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Considerations with water for turfgrass in arid environments

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1 Introduction

Golf courses in the western USA are almost entirely reliant on the irrigation system to meet turf water demand (B. Whitlark, personal observation). Precipitation for many golf courses is scant and when it does occur, only 50% of the rain may be useful to offset irrigation needs. Utilizing an underground irrigation system to meet the turf demands with sprinklers typically spaced 18–24 m apart in varying conditions is extremely challenging. Even the best irrigation systems operate with 20% error and that is in the absence of wind (Gross, 2015). Enter wind exceeding 8 km•hr^{-1} into the equation and that error increases substantially. In the absence of rain, irrigation error is increased simply because of normal and routine use of the irrigation system. Consequently, turf managers in the western USA have learned out of necessity to become excellent at maintaining irrigation systems to deliver water as efficiently as possible. In this chapter, we will discuss tried-and-true strategies that turf managers in the arid western USA use daily to deliver water efficiently to thereby maximize soil moisture consistency and optimize turf playability.

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2 Soil moisture

Golf course superintendents and turfgrass managers are tasked with producing and maintaining a playing surface that offers firm conditions and optimizes turf health (B. Whitlark, personal observation). A key component of that goal is to produce consistent soil moisture across playing surfaces. Managing water resources and inputs represents an important task for golf courses in arid environments.

2.1 Soil moisture uniformity is more important than distribution uniformity

Irrigation distribution uniformity (DU) has been the long-standing evaluative consideration for an irrigation system's efficiency, but the DU has a limited impact on soil moisture (i.e. soil water status in the rootzone) consistency across irrigated areas of the golf course (Zoldoske, 2003). Improving soil moisture consistency is the fundamental goal for golf courses that are looking to maximize water use efficiency and optimize playability in those turf surfaces. Focusing on soil moisture uniformity (MU) is much more impactful for golf course superintendents who are working to provide firm playing surface conditions and healthy turf in conjunction with efficient water use.

An irrigation system that delivers high DU (i.e. >80%) does not guarantee high MU across a golf course. There are many reasons for this, but at the top of the list are soil spatial variability, followed by wind, slope, sunlight exposure, shade, and rootzone compaction. Preliminary results from a field study in Texas, USA (Young et al., 2019), indicated high variability among soil spatial characteristics such as bulk density, volumetric water content, and infiltration rate. With such high variability, it becomes clear why there is so much soil moisture inconsistency across large areas of fairways and roughs. While an irrigation system operating at very high DU may deliver high MU when evaluated indoors and on a flat surface, the DU does not correlate well with MU when evaluated outdoors on actual golf courses.

What is one of the first things golf course superintendents do following installation of a new irrigation system? They change station percentages and adjust cycle and soak times to produce consistent soil moisture and thereby deliver a firm playing surface! These adjustments are made daily, especially in areas of the western USA where turf water demand is met almost entirely through irrigation (B. Whitlark, personal observation). Optimizing MU is a function of careful irrigation management and utilizing turfgrass cultural practices to improve the soil's ability to optimally 'accept' water. The next subsection will provide five irrigation management strategies that are delivering improved MU at golf courses in the southwest USA where water is limited,

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water quality is often poor, and water cost is generally higher than anywhere in the country. The five irrigation management strategies include deep watering, soil moisture monitoring, supplemental irrigation, use of wetting agents, and modification of soil and soil drainage. If these strategies are working well under such challenging irrigation conditions of the southwest USA, they will almost certainly prove beneficial wherever a golf course is located.

2.2 Methods to improve moisture uniformity

Before exploring the five identified soil moisture improvement strategies, it is first worth mentioning the obvious ‘low hanging fruit’ method to improve soil moisture consistency. There are many examples demonstrating how golf course superintendents, greenkeepers, course care managers, sports turf and pitch managers, and turfgrass maintenance practitioners are saving water and optimizing water use efficiency, and here are a few common ideas related to the irrigation system:

- Raising and leveling sprinklers;
- Edging around sprinklers;
- Cleaning organic and inorganic debris from water lines;
- Adjusting sprinkler arcs;
- Adjusting system operating pressure;
- Conducting proactive leak repair/prevention;
- Adjusting the irrigation schedule based on evaporative loss and precipitation;
- Replacing worn sprinkler nozzles;
- Maintaining the on-site weather station.

These are all basic and legitimate methods that need to be employed within all turf maintenance operations (Whitlark, 2012). Turf practitioners are encouraged to address these ‘low hanging fruit’ items and continue to manage and maintain the irrigation system proactively.

2.2.1 Deep watering

The ‘deep and infrequent’ irrigation strategy is a commonly accepted practice for maintaining high-quality turf (Whitlark, 2021). However, many golf course superintendents do not use this strategy outside of putting greens. The practice of ‘frequent and shallow’ irrigation limits gas exchange in the upper rootzone, increases compaction, decreases rooting depth, and compromises soil moisture variability (Murphy, 2002). Consider that even a new irrigation system can only be expected to deliver water at 80% efficiency, and that is with no wind present (B. Whitlark, personal observation). Over time, the error in the water delivery is additive, similar to accumulating compounding interest in a retirement bank account. Watering at a shallow depth and often or more frequently will not improve chronically wet or dry rootzones but only leads to chronically wet surface conditions (B. Whitlark, personal observation). Applying water deeply at routine intervals will improve soil moisture consistency and uniformity across the entire golf course. Deep watering will help overcome irrigation system inefficiencies and soil spatial variability by improving the soil moisture status in chronically dry areas, thus consequently reducing the need for spot watering (Fig. 1).

Brian O'Laughlin, golf course superintendent at Annandale Golf Course in California, USA, schedules irrigation for 'Tifsport' bermudagrass [*C. dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy] fairways at rootzone depths ranging from 13 to 38 mm nightly, depending on the time of year and evaporative demand. The hydraulic limitations of the irrigation pump system and pipe size limit irrigation to no more than about three fairways per night. In 2020, fairways typically were irrigated every sixth night. Surprisingly, recently irrigated fairways were not noticeably wetter than fairways irrigated several nights before. Examination of soil profiles revealed deep moisture and deep roots. Soil moisture was consistent across the fairways and roughs with very little evidence of overly wet or dry areas.

