrigation water came from such non-potable, runoff lakes (Florkowski and Landry, 2002). Water harvesting is usually thought of as treating watersheds to enhance runoff collected for future use (Thomas et al., 1997; Todd and Vittori, 1997; Waterfall, 1998). In the case of golf courses, the landscape is purposely contoured to collect the excess runoff from rainfall, while allowing good infiltration of water into the soil under normal conditions. Some golf courses with large adjacent housing developments are investigating the potential for collecting drainage and runoff from these areas, using their own facility to treat the non-potable water to standards acceptable for turf use, and irrigating the golf course with the water. This practice saves local government the expense of treating the water.

4.2. Selection of turfgrass species/cultivars and landscape plants for water conservation

Development and use of turfgrasses with superior drought resistance/low water use is a primary means of decreasing water needs on turfgrass sites (Kenna and Horst, 1993). *Cynodon* spp. are widely used in warm-season zones and most cultivars exhibit superior drought resistance; but superior drought resistance in many other commonly used species, especially cool-season grasses, is less evident, and will remain so until breeders focus on this as a priority. Some turfgrass breeders are now placing more emphasis on drought resistance, particularly the most important component which is drought avoidance via a greater genetic-based root tolerance to soil stresses that limit root development/maintenance and by shoot characteristics that contribute to an inherent low water use (Duncan and Carrow, 1999). Under more limited irrigation regimes, other stresses besides drought are enhanced and will require attention by breeders and turf managers, namely; high temperature tolerance for cool-season grasses, wear tolerance, salinity tolerance in the case where poor water quality is used, and pests that are favored by reduced growth rates. In addition to assessing and developing drought resistant cultivars among traditional species, non-traditional species bred for superior drought resistance and/or other stress resistance traits will become more commonplace (Brede, 2000; Duncan and Carrow, 2001; Loch et al., 2003).

4.3. Landscape design for water conservation

On homesites, 'Xeriscape' principles are often promoted as water conserving. Interestingly, Vickers (2001) noted that 'beyond Xeriscape' is a move to an all natural landscape. Behind this movement appears to be groups that promote only native plants as appropriate for the natural landscape and use water conservation as the environmental reason, but without a balance of what other adverse human and ecological environmental effects may result, fire hazard, dust hazard, etc., or what about the non-native garden and food crop plants? However, Welch (2003) states that as the original "Xeriscape concept matured and spread, the principle of limited turf use was increasingly scrutinized by horticulturists and turf experts. Today's Xeriscape movement incorporates a more holistic approach to reducing turf irrigation . . . through the principles of Xeriscape, turf irrigation can be reduced while the many benefits of turfgrass can still be derived . . . many turfgrasses are drought-tolerant and can survive extreme drought conditions". These contrasting views illustrate that all 'Xeriscape landscape design' concepts are not equal, which one is used for water conservation purposes has a dramatic effect on the potential for environmental and human hazards. Landscape design focus must not be one-dimensional by focusing on minimizing the turf area, but must apply all of the Xeriscape principles (Cathy, 2003) of planning and design, soil improvement, appropriate plant selection, practical turf areas, efficient irrigation design and scheduling (including the human factor), mulching, and appropriate maintenance. Additionally, any adverse environmental effects of proposed landscaping changes should be considered, namely, wind erosion/dust, water erosion/sedimentation of water features, fire hazard, etc.

