FUNDAMENTAL IRRIGATION STEWARDSHIP

The Effects of Chemical Applications on Water Use and Drought Resistance

Certain chemical applications can improve the drought tolerance of turfgrass and potentially help courses save water. However, practitioners should verify that any product claims are backed by scientific research and supported by field experience.

SNAPSHOT

This strategy deals with following best general turfgrass management practices that leverage applications of proven chemical products to reduce water use. It is a low-impact, low- to medium-cost strategy applicable for most golf courses.

Expected cost	< $25K per acre
Ease of implementation	Daily maintenance
Potential water savings for affected area	< 10%
Highest potential impact areas	Nationwide

OVERVIEW

Turfgrass management and maintenance practices can enhance drought resistance – and potentially help courses save water – by affecting plant physiology, controlling pests or affecting soil properties. Healthy turfgrass will have a better chance of maintaining its vitality, function and visual appeal, even when water is limited. This chapter will briefly discuss the key components of maintaining healthy turfgrass. We know that various maintenance practices, such as mowing and fertilization, can impact how much water the turfgrass will need and utilize. However, we understand that some of these practices may be difficult to change or modify in golf course settings. Therefore, we will focus on practices and strategies that can be adopted to maintain turfgrass quality with less water.

Applying certain chemicals and products to aid turfgrass during drought is a practice grounded in decades of scientific research and years of practical field experience (Schiavon & Serena, 2023). However, many chemicals or products are less proven (or even completely unproven) when it comes to their potential impact on water use and drought resilience, so turfgrass managers should do their homework. Golf course superintendents continually manage complex mechanisms that govern turfgrass responses to water stress and have developed targeted cultural and application programs to alleviate this abiotic stress. By leveraging these practices, superintendents and turfgrass practitioners can reduce the impact of water scarcity or decreased water use and promote healthier, more resilient turfgrass.

It is important to note that while various product applications can be a valuable tool, they are not a stand-alone solution to drought management or water conservation goals. They should be considered part of a comprehensive approach that includes proper irrigation practices, soil management and other cultural practices. Integrated turfgrass management strategies that incorporate chemicals as one element among many can yield the best outcomes in terms of drought resistance and long-term turfgrass health.

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SCENARIOS FOR USE

General Turfgrass Culture

Detailing best turfgrass management practices is beyond the scope of this chapter. However, it is important to at least acknowledge that turfgrass selection and basic culture affect water use. Golf courses should establish the most drought-tolerant turfgrass variety or cultivar that suits other site-specific needs (see Chapter 5 for more information). Although mowing heights can affect turfgrass water use, golf courses typically select heights of cut based on playability goals. Additionally, soil biological, chemical and physical properties can affect water use. Many soil chemistry considerations are discussed below, but biological and physical properties are not. Briefly, proper soil management should evaluate and include aeration and soil amendments to alleviate compaction that impairs water infiltration. It is also important to adequately manage the accumulation of thatch and organic matter near the soil surface, which can increase surface wetness at the expense of deeper water percolation and rooting that promotes drought resistance.

Cultural practices play an important role in promoting drought resistance and optimizing water use.

Leveraging Chemicals to Conserve Irrigation Water

Chemical use in turfgrass management should follow local regulations, product label instructions and research-based best practices to ensure user safety, environmental sustainability and efficacy. Using these foundations, golf course superintendents often develop customized maintenance programs based on their knowledge of turfgrass species, site conditions, and expectations.

Fertilizers

Turfgrass fertilizers provide essential mineral nutrition that promotes growth and resilient playing surfaces able to recover from traffic, drought, and other abiotic and biotic stresses. Proper fertilizer programs are especially important for drought resistance because deficiency, excess, or poor application timing of any nutrient can impair the growth and development of leaves, stems and roots, thus limiting turfgrass performance under stress. For example, sufficient phosphorous is essential for root growth, while excessive nitrogen can favor foliar growth to the detriment of rooting. Too much fertilizer, overall, can cause salinity stress, making it more difficult for roots to absorb water. Proper nitrogen applications, in particular, can improve turfgrass performance and visual color during drought.