Annandale Golf Course is not alone in achieving success with deep watering, but every golf course could potentially employ a slightly different tactic. At Annandale Golf Course, full-circle sprinklers are programmed to run for at least 30 min and part-circle sprinklers run for 15 min, with individual run times adjusted for certain sprinklers based on site-specific conditions. For

Figure 1 Scheduled irrigation to apply water deep into the soil can improve root density and length. *Source:* Image provided by B. Whitlark.

example, sprinklers in low areas may only run 10–15 min, while sprinklers on south-facing slopes may run up to 2 h. Also, soak times typically are set at 15–20 min.

Golf courses with poorly drained soils may have to start with run times only 7–10 min with soak times 20–25 min to avoid runoff. Additionally, golf courses that have had success with deep watering all note that they started with a goal of applying only 6–12 mm water for one evening and gradually increase to higher water volumes. Golf course superintendents can gain confidence by experimenting with one hole (i.e. a par-3 fairway) and utilize deep watering over a 4- to 6-week period before expanding to the entire golf course.

As the day length and sun angles change through the year, the irrigation schedule must change as well. Turf that received full sunlight in the summer may be shaded in the spring and fall and the irrigation schedule must change accordingly to address distinctly different turf water requirements at different times of the year. Turf managers must adapt to these seasonal changes by extending irrigation scheduling intervals during periods of less evaporative demand and/or decreasing the depth of water applied during irrigation events.

The deep and infrequent watering strategy is one that has proven results and golf course superintendents report annual water use is either unchanged or slightly lower when compared to using a frequent and shallow watering schedule (B. Whitlark, personal observation). For example, O'Laughlin reported a savings of US$85 000 in water costs in 2020 using that deep and infrequent irrigation scheduling strategy despite a hot and dry year that would normally require more irrigation inputs to maintain the turf.

2.2.2 Soil moisture monitoring

A high percentage of golf courses use handheld soil moisture meters to help manage water on putting greens (Moeller, 2012). However, if the golf industry is going to significantly reduce water use and improve soil moisture consistency and uniformity across fairways and roughs, the adoption of in-ground moisture sensors is possibly the next option. There are a few early pioneers or adopters using in-ground soil moisture sensors to schedule irrigation in fairways and roughs. Tyler Truman, golf course superintendent at Sun City Palm Desert (Palm Desert, CA, USA), is one of those pioneers. Truman has been using the Toro TurfGuard (Toro Corp., Bloomington, MN, USA) sensors for the past 4 years and has installed four sensors in strategic areas across 16 ha of overseeded Tifway 419 bermudagrass fairways on their Santa Rosa Golf Course. Sensors were placed into representative 'dry,' 'moderately dry,' 'moderately wet,' and 'wet' areas determined by mapping the fairways using the Toro Precision Sense 6000 (Toro Corp., Bloomington, MN, USA) tool. The turf care team reviews the sensor data daily, in addition to field scouting and monitoring evapotranspiration

(ET) data to schedule irrigation. This strategy has yielded more consistent soil moisture conditions across fairways and roughs and has resulted in a 10–14% water savings which translates into an equivalent savings in electrical costs associated with operating the irrigation pumps.

Several United States Golf Association (USGA; Liberty Corner, NJ, USA) funded research studies have also demonstrated significant water savings when using in-ground soil moisture sensors to schedule irrigation compared to using ET-based schedule or a calendar-based schedule (Dyer et al., 2020; Saxena et al., 2020; Straw et al., 2020). A three-year study at the Rocky Ford Turfgrass Research Center (Manhattan, KS, USA) has shown significant water savings after 2 years of study. The total water applied when utilizing data from in-ground soil moisture sensors during the 2019 summer growing season on 'Meyer' zoysiagrass (*Zoysia japonica* L.) turf was 80% less than a calendar-based approach and 44% less than irrigating the zoysiagrass at 60% of reference ET (Dyer et al., 2020). The repeated study demonstrated similar results in the summer of 2020 with the sensor-based irrigation schedule delivering 84% water savings compared to a calendar-based approach and 72% savings compared to the 60% reference ET irrigation (Dyer et al., 2020). Specifically, irrigation totaled 330 mm for the traditional frequency-based water scheduling, 183 mm for the 60% of ET irrigation, and only 51 mm when irrigation was applied using soil moisture sensors. Of note, total precipitation for the duration of the 2020 study was 334 mm.

A field study at California State Polytechnic University (Pomona, CA, USA) has shown test plots on hybrid bermudagrass mowed at fairway height irrigated with the guidance of soil moisture sensor data resulted in less water applied versus plots irrigated based on ET. All sensor and ET data were collected from April 1 through 31 October in 2018 and again in 2019. All plots, regardless of irrigation water inputs, showed acceptable turf quality and turf cover (Saxena et al., 2020).

A collaborative study between the University of Minnesota (St. Paul, MN, USA), Texas A&M University (College Station, TX, USA), and the Toro Corp. evaluated irrigation water inputs as scheduled from in-ground soil moisture sensors compared to traditional (i.e. visual observation of the turf) and ET-based irrigation scheduling at 60% of reference ET. This study was conducted on a golf course, specifically on nine fairways (six par 4's and three par 5's) at Edina Country Club in Minneapolis, MN, on perennial ryegrass (*Lolium perenne* L.) turf. Soil moisture maps were produced using the Toro Precision Sense 6000. Low, medium, and high soil moisture class categories were established on each fairway and one soil sensor is placed in each moisture zone. In the soil moisture sensor treatments, irrigation was triggered when plant available water decreased by 50% in each moisture classification. The plant available water was determined by the difference in soil moisture content at field capacity (i.e. soil water content about 48 h after a rain or saturating irrigation event) and permanent wilting point, which was determined when wet wilt became visually apparent to the golf course superintendent. This field study had only 1 year of data collection in 2020, but results indicated 60% water savings in areas with soil moisture sensor treatments compared to areas irrigated using the deficit ET strategy and 45% savings when compared to irrigation applied based on traditional methods (observational). The mean irrigation applied per week was 6.98 mm for the ET-based treatments, 5.02 mm for the traditional irrigation methods, and only 2.76 mm per week for the soil moisture sensor-based treatments.