On larger, more complex sites, such as golf courses, prior to construction or renovation, many decisions can be made that will foster water conservation or greatly limit it, such as grass choices, irrigation system design/piping and zoning, contouring, and area of well-irrigated turf on the site. Numerous design looks can be achieved with mulch materials; use of alternative, drought-resistant grasses that are left unmowed in non-landing areas; incorporation of native low growing ground covers, shrubs, and trees that require minimal irrigation and possess unique looks; using higher mowing heights on parts of the fairway or adjacent roughs that may receive little or limited irrigation; utilization of features, such as rock, sand bunkers, and non-irrigated mounds. Golfers seem to accept brown turf when it is mowed high or left unmowed, but may not accept as much discoloration or lower plant density on the closely mowed high-use areas. Since golf courses must compete for local and, in some locations, national and international customers, the visual aspects on the close-mowed playing area influences play and the associated tourist industry, i.e., Asian golfers may not come to the Australian Gold Coast if it does not have competitive quality to alternative golf locations. In other instances with less play demand and competition for customers, dormant, semi-dormant, or lower quality turf may be very acceptable on large expanses of many golf courses. Irrigation level on the high use areas also influences the degree of traffic that a golf course or recreational field can tolerate. Contouring is another important design factor, especially avoiding excessive slopes, mounds, and berms that are difficult to irrigate even with an excellent irrigation system. Also, contouring should foster water harvesting.

4.4. Efficient irrigation system design

Irrigation system design and irrigation scheduling (see Section 4.5) are essential for water conservation on irrigated sites. One critical design challenge is to deal with spatial variability, which can be very complex on turf sites with many microclimates resulting from the diverse terrain, soil, and plants (Table 3). Spatial variability must be determined, and adjustments made through landscape design, irrigation system design, and site-specific irrigation scheduling. Even a home landscape can be much more variable than most agricultural fields and golf course sites are very complex in terms of variability. Specific types of variability (Table 3) must be individually identified and quantified. This is an area

Table 3
Spatial variability that influences irrigation scheduling and water-use efficiency

Above-ground—variability across the landscape due to:
Climate variation
Solar radiation (N/S exposure, shade)
Wind speed
Humidity
Air temperatures
Grass/plant type and characteristics—canopy structure, mowing height, growth rate, etc.
Soil variability—both horizontally and vertically due to:
Soil texture
OM content
Soil depth
Slope
Soil water holding capacity
Infiltration
Salinity
pH, fertility, etc.
Irrigation system—good design, zoning, and hardware reduces landscape and soil variability but when the system is not properly designed or operated it becomes another source of variability.

that the author believes will receive more attention in the future so that more precise design of irrigation systems and their operation can be achieved, while also maximizing sensor placement.

In recent years, as water conservation has become a looming reality, there has been a marked increase in entrepreneurial activity to improve irrigation design and scheduling aspects through better hardware, develop software to communicate between controllers and sensors, and improved irrigation concepts. The author's current research is focused on identification and characterization of variability of landscapes and soils; categorizing similar microclimates; and using sensor technology to integrate real-time information by microclimate type into irrigation scheduling by combinations of atmospheric and soil-based means. Within agriculture, the equivalent of incorporating these issues would be the precision agriculture or integrated approach to irrigation management described by Buss (1996).

Irrigation system design is an important component of water conservation on turfgrass sites in order: (a) to apply water in an efficient manner so as to limit water losses by runoff, leaching past root systems, or unnecessary evaporation from water standing on the surface; (b) to allow adequate irrigation of areas as needed within the time constraints imposed by night time irrigation, salt leaching, water control authorities, etc.; and (c) to make site-specific or precision water applications accurately on individual, microclimate areas, according to their needs. In this latter aspect, control of water application on a site-specific basic will often include control of the water rate and depth of percolation for maintaining root viability; and on areas with poor water quality to insure salt movement downward, while preventing capillary rise back into the root zone. Many of the fundamentals of good irrigation design are known and have been applied to a certain extent, especially in more arid and semi-arid locations (Irrigation Association, 2003a, 2003b). However, for maximum water use-efficiency, full incorporation of these principles must be "the norm" for the next generation of irrigation systems and renovations of existing systems. Water must be applied on a precision basis in a BMPs water conservation plan—and this cannot be accomplished with a poorly designed irrigation system. Highly automated irrigation systems will initially cost more, but in the long term save water/money and allow true implementation of environmental stewardship principles by the turf facility.