Nitrogen

As a principal driver of plant growth, moderate nitrogen fertility is important before and during drought stress. Insufficient nitrogen will lead to a quicker decline in turfgrass quality during drought, and excessive nitrogen may impair root proliferation and drought resistance (Kopp & Jian, 2013). While the benefit of sufficient nitrogen during drought stress has been shown in several turfgrass species, evapotranspiration (ET) rates generally increase with nitrogen fertilizer use, which further highlights the importance of moderation. Generally, nitrogen should be applied at infrequent, low rates from a slow- or controlled-release source during drought (Harivandi & Gibeault, 1990).

Moderate nitrogen fertility helps turfgrass withstand drought stress, but applying too much nitrogen can be problematic during a drought.

Phosphorus, potassium and other nutrients

Phosphorous and potassium have been associated with the alleviation of, or hastened recovery from, drought stress. However, their relative benefit often depends on the supply of other nutrients. The beneficial effects of iron fertilizer on creeping bentgrass are not associated with increased drought tolerance (Glinski et al., 1992). Silicon is an alleged "beneficial" (i.e., technically nonessential) micronutrient that has received a lot of attention. Some research has demonstrated that silicon can improve drought tolerance. However, high application rates and the relative lack of field experiments make the value of silicon in drought management questionable. The direct effects of other nutrients on turfgrass drought resistance or tolerance are relatively unstudied.

The best approach for advancing drought resistance with fertilizer is to soil test at least annually with a goal of maintaining soil nutrients slightly above research-based recommendations. Locally calibrated recommendations based on Sufficiency Level of Available Nutrients (SLAN) or Minimum Levels for Sustainable Nutrition (MLSN) are appropriate (Thompson et al., 2023). Of course, traditional soil testing cannot guide the scheduling of some nutrients, such as nitrogen or sulfur, and so plant responses must inform decision making.

Pesticides

Pests can affect turfgrass performance during drought in two ways. First, a prior infection or infestation can reduce turfgrass vigor, reduce drought resistance and inhibit recovery. Second, pests may take advantage of drought-stressed turfgrass and further reduce quality and performance. Therefore, it becomes even more important to manage pests during such conditions. For example:

Herbicides control weeds in turfgrass areas. Weeds compete with turfgrass for water, and drought conditions can exacerbate the proliferation of certain weeds. Preemergence herbicides can be especially useful to prevent weed emergence and maintain playing surface quality when turfgrass is drought stressed or even dormant.

Insecticides help manage turfgrass insect pests such as white grubs, chinch bugs and armyworms. The first sign of damage from root-feeding pests often is wilt, so it is especially important to control these pests to ensure a healthy root system that can access available soil water.

Nematicides help manage nematode infestations, most often in putting greens. Like root-feeding insects, wilt often is a symptom of nematode feeding and improved drought-performance of nematicide-treated turfgrass is associated with increased root biomass (Trenholm et al., 2005).

Fungicides help manage foliar diseases such as dollar spot or brown patch, or root diseases such as take-all patch or Pythium root rot. Turfgrass health benefits from fungicides are similar to those already discussed for insecticides and nematicides. Claims of improved drought tolerance in the absence of disease pressure have become more common with certain groups of fungicides, even though research often does not support the claims (Schiavon et al., 2022). An exception is acibenzolar-S-methyl (ASM), which has been shown in research settings to enhance drought performance in creeping bentgrass by reducing transpirational water loss (Jespersen & Huang, 2017; Shekoofa et al., 2016).

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However, manufacturing companies typically include ASM in fungicide mixes, rather than selling it individually, and more importantly, the frequency and cost of using ASM as a drought-management tool is not economical for most golf courses.

Plant Growth Regulators

Plant growth regulators (PGRs) have many uses including reducing mowing requirements, inhibiting seedheads, promoting the growth of some grasses over others, and enhancing weed control. Because they partially arrest plant growth, PGRs commonly reduce ET rates and some have been shown to improve drought tolerance in turfgrasses and other plants. PGRs are distinguished by class, from A to F. For water conservation purposes on golf course turfgrass, typically only class A and B materials are utilized. Class A PGRs are late-step gibberellic acid inhibitors, while Class B PGRs are early-step gibberellic acid inhibitors.