2.2.3 Supplemental irrigation

Hand watering, while necessary and marginally effective, does not facilitate optimum moisture uniformity and depth that can be achieved with low-precipitation portable sprinklers (B. Whitlark, personal observation). The Desert Mountain Club (Scottsdale, AZ, USA) uses low-precipitation sprinklers effectively on a variety of different turf species including perennial ryegrass, overseeded Tifway 419 bermudagrass, and creeping bentgrass (*Agrostis stolonifera* L.) fairways, despite a very efficiently operated irrigation system. A trailer is used to store and transport sets of portable sprinklers around the golf course for targeted irrigation as needed. Scott Bower, Director of Operations at The Martis Camp Club (Truckee, CA, USA), uses portable low-precipitation sprinklers daily during the short growing season (i.e. May/June through September). There is a total of 36 sets of portable sprinklers and two sets are placed adjacent to each fairway for easy deployment. The irrigation control network operates those portable sprinklers for a set amount of time ahead of play in the morning and also following fairway mowing. The portable sprinklers are often placed near cart paths and other strategic areas in the rough during play. The portable sprinklers typically run for 30 min at a time. While this may sound like a simplistic approach, the routine use of low-precipitation portable sprinklers at the Martis Camp Club has been a successful supplemental irrigation practice (Fig. 2).

2.2.4 Wetting agents

A wetting agent, the turf industry's commonly used term for a soil surfactant, is used to improve soil moisture consistency and uniformity, especially in sand-based rootzones (Fidanza et al., 2020; Zontek and Kostka, 2012). The USGA Green Section has published extensive resources on wetting agent use for golf course turf (https://www.usga.org/content/usga/home-page/course-care/digitalcollections/understanding-wetting-agents.html). Several studies have demonstrated that using wetting agents throughout the growing season

Figure 2 Example of low-precipitation portable sprinklers employed to address chronic dry areas by deeply wetting the soil. *Source:* Image provided by B. Whitlark.

can maintain turf quality while reducing water use (Fidanza et al., 2020). For example, a two-year study at the University of California (Riverside, CA, USA) evaluated the ability of mineral oil, fungicides, and wetting agents to improve turf quality and increase soil volumetric water content (Serena and Baird, 2021). The study revealed that 'all tested products could maintain acceptable quality for at least 12 weeks when irrigated at 55% reference ET replacement, better than the untreated control.' The best-performing treatments in this study were the mineral oil and a mixture of fungicides which demonstrated acceptable turf quality at only 34% and 33% ET replacement compared to the control which received 69% ET replacement (Serena and Baird, 2021). This research suggests that wetting agents, a fungicide combination, and mineral oil can improve rootzone moisture uniformity, increase rootzone moisture content, and produce acceptable turf quality under deficit irrigation (Serena and Baird, 2021). While the economics of applying these treatments may not be pragmatic for some golf facilities, this study demonstrates there is potential to reduce water inputs in conjunction with applying products according to the protocol outlined in this study.

2.2.5 Modify soil and improve drainage

There are many golf courses where soil physical limitations severely restrict water infiltration, resulting in poor soil moisture consistency and uniformity, poor turf surface playability, and compromised turf health (Whitlark, 2014). Soil infiltration refers to the ability of the soil to allow water to move into and through the soil profile. A proven strategy to improve rootzone conditions is sand topdressing. A USGA-funded field study demonstrated the value of an annual sand topdressing program to improve fairway soil conditions (Whitlark, 2014). In that study, all courses that had applied ≥7.6 cm topdressing sand over several years (i.e. 25 mm sand is equal to approximately 358.6–403.5 metric tons•ha^{-1}) observed a 2000% increase in infiltration rate (Whitlark, 2014). Also, plant available water increased by 254% from sand topdressing when compared to no soil modification (Whitlark, 2014). Furthermore, soil moisture consistency across golf course playing areas has improved for those golf courses that modified their poor soils through sand topdressing (Whitlark, 2014). Specifically, they observed less wet and dry areas and therefore more consistent playing surfaces, which they relate to as improved soil consistency (Whitlark, 2014). Of note, sand topdressing (Fig. 3) may not be advisable for fairways on every golf course, and it is strongly recommended to work with a physical soil testing laboratory before initiating a fairway sand topdressing program (B. Whitlark, personal observation).

Improving surface and subsurface drainage is another key strategy to improve soil moisture infiltration and uniformity. For example, a rootzone drainage network allows for increased site-specific watering on mounds and south-facing slopes without creating saturated conditions in low-lying areas (Whitlark, 2020). Several courses in southern Arizona have demonstrated the value of a subsurface drainage network in flat or low-lying areas (B. Whitlark, personal observation). The drainage allows golf course superintendents to apply enough water to leach salts from the system and supply adequate soil moisture to produce healthy turf on adjacent mounds and south-facing slopes without creating waterlogged and chronically wet conditions in areas where drainage has been installed.

Figure 3 Fairway sand topdressing can improve rootzone conditions for soil with limited water permeability. *Source:* Image provided by B. Whitlark.

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3 Case studies

3.1 Turfgrass conversion can result in significant water savings

Golf courses in the western USA face increasingly stringent demands to reduce irrigation water inputs. In addition to imposed water restrictions, water costs continue to increase, some have seen costs skyrocket by over 500% in the past few years. Many courses in California have addressed these challenges by converting from cool-season turfgrass to warm-season turfgrass such as bermudagrass, seashore paspalum, or zoysiagrass (John Marman, West Coast Turf; Scottsdale, AZ, USA; personal communication). The vast majority of those golf courses have converted tees, fairways, and roughs to hybrid bermudagrass. The following case studies illustrate examples from golf courses that have been successful in converting to bermudagrass.