4.5. Improved irrigation scheduling

Irrigated sites can be over-watered because people do not irrigate according to plant needs, including Xeriscapes. In Phoenix, Xeriscapes actually used 30% more water than conventional landscapes. This illustrates the critical point that it is people who over-irrigate (Vickers, 2001). Means must be developed to couple irrigation applications to true plant water needs. The best designed irrigation system will not efficiently apply water unless it is properly programmed. Irrigation scheduling is normally by experience of the turf manager using indicator spots or problem areas where drought symptoms are first observed to aid in deciding when to irrigate. Many golf courses and some other turf sites have an on-site weather station where estimated ETo data is available; but ETo data must be adjusted for each microclimate site, since grass, soil type, radiation, wind, and other environmental or management conditions will differ from the weather station site. For example, each microclimate adjustment is made by multiplying a landscape coefficient (K_L) by the ETo to obtain an estimated turf ET (ETc). Unfortunately, the K_L factor differs with grass, season, weather front, and microclimate soil/atmospheric conditions, while the ETo does not take into account the soil (current soil moisture level by depth) nor plant (depth of viable root system, current level of stress) conditions.

Irrigation scheduling of the future will involve real-time information from within an irrigation zone to provide more site-specific guidance (Sudduth et al., 1999). One approach will be soil sensors that are now capable of monitoring soil moisture in 50–100 mm zones at multiple depths down to 1 m in a real-time mode with remote transfer of the data for ease of use (Charlesworth, 2000; Moller et al., 1996). Precision application of irrigation for prevention of moisture stress and for salt control, requires precise information on current conditions by soil depth. A common question that arises with soil moisture sensors is whether a soil measurement represents the area due to spatial variability across a landscape and within the soil. Comments related to this question are:

- For any means of irrigation scheduling to be efficient, adjustments must be made for the microclimate site. Soil sensors offer the capability for being the most site-specific moisture monitoring approach within the vertical plane throughout the root zone. However, microclimate site assessment must be more stringent than is practiced in a current water audit (Irrigation Association, 2003a) and must be quantified so that: (a) zoning can be more specific; (b) sensors can be accurately placed; (c) similar microclimates can be classed together so that one representative site can be used as an indicator for other similar sites; and (d) so K_L values can be daily adjusted via soil sensor and atmospheric sensor (such as in shaded areas) data by adjustment of weather station ETo for actual microclimate water use.
- New sensors and software have greater capabilities than many now visualize when they think of a soil sensor. They offer real-time data, multiple depth moisture readings, translation of the information into useful formats with appropriate software, and the ability to electronically transfer data to remote sites. These attributes can be useful for documenting the need to irrigate a site and maintaining a history of soil moisture statue.
- Soil sensor placement must be done carefully to represent the diverse characteristics of the area. Their installation must follow the guidelines to make sure good soil-to-sensor contact exists and calibration must be accurate, but these issues can be addressed.
- As noted, soil sensors are only effective when they are used within a carefully zoned irrigation system that has a high uniformity of water application or a system with the ability to control water delivery to specific parts of a zone (Buss, 1996). Then, sufficient sensors must be placed to represent a microclimate zone, but one such zone may then represent several other similar ones.
- It is the difference in water content between readings that is important and not absolute moisture content information, because the difference is an actual measure of water used and it indicates where the water was extracted within the root zone. There is less spatial variability in the difference data than within an absolute value when comparing across several sensors.