Trinexapac-ethyl (TE; PrimoMaxx) and prohexadione calcium (Anuew) are the only Class A PGRs and are primarily foliar absorbed. TE, in particular, has been repeatedly shown to improve turfgrass appearance and metabolic function during drought stress (Schiavon & Serena, 2023). In warm-season turfgrass, TE has been shown to reduce water use by 15% to 30% in research settings (Schiavon et al., 2019). Paclobutrazol (Trimmit) and flurprimidol (Cutless) are Class B PGRs and are primarily root absorbed. Paclobutrazol has been shown to reduce visible stress during drought, primarily in cool-season turfgrass (Shahrokhi et al., 2011).

While exact water savings can vary based on specific conditions and PGR type, reductions ranging from 15% to 20% are plausible (Schiavon & Serena, 2023). These water savings are challenging to quantify because several studies have evaluated various ET levels, and only estimated these savings. Golf course case studies are needed.

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Soil and Water Conditioners

Soil and water chemistry can affect how water enters and moves within soil and whether it is accessible by plant roots. The main challenges are typically salinity, sodicity and/or water-repellent soils.

Salinity and sodicity

Soil and water salinity are defined as a higher-than-usual concentration of dissolved salts. For most turfgrasses, when the soil has an electrical conductivity of the saturated paste extract higher than 4 decisiemens per meter (dS/m), it is considered saline. Sodicity is when the soil has a concentration of exchangeable sodium higher than 6% compared to other cations (Harivandi et al., 1992).

Entire textbooks have been written on managing salts and sodium, which is beyond the scope of this chapter (see

Duncan et al., 2009). Briefly, high soil salinity can cause drought stress that can only be mitigated by leaching salts through the soil or rootzone. Irrigation water that is high in salts can be treated with reverse osmosis and/or blended with higher quality water to reduce salinity levels. High soil sodicity deflocculates (disperses) soil particles and can only be remedied by displacing excess sodium with calcium or magnesium products followed by leaching. Water high in sodium can be treated with gypsum or acid injection. Golf courses using recycled wastewater for irrigation will experience these issues and should refer to the chapter in this guide dedicated to that subject for more information.

Water-repellent soils

Soils become water-repellent (hydrophobic) when organic compounds and substances coat soil particles. Sandy soils are most likely to experience water repellency conditions, which leads to “localized dry spots” that can persist and are difficult to rewet.

Hydrophobic conditions lead to poor turf quality and inefficient water use.

Soil surfactants

Soil surfactants, also known as wetting agents, reduce the surface tension of water, which improves the polar attraction between water molecules and soil particles. This improves water infiltration and soil moisture uniformity, especially in hydrophobic soils prone to excessive localized drying (USGA, 2018). Some products are marketed as "penetrants" while others are labeled as "retainers" to indicate distinct performance mechanisms related to water movement. However, the properties and practical effects among surfactants on both rootzone volumetric water content (VWC) and turfgrass quality are often similar; differences that do occur are inconsistent and do not necessarily correspond to the marketing terminology (O'Brien et al., 2023). At the same time, surfactant products have demonstrated considerable variability in performance across locations and over time, indicating that both weather and maintenance practices influence wetting agent performance (Throssell, 2005). Considering these external factors and collecting data – such as percent VWC and firmness – before and after soil surfactant applications will help superintendents better understand and optimize the benefits these products can provide to their specific course.

Soil surfactants improve water infiltration and soil moisture uniformity. The plots in this image are from a study of various surfactant programs, with the top-left plot being nontreated.

Soil surfactants are widely used in golf course management, especially on putting greens, and extensive research supports their general benefit (Fidanza et al., 2020; Schiavon & Serena, 2023). Soil surfactants have been studied for their potential to improve turfgrass quality under reduced irrigation regimes. In some studies (Schiavon et al., 2014), surfactant-treated bermudagrass maintained acceptable quality when irrigated at 50% of reference ET. Similar studies further support that soil surfactants can lead to water savings of 20% or more, depending on turf species, climate, traffic and duration of drought (Nolan & Fidanza, 2024). It is important to deliver the soil surfactant to the rootzone through post-application irrigation to realize the water-savings potential.