3.1.1 Birnam Wood Golf Course

Birnam Wood Golf Course (Santa Barbara, CA, USA) historically maintained a mixed stand of cool-season turfgrasses, sometimes referred to as the 'California Turf Surprise' (B. Whitlark, personal observation). This turf composition produces acceptable playing conditions but never delivers a premier golf experience and the water demand is higher than it would be for warm-season turf. Historically, the golf course budgeted for about 23 hectare meter of water use annually (228 193 839 L) with a cost of nearly US$200 000.

The golf course's leadership recognized an opportunity to improve the consistency of playing conditions and reduce resource inputs, most notably irrigation water by converting the cool-season turf to warm-season bermudagrass. In 2015/2016, the golf course converted 21 ha to 'Santa Ana' bermudagrass in fairways and Tifway 419 bermudagrass in roughs. In addition, 4.9 ha of irrigated turf was removed and replaced with low water use landscaping, although the golf course irrigation system has yet to be modified to accommodate independent water delivery to the golf course turf and the landscape areas that have different water demands.

Post renovation, the golf course budget is about 16.6 hectare meter of water use annually, which meant a 25% reduction in annual water inputs. Of note, the cost of water has increased by over 500% in the past decade. With that increased cost, the 25% water reduction saves the facility over US$100 000 annually. The conversion to bermudagrass has also saved approximately US$100 000 per year in fertilizer, seed, and plant protection products. The cost of the project was about US$1.25 million, and within 7 years, the golf course has already achieved a 100% return on investment.

3.1.2 Menlo Country Club

Menlo Country Club (Menlo, CA, USA) converted the sixth fairway from perennial ryegrass to Santa Ana bermudagrass in 2018. Golf course superintendent Chris Eckstrom has documented significant water savings on this fairway. He noted that 25% water savings is very realistic and feels confident that 30% is achievable. The bermudagrass fairway is irrigated once every three nights during the summer months and generally at the same depth (i.e. same irrigation runtime) as the perennial ryegrass fairways, which are irrigated nightly. For example, while the perennial ryegrass receives 30 min of runtime over a three-day period (i.e. 10 min per night), the bermudagrass only receives 10 min of runtime over the same three-day period.

In 2021, the golf course converted the remaining 22.3 ha of perennial ryegrass fairways to Santa Ana bermudagrass and replaced an additional 1.6 ha of turf with low water use naturalized grasses. The golf course realized a 20% water savings during that first-year grow-in period. With water budget of nearly US$1 million annually and water costs increasing 5–8% every year, the return on investment on the US$2.6 million project cost will be less than 8 years. Additional economic savings have been realized with reduced use of plant protectants, and golf course members are pleased with the improvement in the consistent quality of those and year-round playing conditions of those bermudagrass fairways.

3.1.3 The Santa Lucia Preserve Golf Course

The Preserve Golf Club (Carmel, CA, USA) is reliant on rainwater to meet its turf water demand for its 18-hole facility. In drought years, there was not enough water to meet the demand of the cool-season turf and, consequently, water was strategically shut off to areas of the golf course with lower priority such as roughs, tee surrounds, and even in fairways between the tees and landing areas. Golf course leadership realized that cool-season turf is not a sustainable playing surface. Therefore, in 2016, the golf course converted 11.3 ha of fairways to Santa Ana bermudagrass. A fraise mowing technique was used to remove the existing turf and to pulverize the soil and surface organic matter layer with a RotaDairon (Dairon SAS, Mulsanne, France). Since conversion of those fairways to Santa Ana bermudagrass, the club is using 13–14% less irrigation water annually. They were using about 283 905 884 L of water annually and now use about 246 051 766 L. The water saving is less, however, than what other golf courses have achieved simply due to the amount of land converted. At the Preserve Golf Club, there is 29 ha of irrigated turf, with only 11 ha of bermudagrass. The remaining 18 ha remain as cool-season turf on tees, roughs, green surrounds, and greens. At some point, it will be necessary to convert those areas to bermudagrass to finally eliminate the 'water thirsty' cool-season turfgrass.

A common theme among these California golf courses (i.e. Birnam Wood Golf Course, Menlo Country Club, and The Preserve Golf Club) that have made the conversion to warm-season turfgrass is a 25% or more annual irrigation water reduction or savings. Furthermore, in drought years and when facing local water use restrictions, these golf courses are much better equipped to continue to produce acceptable turf playing conditions during imposed water use reductions, as well as much better equipped to promote turf recovery once water restrictions are removed or until the rains arrive. Overall, on those California golf courses, bermudagrass delivers more consistent, firmer playing conditions year-round when compared to the 'hodge-podge' of cool-season turf grasses.

3.2 Native grasses and alternative plant materials following turfgrass removal

Water in the desert areas of southwest USA is a precious resource, and persistent drought conditions exacerbate water's limited availability and quality for turfgrass and landscape areas. Golf courses with more than 40 ha of intensely managed turf are regulated to reduce playable acreage for only greens, tees, and target fairways to conserve irrigation water. When turf is removed from the perimeters of those playable areas, the land must still be maintained aesthetically and also retain its functionality. A substitute for removed turf can be native plant materials that require lower maintenance inputs and irrigation water. The University of Arizona (Tucson, AZ, USA) has been evaluating and comparing the establishment and performance of several native grass species for potential adoption and installation when and where turfgrasses are removed (B. Whitlark, personal observation). Golf courses in Arizona have been implementing the use of alternative plant materials with varying success.