Another emerging technology is the use of plant-based monitoring of plant stress in irrigation scheduling using precision agriculture concepts (Frazier et al., 1999). Currently, the most effort is in measuring light reflectance from the turf canopy within the 350–1100 nm wavelength region, which includes the visible/PAR (photosynthetically active radiation) region of 400–750 nm (Geuertal et al., 2000). Loss of color and/or leaf area can increase reflectance within certain wavelengths that may be used in models to estimate overall plant stress, irrigation need, or perhaps a nutrient stress. For example, Jiang and Carrow (2005) investigated turf quality and leaf firing responses versus narrow-band reflectance in the 400–1100 nm region under progressive drought stress for five turfgrass species and several cultivars within species. Models based on narrow-band reflectance data to predict drought stress differed with species and for cultivars within a species; and models exhibited coefficients of determination (R^2) of only 0.40–0.60 (Jiang and Carrow, 2005). Other approaches may become possible, such as using a wider wavelength range of 350–2500 nm where several ‘water bands’ occur, use of the infrared thermal region of 8000–14,000 nm, fluorescence reflectance, digital imaging data, and others. However, even with an accurate plant-based method, the question of how much water to apply is still a major problem.

4.6. Altering management practices to enhance water-use efficiency

Various management practices can substantially affect water-use efficiency, especially practices that maximize water infiltration and turfgrass root development and maintenance (Carrow, 1994). Cultural operations may alter the soil conditions to reduce water loss from runoff, leaching or excess evaporation and to improve soil water retention. Although a particular turfgrass may have the genetic potential to be drought resistant, without proper management, it may exhibit low water-use efficiency.

4.7. Education

Educational efforts will be needed for policy makers, water management authorities turfgrass managers, turf students, facility officials and members and crew members who are concerned with water conservation and management on turfgrass areas. The challenge for extension specialists and research scientists will be to produce in-depth information packages containing both scientific principles and specific practices for turf managers and consultants in the industry (Carrow et al., 2001). Turf mangers will be more likely to embrace new technology if they have ready access to good educational opportunities from well-trained consultants and specialists.

4.8. Water conservation and contingency plans

A water conservation plan conserves water on a continuous basis, whereas a contingency plan deals with water-conserving measures during severe water shortages. At the turfgrass facility level, it is essential that owners, members and officials assist in formulating these plans, understand their implications, and adopt the plans. Facility policies must include water conservation.

4.9. Other water conservation practices

In addition to the practices already outlined, other practices include: (a) monitoring a water conservation program to assess success by documenting water use (for example, by water meters) and relating it to turfgrass performance, (b) periodic site water audits can identify leaks, irrigation head malfunctions, design limitations, irrigation scheduling problems or other wasteful water use, and (c) indoor water conservation plans for any buildings on a facility (Vickers, 2001).

5. Challenges to water conservation

Considerable information exists about many aspects of turfgrass water conservation practices, which could be implemented rapidly to achieve water savings on most sites. Incorporating new developments in grasses, technology, concepts, and scientific knowledge would produce additional water savings over time. Many turfgrass managers already follow some water conservation practices at their sites, but full implementation is often hindered by certain challenges:

- Agronomic—the current turfgrass on a site may not be very well adapted or drought resistant.
- Educational—managing for water conservation requires a whole systems approach by the turf manager and it is a complex issue. Facility owners may not understand the complexities.
- Financial—high costs can be associated with implementing some water conservation measures.
- Institutional—government regulations can foster (water price structure) or hinder (regulations requiring irrigation to be done on a calendar schedule rather than plant need basis) adoption of conservation practices.
- Management—the facility owner/management must place priority on water conservation on an on-going basis in order for the turf manager to fully implement a conservation program.

6. Conclusions

In summary, water conservation will become increasingly necessary on many turf sites, regardless of the climatic zone. Considerable knowledge already exists about many practices within this complex soil-plant–water source–climate–man system that can be implemented rapidly to achieve a certain degree of water conservation or water-use efficiency without sacrifice of turf performance. In addition to the current state of science, turf managers will be presented with a host of new tools for better water management and ongoing changes in equipment, chemicals and practices. In depth, continuing education will become necessary as new technology and new grasses must be integrated into 'BMPs for water conservation' to be truly efficient, properly implemented, and carefully monitored; but this paradigm will require whole-hearted involvement by all owners/facility officials and the turf manager associated with a turfgrass facility.