A cautionary note about "physical water conditioners"

Physical water treatment devices, such as magnetic conditioners, are commonly used in the golf industry. These devices are placed in the irrigation system main water supply line and are primarily marketed as an easy and effective method to treat water. Manufacturers claim that the devices improve water quality, save water and offer other benefits. However, most of the case studies and testimonials presented by manufacturers lack scientific rigor, are not properly replicated in space or time, and lack nontreated controls for comparison. Therefore, this information should always be taken with skepticism. Despite marketing claims, scientific studies have reported no benefit from the use of physical water conditioners (Leinauer et al., 2012). Studies have been conducted under different water salinity levels, drought levels and with different grasses, all without positive results from physical conditioners.

Colorants

Turfgrass colorants include paints, pigments and dyes. The relative amount of binder differentiates these products, mostly in terms of longevity. For example, pigments have less binder, are typically applied at lower rates to growing turfgrass, and do not last as long as paints, which have more binder and are applied at higher rates, often to provide green color to dormant turfgrass. Presently, the primary benefit of colorants is to improve aesthetics and definition during winter dormancy without overseeding. Estimates from Arizona indicate that an acre of non-overseeded bermudagrass requires around 4.5 acre-feet (1.47 million gallons) of water per year, whereas overseeding an acre of bermudagrass increases annual water use to 6.2 acre-feet (2.02 million gallons). Colorants can also be used to temporarily improve turfgrass color during drought stress.

In a study conducted at Clemson University on creeping bentgrass, four commonly used pigments were tested under drought conditions. Although these products did not enhance physiological processes associated with turf performance, they did increase turfgrass quality under drought stress conditions. One product containing titanium dioxide (TiO_2), which is often used in sunscreen, reduced ET rates (McCarty et al., 2014). A recent field study at the University of California, Riverside (UCR), demonstrated that pigment products maintained higher bermudagrass quality under drought conditions (2023 UCR Turfgrass and Landscape Research Field Day Booklet).

Product selection is ultimately predicated on whether leaf surface transparency is needed to support photosynthesis. Further, because pigments affect light transmission, repeated use on actively growing turf may contribute to reduced health over time. Colorants have also been shown to increase heat stress in creeping bentgrass, so care should be taken, especially with paints designed to provide color during winter dormancy (McCarty et al., 2017). Oftentimes, colorants are premixed or tank-mixed with other products, such as fungicides. There is a lack of research specifically investigating the benefit of colorants alone on turfgrass drought resistance.

Using turf colorants to enhance the aesthetics and definition of dormant playing surfaces has helped some courses discontinue winter overseeding, which can lead to significant water savings. (USGA/Chris Keane)

Other Compounds

The products listed below have shown potential to reduce turfgrass water use, but there has been limited research into their effectiveness for drought management and water conservation and their potential benefits for these purposes have yet to be tested on a large scale. However, there is potential for forthcoming experimentation, evaluation and use.

Biostimulants

Many compounds can be used to activate plant defense mechanisms and increase abiotic stress resistance or tolerance, even for drought. However, the effects of these products often are incremental and most pronounced in controlled environments, such as research greenhouses or growth chambers. It can be difficult to reproduce significant or observable results in field research or “real-world” settings. For example, abscisic acid (ABA) is considered a phytohormone and is often categorized as a biostimulant. Exogenous applications of ABA have been shown to improve drought tolerance in several turfgrass species. Research has mostly been limited to growth chambers, but field testing may further support potential benefits of ABA in turfgrass water conservation. Biostimulants should not be considered as a replacement for thoughtful water management and any use should be critically evaluated, including searching for supporting nonbiased research and monitoring field experiences with use areas compared to a nontreated control plot.

Soil amendments

The primary benefit of soil amendments in turfgrass management is to improve the physical properties of soil, including water retention and availability. Organic amendments increase nutrient and water retention, particularly in sandy soil. For example, using biochar as a replacement for peat moss in putting greens has shown potential benefits for bentgrass growth, with the possibility of also improving drought tolerance (Vaughn et al., 2018). Additionally, in a research trial in Riverside, California, biochar was incorporated into the soil and demonstrated benefits in maintaining tall fescue quality under drought conditions (Montgomery, 2018).