3.2.1 Briarwood Country Club, Camelback Golf Club, and Wigwam Golf Club

Three field experiments were conducted with 17 plant species including 14 native grasses, an introduced annual forage grass, a native forb, and an introduced landscape groundcover (Table 1). The small plot replicated experiments were established on three golf courses: Camelback Golf Club (Scottsdale, AZ, USA) in May 2016; Briarwood Country Club (Sun City West, AZ, USA) in June 2017; and Wigwam Golf Club (Litchfield Park, AZ, USA) in June 2019. The USDA Plant Material Center (Tucson, AZ, USA) provided seed for most of the native grasses and a native forb; the former University of Arizona

Table 1 Native grasses and plant species were evaluated for planting at those sites where turfgrasses were removed in Arizona, USA

Plant species	Common name and cultivar	Planting rate (kg ha^{-1})	Location[a]
Andropogon halii	Sand bluestem 'Chet'	5.5	W
Aristida purpurea	Purple threeawn	10	W
Bouteloua dactyloides	Buffalograss	244	B, C, W
Bouteloua curtipendula	Sideoats grama 'Vaughn'	12.45	W
Bouteloua gracilis	Blue grama	4.48	B, C, W
Eragrostis intermedia	Plains lovegrass	1.12	B, C, W
Eragrostis tef	Tef	5.6	B, C
Eragrostis trichodes	Sand lovegrass 'Bend'	3.4	W
Hilaria jamesii	Galleta 'Viva'	471	W
Hilaria rigida	Big galleta	195	B, C
Lippia nodiflora	Kurapia	17 628[b]	B, C
Muhlenbergia asperifolia	Alkali muhly	1.35	B, C
Schizachyrium scoparium	Little bluestem 'Cimarron'	5.5	W
Sporobolus airoides	Alkali sacaton	3.36	B, C, W
Sporobolus contractus	Spike dropseed	1.12	B, C
Sporobolus cryptandrus	Sand dropseed	1.12	B, C, W
Zinnia acerosa	Desert zinnia	2.47	B, C

[a]Field experiment locations and establishment year: B = Briarwood Country Club (Sun City West, AZ, USA), 2017; C = Camelback Golf Club (Scottsdale, AZ, USA), 2016; W = Wigwam Golf Club (Litchfield Park, AZ, USA), 2019.
[b]Small plugs planted.

Karsten Turfgrass Research Facility (Tucson, AZ, USA) provided seed for *Hilaria rigida* (big galleta) and *Sporobolus cryptandrus* (sand dropseed) in 2016 and 2017, a commercial vendor was the source of seeds in 2019, and Kurapia Inc. (South Pasadena, CA, USA) provided Kurapia plugs for all three sites.

During the May–June timing of each installation at each site, supplemental overhead irrigation was required to germinate and establish the seeded native grasses and Kurapia transplants in all three experiments. At Camelback GC, an overhead sprinkler system was installed to irrigate the experimental area and approximately 6.6 mm was applied daily during the first month of establishment. At Briarwood CC, an existing irrigation system was utilized and approximately 1.02 mm was applied daily during the establishment period. At Wigwam GC, an existing overhead irrigation system was utilized during the establishment period. At Wigwam GC, an additional fourth replicate was planted in August 2019 to coincide with monsoon rains, and more effective germination and emergence were incidentally observed as a result of the rains.

Once established and into subsequent years, the intention was to eliminate supplemental irrigation and depend on seasonal rains during the summer monsoons (i.e. July–September) and rain during the winter-spring season (i.e. November–April).

At all three locations, a starter fertilizer (0.56 kg nitrogen•ha^{-1} and 2.8 kg P_2O_5•ha^{-1}) was applied only once for all plantings at the time of seeding or soon after standing emergence. The experimental area at Camelback GC was mowed in the late spring to early summer (i.e. May–June) and then again in September or December after the grasses matured. At Briarwood CC and Wigwam GC, the native grasses were mowed once per year during the fall to winter season.

At two test locations in 2016 and 2017, *Eragrostis tef* (tef), an annual forage grain crop, demonstrated the best rate of germination and stand establishment among the grasses and Kurapia successfully established from transplanted plugs. *Eragrostis* intermedia (plains lovegrass), *Bouteloua gracilis* (blue grama), *H. rigida* (big galleta), *Sporobolus cryptandrus* (sand dropseed), *S. airoides* (alkali sacaton), and *S. contractus* (spike dropseed) showed adequate emergence, establishment, and survival. *B. dactyloides* (buffalograss) failed to emerge at Briarwood CC and was very slow to establish at Camelback GC and Wigwam GC, and *Zinnia acerosa* (desert zinnia) did not emerge at Briarwood CC or Camelback GC nor in a separate laboratory germination test.

At Wigwam GC, *Andropogon halii* (sand bluestem 'Chet'), *Schizachyrium scoparium* (*little bluestem*) ('Cimarron'), and *Aristida purpurea* (purple threeawn) successfully emerged following that later planting in late summer during the monsoon rain period. Also, purple three awn aggressively spread beyond the small planted plots, and buffalograss, the dropseeds, big galleta, and alkali sacaton all emerged and established successful stands.

A desirable aesthetic characteristic of plant materials is to maintain visual greenness year-round. Most native grasses become dormant and turn brown in the winter season when temperatures fall and frosts occur (K. Umeda, personal observation). Desert grasses in the low desert of Arizona may slow down in growth with the lack of rainfall and the onset of intense summer heat in May–June. Under mild winter conditions when hard freezes did not occur, plains lovegrass, alkali sacaton, and Kurapia retained acceptable green color throughout the winter. *Muhlenbergia asperifolia* (alkali muhly) and blue grama maintained some green color during the winter, and the dropseeds and big galleta did not retain their green color.

Initial seeding rates that were used ensured successful stand establishment of the grasses. After establishment, during subsequent years of growth, thick and dense stands began to thin among the bunch grasses. Shorter bunch grasses could be encouraged in areas adjacent to the fairways and gradually taller grasses could be transitioned further away, while colorful wildflowers could be integrated among the grasses. Sustaining long-term succession of native grasses and wildflowers to continuously provide a natural appearance will require monitoring and considerable labor resources to maintain and occasionally seed desirable plant materials, especially annual wildflowers (K. Umeda, personal observation). Perennial shrubs and volunteer desert trees may encroach upon those native grass sites and could require timely maintenance if those species interfere with play, aesthetics, or functionality of the desired turf and native grass areas.

On golf courses, players' pace of play is critical, and lost golf balls in deep grasses are not a desirable feature for native grasses in non-play areas. Kurapia has a prostrate growth habit that provides uniform and complete surface coverage. Buffalograss, gramas, galletas, and alkali muhly tended to provide full surface cover and depth where golf balls could be difficult to find. The alkali sacaton, purple three awn, dropseeds, and bluestems grow as bunch-type grasses where establishment spacing provides visible bare ground in between plants where golf balls could be potentially found.