References

Aronson, L.J., Gold, A.J., Hull, R.J., Cisar, J.L., 1987. Evapotranspiration of cool-season turfgrasses in the humid Northeast. Agron. J. 79, 901–905.

Balogh, J.C., Watson, J.R., 1992. Role and conservation of water resources. In: Balogh, J.C., Walker, J.W. (Eds.), Golf Course Management and Construction: Environmental Issues. Lewis Publishing/CRC Press, Boca Raton, FL, pp. 39–104.

Bastug, R., Buyuktas, D., 2003. The effects of different irrigation levels applied in golf courses on some quality characteristics of turfgrass. Irrig. Sci. 22, 87–93.

Beard, J.B., Green, R.L., 1994. The role of turfgrasses in environmental protection and their benefits to humans. J. Environ. Qual. 23, 452–460.

Brede, D., 2000. Turfgrass Maintenance Reduction Handbook. John Wiley & Sons, Hoeboken, NJ.

Buss, P., 1996. The Fourth Agriculture Revolution—the Australian Solution. In: Proceedings of the Irrigation Association of Australia Conference. Adelaide, South Australia, 14–16 May. IAA, Hornsby, NSW.

Carrow, R.N., 1994. A look at turfgrass water conservation. In: Snow, J.T. (Ed.), Wastewater Reuse for Golf Course Irrigation. Lewis Publishing/CRC Press, Boca Raton, FL, pp. 24–43.

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

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

Carrow, R.N., Duncan, R.R., 1998. Salt-affected Turfgrass Sites: Assessment and Management. John Wiley & Sons, Hoboken, NJ.

Carrow, R.N., Duncan, R.R., 2000a. Strategies for water conservation in turfgrass situations. In: Proceedings of the Irrigation Association of Australia Conference, 23–25 May 2000, Melbourne, Vic., pp. 543–548.

Carrow, R.N., Duncan, R.R., 2000b. Wastewater and seawater use for turfgrasses: potential problems and solutions. In: Proceedings of the Irrigation Association of Australia Conference, 23–25 May 2000, Melbourne, Vic, pp. 678–683.

Carrow, R.N., Broomhall, P., Duncan, R.R., Waltz, C., 2002a. Turfgrass water conservation I. Primary strategies. Golf Course Manag. 70 (5), 49–53.

Carrow, R., Broomhall, P., Duncan, R.R., Waltz, C., 2002b. Turfgrass water conservation II. Strategies and challenges. Golf Course Manag. 70 (6), 49–53.

Carrow, R.N., Duncan, R.R., Shearman, R.C., 2001. Providing relevant information to turfgrass managers: challenges and implications. Int. Turfgrass Soc. Res. J. 9, 53–60.

Carrow, R.N., Duncan, R.R., Waltz, C., 2005. Golf Course Water Conservation: Best Management Practices (BMPs). Workbook for Golf Course Superintendents Association of America Seminar. Lawrence, KS. Online at www.georgiaturf.com.

Cathy, H.M., 2003. Water right—conserving our water, preserving our environment. Int. Turf Producers Found., In: http://www.turfgrasssod.org/.

Charlesworth, P., 2000. Soil water monitoring. Irrigation Insights No. 1. CSIRO Land and Water, Canberra, ACT.

Duncan, R.R., Carrow, R.N., 1999. Turfgrass molecular genetic improvement for abiotic/edaphic stress resistance. Adv. Agron. 67, 233–305.

Duncan, R.R., Carrow, R.N., 2001. Seashore Paspalum: The Environmental Turfgrass.. John Wiley & Sons, Hoboken, NJ.

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

Firewise, 2004. Firewise landscaping. http://www.firewise.org/pubs

Florkowski, W., Landry, G., 2002. An economic profile of golf courses in Georgia: course and landscape maintenance. Research Report 681. College of Agriculture and Environmental Sciences, University of Georgia, Athens, GA.