It is important to note that with an established turfgrass system, the soil will be higher in organic matter compared to new turfgrass stands or many agricultural soils. It is also difficult to apply and incorporate these compounds into established rootzones. Therefore, most of these soil amendments are added during construction or renovation. Inorganic amendments like sand topdressing can be easily incorporated, but their benefits are not associated with increasing drought tolerance.

There have been some instances of organic compounds that have been incorporated into established turfgrass systems, with benefits lasting up to five years. However, limited information and research are available on the benefits of these compounds in water conservation. Amendments like zeolite and clay can bolster the ability of turf and other plants to withstand drought, potentially reducing water requirements (Miller, 2000). Other research investigated incorporating compost as a topdressing after hollow-tine aeration on Kentucky bluegrass and showed improved water retention and more-efficient water use (Johnson et al., 2009).

Nanocarbon is an emerging soil amendment derived from activated charcoal. In preliminary research reports from UCR, nanocarbon reduced bermudagrass water use by 35% (2021 UCR Turfgrass and Landscape Research Field Day Booklet). Nanocarbon enhances water and nutrient adsorption by increasing both the surface area of soil particles and contact with plant roots (Younas et al., 2021). Moreover, nano-biochar has been shown to improve photosystem function and increase protective enzymes in pear orchards subjected to drought conditions (Lyu et al., 2016).

Though the potential benefits of many soil amendments are intuitive, it’s important to remember they may not be cost-effective over large areas.

BENEFITS

Water Conservation

A list of product categories with the most potential for water conservation – as supported by research and practical application – is available in Table 1 along with cost estimates and potential water savings. Many of the products discussed above are not included and users should be thoughtful about any exceptional marketing claims not accompanied by independent, replicated and authenticated research. Also, be aware of product label maximums and the ill-advised repeated use of certain products, such as a single type of fungicide, when considering a product.

Many chemical interventions for drought management are cost-effective and can be easily integrated into existing turfgrass management programs, resulting in a seamless adoption of water-saving measures. However, the trade-off for ease of implementation means a smaller potential impact on water conservation relative to other improvements. Do not expect miracles.

Table 1. The estimated cost and potential water savings of chemicals that can reduce irrigation requirements.

Chemical Category	Application Cost ($/Acre)	Estimated Midpoint* Annual Cost for 25 Acres ($)	Estimated Water Savings in Treated Areas (%)	Typical Application Schedule
Fertilizers	50 to 90	21,000	5%	Monthly
Plant growth regulators	100 to 200	97,500	20%	Based on GDD or Biweekly
Soil surfactants	50 to 200	37,500	20%	Monthly
Colorants	50 to 90	21,000	5%	Monthly
Fungicides	200 to 500	227,500	10%	Biweekly

*Midpoint is the average of the highest and lowest cost per acre. Costs were estimated by talking to superintendents and sales representatives in the turf industry.

Cost and water savings in the table above are estimates and will vary at individual courses on account of many factors. The potential water savings for each product category noted in this table are not cumulative – applying two products will not necessarily increase the water savings from applying one. Costs assume yearlong use at the schedule in the far-right column, which may not be practical and might exceed product label specifications or logical best use considering issues like preventing the selection of fungicide-resistant pest populations.

While applying the products in this table may help courses save water, we are always faced with the question of return on investment. When making these applications, consider the cost versus likely benefits. For example, applying a soil surfactant or PGR will be a more cost-effective and proven method to conserve water than applying fungicides. The cost-benefit analysis should also include other strategies for water conservation. A course may be able to save more water at less cost using an entirely different approach than making chemical applications.

Improved Turfgrass Quality

Practices such as the application of growth regulators, nitrogen fertilizer and soil surfactants help to improve turf quality. These strategies help superintendents maintain healthier, more-resilient turfgrass that can withstand stress and recover quickly from adverse conditions. The integration of such practices into maintenance routines, along with proper irrigation and soil management, forms a comprehensive approach that maximizes the long-term benefits of improved turfgrass quality.