Native grasses can be utilized effectively for golf courses if a natural desert grassland appearance is desired. Wildflowers can be integrated with the native grasses, and native desert-adapted shrubs and trees can provide perennial plant material to those areas. Irrigation water inputs will be reduced to only supplemental applications when severe drought occurs, and golf course labor can be directed away from those non-play areas to focus on those turf areas in play.

3.2.2 Camelback Golf Club – Ambiente Golf Course

The Ambiente Golf Course at Camelback Golf Club (Scottsdale, AZ, USA) is located in a floodplain through a heavily populated urbanized residential corridor. It was formerly turfed entirely with a total of 91 ha of common bermudagrass turf along with non-native desert-adapted pine trees along the fairways. It reopened in the fall of 2013 following an extensive renovation that reduced playable turfgrass areas to 32 ha. The drainage wash channel area on the golf course was deepened and strategically placed lakes were created and contoured to hold excess water during flooding events and also for irrigation water-holding purposes. The deepened channel prevented flood waters from rising to interfere with golf course playability. The ponds provided new habitats for fish and amphibians.

Few of the pine trees along the perimeter of the golf course adjacent to residential properties were preserved. Approximately, 20 ha of land adjacent to residences around the golf course perimeter and 28 ha of non-play areas in the drainage wash channel area were planted with native grasses and wildflowers (Table 2). During the initial winter following the establishment of those seed

Table 2 Wildflower and grass seed mixtures for the Ambiente Golf Course at Camelback Golf Club (Scottsdale, AZ, USA)

Scientific name	Common name	Plant family
Wildflowers		
Ambrosia deltoidea	Triangle-leaf bursage	Asteraceae
Baileya multiradiata	Desert marigold	Asteraceae
Calliandra eriophylla	Fairy duster	Fabaceae
Dyssodia spp.	Daisy family	Asteraceae
Encelia farinose	Brittlebush	Asteraceae
Eschscholzia californica	California poppy	Papaveraceae
Gaillardia pulchella	Firewheel	Asteraceae
Linaria maroccana	Baby snapdragon, annual toadflax	Plantaginaceae
Linum spp.	Flax	Linaceae
Lupinus spp.	Lupine	Fabaceae
Penstemon parryi	Parry's penstemon	Plantaginaceae
Ratibida columnifera	Prairie coneflower (Mexican hat)	Asteraceae
Sphaeralcea ambigua	Globe mallow	Malvaceae
Grasses		
Aristida purpurea	Purple three awn	Poaceae
Bouteloua curtipendula	Side oats grama	Poaceae
Hilaria rigida	Galleta	Poaceae
Sporobolus airoides	Alkali sacaton	Poaceae

mixes, approximately, 75% of the plant material yielded a high variability of colorful annual wildflowers. The visual aesthetics of those colorful wildflowers were considered highly favorable to the citizens of Paradise Valley (AZ, USA). Approximately 8 years after its establishment in 2013, the succession of plants has now converted to 5% wildflowers and 50% native grasses, with almost half of the ground surface area as bare ground. Volunteer mesquite and palo verde trees have emerged, and small emerged trees were selectively removed by hand to not interfere with golf course routing or play. Since the renovation of these planting areas, the plant community succession has created habitats for desert birds and wildlife and foraging opportunities for pollinators.

Typically, the low desert in the southwest USA is not characterized as a dense understory of annual or perennial grasses. Cactus, mesquite trees, and palo verde trees are not accustomed to fire regimes that are common in grassland areas of the plain states of the USA. Bare ground is typically observed between cactus, desert trees, and shrubs. Most desert native plants are supported by winter rains from November to April and summer monsoon rains from July through September, thus totaling 12–25 mm precipitation annually. Invasive weeds have infiltrated the desert region contributing to many desert wildfires. *Bromus rubens* (red brome) a winter annual grass, *Pennisetum ciliare* (buffelgrass) a perennial forage grass that has become weedy, and *Oncosiphon pilulifer* (stinknet) are examples of fire-carrying invasives spreading in the desert region.

The maintenance of the native grasses and wildflowers at Ambiente Golf Course has been fine-tuned to two mowings per year. The first mowing in late summer following summer growth resulting from the monsoon rains, and a second mowing after the spring bloom of wildflowers. However, the desired goal is to mow only once per year to further save on labor costs. Of note, selective herbicides have been applied in recent years when red brome and other *Bromus* or *Hordeum* spp. invaded the open spaces among the native species' plantings following winter rains.

The major highlight of the renovation project at Ambiente Golf Course was not only the reduction in turf area but also significant water conservation was achieved by irrigating only tees, fairways, and putting greens. Supplemental irrigation water is applied to the native species areas only during extreme drought periods. In 2020, records indicated that only 60.5 ML water were used to maintain the native grasses and wildflowers. In prior years, 211.7 ML water were used in 2015 and 71.8 ML water in 2017. Overall, 170.1 ML year^{-1} were saved between the periods of 2013 and 2016 versus pre-renovation from 2000 to 2009 Also, the overall annual reduction in irrigation water consumption at Ambiente Golf Course was over 1 million m^3 in 2006 to just over 800 000 m^3 in 2020.

3.3 Subsurface drip irrigation for golf courses

Sprinkler systems are the most used irrigation systems for turf-dominated landscapes and golf courses, despite their inefficiencies (B. Leinauer, personal observation). Sprinkler overspray, overlap, wind drift, and evaporation all contribute to water losses that increase overall water consumption and/or decrease turf quality. Subsurface irrigation systems, however, are considered to irrigate more efficiently because water is applied directly to the rootzone, thereby avoiding problems such as overspray, runoff, and wind drift. Drip irrigation systems have been frequently used to irrigate trees, shrubs, flower beds, or vegetables but have received little acceptance for turfgrass irrigation. The benefits of subsurface drip systems (SDIs) have been documented for agricultural and horticultural crops as well as trees (Burt and Styles, 1999). They also offer a solution for lawns that are difficult to irrigate – such as narrow strips, slopes, or unusual, irregular-shaped areas, which is the case for many residential lawns – and bunker slopes and tee areas on golf courses.