Frazier, B.E., Walters, C.S., Perry, E.M., 1999. Role of remote sensing in site-specific management. In: Pierce, F.J., Sadler, E.J. (Eds.), The State of Site Specific Management for Agriculture. American Society of Agronomy, Madison, WI, pp. 149–160.

Geuertal, E., Shaw, J., Han, D., 2000. Multispectral radiometry: opportunities for detecting stress in turfgrass. Turfgrass Trends 9 (9), 1–3.

Gibeault, V.A., Cockerham, S.T. (Eds.), 1985. Turfgrass Water Conservation. Publication No. 21405. Cooperative Extension Service, University of California, Oakland, CA.

Gibeault, V.A., 2002. Turf protects the environment, benefits health. UCRTRAC Newsletter, Dec 2002. University of California, Riverside, CA.

Irrigation Association, 2003a. Turf and landscape irrigation best management practices. September on-line publication http://www.irrigation.org/

Irrigation Association, 2003b. Landscape irrigation scheduling and water management. September on-line publication http://www.irrigation.org/

Jiang, Y., Carrow, R.N., 2005. Assessment of narrow-band canopy spectral reflectance and turfgrass performance under drought stress. HortScience 40 (1), 242–245.

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

Kjelgren, R., Rupp, L., Kilgren, D., 2000. Water conservation in urban landscapes. HortScience 35, 1037–1040.

Kneebone, W.R., Kopec, D.M., Mancino, C.F., 1992. Water requirements and irrigation. In: Waddington, D.V., Carrow, R.N., Shearman, R.C. (Eds.), Turfgrass. Monograph No. 32. American Society of Agronomy, Madison, WI, pp. 441–472.

Loch, D.S., Barrett-Lennard, E., Truong, P., 2003. Role of salt tolerant plants for production, prevention of salinity, and amenity value. In: Proceedings of the Ninth National Conference on Productive Use of Saline Lands (PURSL). Rockhampton, Qld, Australia 29 September–2 October 2003.

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

Moller, P., Johnston, K., Cochrane, H., 1996. Irrigation management in turfgrass: a case study from Western Australia demonstrating the agronomic, economic, and environmental benefits. In: Proceedings of the Irrigation Association of Australia, 14–16 May 1996, Adelaide, SA, pp. 109–119.

People's Daily (Online), 2000. Bejing pledges to cut off sources of dust pollution by end of June. People's Daily, March 22, 2000. http://www.fpeng.peopledaily.com

Richie, W.E., Green, R.L., Klein, G.H., Hartin, J.S., 2002. Tall fescue performance influenced by irrigation scheduling, cultivar, and mowing height. Crop Sci. 42, 2011–2017.

Sudduth, K.A., Hummel, J.W., Birrell, S.J., 1999. Sensors for site-specific management. In: Pierce, F.J., Sadler, E.J. (Eds.), The State of Site Specific Management for Agriculture. Amererican Society of Agronomy, Madison, WI, pp. 183–210.

Thomas, J.R., Gomboso, J., Oliver, J.E., Ritchie, V.A., 1997. Wastewater re-use, stormwater management, and national water reform agenda. CSIRO Land and Water Research, Position Paper 1, Canberra, ACT.

Todd, W.P., Vittori, G., 1997. Texas Guide to Rainwater Harvesting. Center for Maximum Potential Building Systems, Austin, TX.

Vickers, A., 2001. Handbook of Water Use and Conservation. Waterplow Press, Amherst, MA.

Waterfall, P.H., 1998. Harvesting rainwater for landscaping use. Arizona Deptartment of Water Resources, Tucson, AZ.

Welch, D.F., 2003. Refining the concept of Xeriscape. In: Cathy, H.M. (Ed.), Water Right: Conserving Our Water/ Preserving Our Environment. International Turf Producers Foundation, Rolling Meadows, IL, pp. 39–41, http://www.TurfGrassSod.org.

WRA, 2003. Smart water: a comparative study of urban water use across the Southwest. Western Resource Advocates, Boulder, CO. http://www.westernresourceadvocates.org