CONSIDERATIONS

Application Timing

To ensure the best results for any product, it is recommended to begin applications at least one to two months before environmental conditions occur that promote drought stress. It is important to note that recurring applications are necessary for the products in the table above. Additionally, recent research has explored PGR reapplication based on air temperature using growing degree-day models (Kreuser at al., 2017). Research suggests that similar models can be used for other products, as their degradation is also temperature dependent, but more validation is needed (Carlson & Kreuser, 2023).

Record-Keeping and Observations

Maintain a detailed record of all applications – including dates, product amounts, delivery parameters and observations, along with environmental conditions obtained from a weather station. Periodically review the results of the treatment applied. This will help track the effectiveness of the applications and any potential side effects from use. If necessary, adjust the application rates or timing, or switch products based on observations.

An excellent practice is to include a nontreated plot for comparison. This can be accomplished by leaving a nontreated, adjacent strip of turfgrass or by blocking the application in one to two spots with a small sheet of plywood or similar covering.

Nontreated check plots are a good way to evaluate the impact of any application.

Education

New products are continually being developed and existing products are often the subject of ongoing research, especially when there are claims of potential water savings. Continuously educate yourself about the latest research and developments in chemical mitigation for drought stress and water conservation in turfgrass. Attend workshops, regional field days, seminars and webinars to learn about new products, the latest findings and best practices.

Health and Environmental Impacts

All of the products described in this chapter have health and environmental risks if used improperly. To reduce risk, products must be used according to label instructions as well as local, state and federal regulations. Adhere to all requirements for pesticide applicator licenses and additional best practices for use, storage and handling of any products.

Unresolved Technical and Cost Factors

While many chemical products can temporarily relieve drought stress when used preventatively, they should not be a permanent solution. Further, many products have not undergone rigorous testing or evaluation, casting doubt on the veracity of claims. It's crucial for golf course superintendents to approach these products with caution, ensuring they are well informed about the potential risks and benefits.

TIPS FOR SUCCESS

Sound turfgrass management is the foundation for drought resistance.

Maintaining healthy turfgrass and providing the best possible soil conditions and growing environments is essential for promoting drought resistance. Chemical applications are part of turfgrass management and water conservation, but they are not an alternative to a well-rounded and holistic agronomic program.

Only consider products with claims based on unbiased research.

Plant growth regulators and soil surfactants offer the most potential for water savings among the chemicals used in turfgrass management. Colorants may make it easier to reduce overseeding and therefore water use. Review guides based on scientific literature and consult with technical experts and colleagues to choose suitable products with verified claims.

Using products on larger areas means more potential water savings and higher costs.

Many golf courses currently use some or all of the products described in this chapter, but the applications are typically focused on greens. While decreasing water use on greens may deliver better playing conditions, it will not substantially reduce total water use at the facility because of the relatively small area involved. Applications in fairways and rough have the potential to save more water, but also involve more expense. Keep in mind that as the cost of applications increases, money intended for water-saving efforts may be better spent in other ways.

Timing and application method matters.

An effective product may not yield the desired impact on water use if it is not applied properly or at the right time. Begin applications at least one to two months before drought stress is likely to develop, following label specifications. Pay special attention to post-application irrigation requirements. Products that are designed to improve water movement in the soil typically need to be watered-in thoroughly to achieve maximum effect.

Using a GPS-guided sprayer makes applications more accurate and efficient, which saves time and product.

Consider using a GPS sprayer to make applications more efficient and reduce application costs.

Chemical applications designed to reduce water use or improve drought resistance can be very expensive, especially over larger areas like fairways and roughs. GPS-guided sprayers are more accurate and efficient than traditional sprayers and can help save significant amounts of time and product, especially in large or complex application areas.

For soil surfactants, map and track volumetric water content with soil moisture sensors.

Tracking VWC before and after applying soil surfactants will help you understand how to optimize their use and help you determine when a reapplication might be necessary. Ideally, place sensors in areas that represent typical moisture zones at your course, including areas that tend to be dry or water repellent.

REFERENCES

Carlson, M., & Kreuser, W. C. (2023). Longevity of a soil wetting agent can be quantified by air temperature based growing degree days [Abstract]. *ASA, CSSA, SSSA International Annual Meeting,* St. Louis, MO. https://scisoc.confex.com/scisoc/2023am/meetingapp.cgi/Paper/150027

Duncan, R.R., Carrow, R.N., & Huck, M.T. (2009). *Turfgrass and landscape irrigation water quality: Assessment and management.* CRC Press.