Subsurface drip irrigation generally applies water from either a point or a line source. Both systems use a polyethylene pipe at depths that vary depending on the plant or ground cover which is irrigated (Burt and Styles, 1999). Line source systems seep water uniformly along the length of the line and are often referred to as soaker or porous hose lines. Point source systems, also called drip lines, are equipped with either non-pressure-compensating or pressure-compensating drip emitters spaced equally (i.e. 30 cm, 45 cm, 60 cm) and fitted into the pipes.

Advantages of SDI include the uninterrupted use of the turf area during irrigation, energy savings as a result of lower operating water pressure, no human exposure to irrigation water, reduced turf disease pressure, and water savings because irrigation is limited to only the turf area and is not affected by wind drift or evaporation (Camp, 1998) (Fig. 4). Arguments against the use of SDI include high installation costs, a perceived interference with regular maintenance, and a perceived inability to leach salts (Sevostianova et al., 2011a). The suitability of SDI for turf was first demonstrated 40 years ago, but

Figure 4. Cross-section of turfgrass rootzone with a drip line surrounded by roots and no visible roots penetrating the emitter (left); aerial image of sprinkler irrigated tee box illustrating the irrigated area greater than the actual turfgrass area, as indicated by the lush green vegetation beyond the tee area perimeter (top right); and a subsurface drip irrigated tee box with the irrigation zone strictly limited to the turfgrass tee area (bottom right).

the technology has never gained significant market acceptance (B. Leinauer, personal observation). However, SDI has recently begun to receive greater attention in the context of water conservation and environmental sustainability and has been mandated by some water agencies for narrow and irregularly shaped turf areas (California Department of Water Resources, 2009).

Studies investigating turfgrass establishment with subsurface irrigation systems have given conflicting results. Snyder et al. (1974) investigated emitter spacing and depth for drip irrigation under bermudagrass and reported that a maximum distance of 60 cm between emitters can be allowed without a reduction in turfgrass quality. Manufacturers of drip irrigation systems recommend an emitter spacing between 30 cm and 60 cm and a line depth of 10 cm to ensure uniform water distribution, regardless of the soil type into which the system is installed. Leinauer and Makk (2007) documented a delayed establishment of subsurface drip-irrigated creeping bentgrass in a sand-based USGA-type rootzone, when compared to sprinkler irrigation. Johnson (2007) compared the establishment of several cool-season turfgrasses under SDI and aboveground sprinkler irrigation and reported that successful establishment with SDI depended on the turfgrass species and a cultivar used. Leinauer et al. (2010a) used SDI in an establishment study and reported efficient and uniform water distribution at the surface with the drip system and successful turfgrass establishment. Schiavon et al. (2012) and Serena et al. (2014) demonstrated that bermudagrass and seashore paspalum can be established successfully from seed and sod when SDI is used in combination with saline water. Subirrigation systems may have some limitations in leaching salts from the rootzone. Particularly the fraction of the rootzone above the emitters (i.e. where most of the roots are accumulated) that receives water only through capillary rise may not be sufficiently flushed with water to leach out the salts. Two studies (Devitt and Miller, 1988; Choi and Suarez-Rey, 2004) have demonstrated that warm-season turfgrasses irrigated with either high saline water or with effluent water can be successfully grown using SDI; however, long-term salt accumulation around drip emitter has not been investigated.

Several reports have documented irrigation water savings at no loss in turf quality when subirrigated from an adjustable water table, or SDI, compared to aboveground sprinkler irrigated turf (Leinauer et al., 2004; Sevostianova et al., 2011a,b). In areas with irrigation water restrictions where the implementation of water conservation strategies is mandated, the use of subsurface irrigation technologies will likely to increase (Duncan et al., 2009; Leinauer et al., 2010b). Thus, applying water directly to the rootzone with SDI can result in improved water conservation and an efficient irrigation system.

Information is limited on the long-term performance of SDI systems in heavily trafficked and intensively managed turfgrass systems as often observed in certain areas of a golf course. Consequently, a multi-year field study was conducted to investigate the effects of different SDI systems and a standard pop-up sprinkler irrigation system on turfgrass performance and irrigation water consumption on golf course tee areas.

3.3.1 Materials and methods

The study was conducted at the Club at Las Campanas (Santa Fe, NM, USA) in an area with an arid climate at 2133 m elevation. The championship tee boxes used for the study were constructed with a 20-cm-deep sand rootzone overlaying a 10-cm-deep pea gravel layer. Creeping bentgrass was established to the existing tee boxes that were between 18 and 25 years old. The first SDIs were installed in May 2016 and included Toro Rootguard® DL2000™ (Toro Co., Bloomington, MN, USA) delivering 2.0 L•hr^{-1} and operating at 241 kPa and Rainbird XSF (Rainbird Inc., Azusa, CA, USA) with copper shield technology, delivering 2.3 L•hr^{-1} and also operating at 241 kPa. In May 2017, Netafim Techline CVXR (Netafim Irrigation Inc., Fresno, CA, USA), delivering 2.0 L•hr^{-1} and operating at 344 kPa, and Hunter Eco-Mat (Hunter Industries Inc., San Marcos, CA, USA), delivering 2.0 L•hr^{-1} and operating at 241 kPa, were added to the study. Each system was installed with 30 cm spacing between lines, except for one Toro and one Rainbird system, for which a spacing of 23 cm between lines was chosen. Emitters were spaced 30 cm apart and all lines were installed at rootzone depths of approximately 15 cm. A screen filter and a pressure regulator were installed on each tee box before the main valve, in addition to an air release valve and an automatic flush valve. Two tee boxes irrigated with Rain Bird 5004 rotor sprinklers (Rainbird Inc., Azusa, CA, USA) were designated as the controls. Each SDI system and the controls were equipped with water meters installed after the valves. Water use for each tee box was recorded and the turf surface area was calculated. The amount of water delivered to each tee box was reported relative to the irrigated area. However, during the investigative period, irrigation was scheduled manually and not standardized across tees or SDI systems. Therefore, comparisons between SDI products regarding water use must be made with caution.

Two approaches were used to install the SDI systems under the pre-existing turf. The first strategy was to remove the sod and, using a disk trencher, cut into the sand profile. After the system was installed, the sod was returned into place, followed by sand topdressing and irrigation using the overhead sprinkler system. The second approach was to trench directly into the existing turf. After the system was installed, the lines were re-compacted, and the turf was then sand topdressed, followed by irrigation with the overhead sprinkler system.

Turfgrass maintenance was conducted similarly among all other tee boxes at the golf course. This included irrigation at approximately 100% ET rate replacement, daily mowing, fertilization, sand topdressing, and verticutting as needed. Due to concerns about potential damage to the irrigation systems, SDI tee boxes were not aerified until fall 2020.

3.3.2 Results

With the help of the in-ground sprinkler system, turf stands recovered within a few months from post-installation injury or disruption. Spacing the drip lines 23 cm apart resulted in no different recovery and turf quality than a spacing of 30 cm. SDIs installed using the sod removal approach resulted in a faster recovery, and overall better turfgrass quality during the first months of the study (Fig. 5). On two occasions, drip lines were inadvertently installed at the incorrect depth, resulting in uneven turf establishment and ultimately led to the system being re-installed. After 1 year of installation, all SDI systems performed equally well based on turfgrass quality, with little to non-visible signs of differences between SDI systems.

Normalized difference vegetation indices were measured and did not show any differences in stress between the controls and the SDI-irrigated tee boxes. The irrigation water use by SDI-irrigated tee boxes was lower compared to tee boxes irrigated with traditional pop-up sprinklers (Table 3). Sprinkler-irrigated tee boxes received approximately 2–5 times more water compared to the SDI-irrigated tee boxes (Table 4). Over the four-year investigative period (i.e. 2017–2020), SDI-irrigated tee boxes used on average between 38% (2019) and 60% (2020) less water than the sprinkler-irrigated counterparts. The higher irrigation amounts used by sprinkler systems were due in part to overspray. Pop-up sprinklers irrigated beyond the tee box area and ended up irrigating the surrounding native vegetation. In contrast, the SDI systems delivered the water only to the designated area. The growth of the native vegetation surrounding tee boxes was significantly reduced in SDI-irrigated tee boxes (i.e. from not receiving any additional water), thereby reducing or eliminating the need for vegetation maintenance of those areas (Fig. 5).

Figure 5 Example of tee boxes 1 month after subsurface drip irrigation (SDI) installation. Left: trench lines were dug directly into the turf canopy and rootzone. Right: sod was removed, SDI was installed by trenching only into the rootzone and sod was returned in place.

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Table 3 Irrigation water use (mm) of subsurface drip (Hunter, Netafim, Rainbird, Toro) systems and aboveground pop-up sprinkler (control) system irrigated on golf course tees in Santa Fe, NM (USA) during summer months (i.e. May–August) 2017–2020

	2017	2018	2019	2020
	mm	mm	mm	mm
Control[a]	2310	3050	1830	2570
Hunter[b,c]	–	640	890	610
Netafim[b,c]	–	860	1350	1350
Rainbird[b]	1070	1090	860	660
Toro[b]	990	1170	1450	1370

[a]Water use values represent the average of two tee boxes.
[b]Water use values represent the average of three tee boxes.
[c]Irrigation system was added later to the study, and therefore data not available for 2017.

Table 4 Reduction in water use (mm) when subsurface drip (Hunter, Netafim, Rainbird, Toro) systems as compared to aboveground pop-up sprinkler irrigation. Water-use values (calculated as the average of three tee boxes) represent percent water savings or reduction compared to sprinkler irrigation (calculated as the average of two tee boxes)

	2017	2018	2019	2020	Four-year average
		% water savings			
Hunter[a]	–	79	52	73	68
Netafim[a]	–	72	26	47	48
Rainbird	54	64	53	75	62
Toro	57	62	21	47	47

[a]Irrigation system was added later to the study, and therefore data not available for 2017.

4 Conclusion

Golf course managers in arid environments must manage every drop of water like it is their last. Water restrictions continue to tighten and water costs are increasing exponentially in many areas. While superintendents in arid environments utilize onsite weather data to schedule irrigation, current research and new technologies offer ways to optimize soil moisture consistency and reduce water inputs. Courses in California are converting fairways and roughs from cool-season grass to warm-season grasses, saving 25% or more annual water use. Despite high conversion costs, the return on investment is typically less than 10 years. Significant water savings have been achieved in southern Nevada, California, and Arizona by removing irrigated turf and replacing with desert landscape or native grasses. Portable soil moisture meters are widely used and inground soil moisture sensors are gaining popularity for use in large turf areas such as fairways and roughs. Early indications are that this technology may yield substantial water savings and deliver more consistent playing conditions. Subsurface drip irrigation has been shown to save 40–80% water compared to overhead irrigation and this technology is growing in popularity for bunker surrounds and teeing grounds.

Diligence, daily observation, constant adjustment of the irrigation system and practices, and a good overall turfgrass management plan are required to optimize soil moisture uniformity across a golf course. The work is never done as the weather is constantly changing, sun angle changes dramatically from winter to summer and sprinklers fall out of adjustment – to name just a few of the variables involved. Hopefully, the strategies provided in this chapter will prove useful to improve soil moisture consistency at your golf course. In summary, the golf industry is adapting to water-related challenges through adopting new technologies and building on strategies illuminated through water-related research.

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6 Where to look for further information

Research is needed in the broad area of water conservation for golf courses. Topics such as new irrigation technologies including inline drip irrigation for large turf areas, breeding warm season grasses that retain green color year-round in southern states and are drought tolerant and utilization of in-ground soil moisture sensors to schedule irrigation are just a few examples that need further exploration. The golf industry will look to the United States Golf Association (USGA) as the primary source of guidance and funding for researchers in the future. Other entities include the Golf Course Superintendents Association of America (GCSAA) who also award grants for turfgrass research. Additionally, federal agencies such as the United Stated Department of Agriculture (USDA) and the National Science Foundation (NSF) are interested in funding turfgrass research that addresses water conservation.

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