Fidanza, M., Kostka, S., & Bigelow, C. (2020). Communication of soil water repellency causes, problems, and solutions of intensively managed amenity turf from 2000 to 2020. *Journal of Hydrology and Hydromechanics,* 68, 306-312.

Glinski, D.S., Carrow, R.N., & Karnok, K.J. (1992). Iron fertilization effects on shoot/root growth, water use, and drought stress of creeping bentgrass. *Agronomy Journal,* 84(3), 496-503.

Harivandi, M.A., & V.A. Gibeault. (1990). Managing turfgrasses during drought. California Cooperative Extension.

Harivandi, M.A., Butler, J.D., & L. Wu. (1992). Salinity and turfgrass culture. In D. V. Waddington, R. N. Carrow & R. C. Shearman (Eds.) *Turfgrass* (Series 32, pp. 207–229). American Society of Agronomy.

Jespersen, D., Yu, J., & Huang, B. (2017). Metabolic effects of acibenzolar-S-methyl for improving heat or drought stress in creeping bentgrass. *Frontiers in Plant Science,* 8, 1224.

Johnson, G.A., Qian, Y.L., & Davis, J.G. (2009). Topdressing Kentucky bluegrass with compost increases soil water content and improves turf quality during drought. *Compost Science & Utilization,* 17(2), 95-102.

Kopp, K.L., & Jiang, Y. (2013). Turfgrass water use and physiology. In J.C. Stier, B.P. Horgan, & S.A. Bonos (Eds.), *Turfgrass: Biology, use, and management* (pp. 319-345). ASA, SSSA & CSSA.

Kreuser, W. C., Young, J. R., & Richardson, M. D. (2017). Modeling performance of plant growth regulators. *Agricultural & Environmental Letters,* 2(1), 170001.

Leinauer, B., Barrick, T., Serena, M., Schiavon, M., Maier, B., & Robertson, C. (2012). Usefulness of non-chemical water conditioners for managing turfgrasses and their rootzones. *Applied Turfgrass Science,* 9(1), 1-11.

Lyu, S., Du, G., Liu, Z., Zhao, L., & Lyu, D. (2016). Effects of biochar on photosystem function and activities of protective enzymes in *Pyrus ussuriensis* Maxim. under drought stress. *Acta Physiologiae Plantarum,* 38, 1-10.

McCarty, L. B., Gann, J. R., Wells, C. E., & Gerard, P. D. (2014). Creeping bentgrass field response to pigment-containing products. *Agronomy Journal,* 106(4), 1533-1539.

McCarty, L., Gore, A., Brown, P., Martin, S. & Wells, C. (2017). Potential health benefits of pigment-containing products on creeping bentgrass and hybrid bermudagrass. *International Journal of Plant & Soil Science,* 15(3), 1-13.

Miller, G. L. (2000). Physiological response of bermudagrass grown in soil amendments during drought stress. *HortScience,* 35(2), 213-216.

Montgomery, J. F. (2018). The Impacts of *Biochar on Turfgrass Health and Drought Tolerance*. [Doctoral dissertation, University of California, Riverside]. UC Riverside Electronic Theses and Dissertations.

Nolan, G., & Fidanza, M. (2024). Evaluation of two soil surfactants for soil water management of creeping bentgrass on a wettable clay loam rootzone during an imposed dry-down period. *Journal of Environmental Horticulture,* 42, 40-45.

O'Brien, D., Fidanza, M., Kostka, S., & Richardson, M. (2023). Penetrants vs. retainers: Understanding wetting agent claims and the science behind them. *USGA Green Section Record,* 61(10).

Schiavon, M., Orlinski, P., Petelewicz, P., Pudzianowska, M., & Baird, J. H. (2019). Effects of trinexapac-ethyl, surfactant, and nitrogen fertilization on bermudagrass water use. *Agronomy Journal,* 111(6), 3057-3066.

Schiavon, M., Petelewicz, P., Orlinski, P. M., & Baird, J. H. (2022). Effects of fungicides on creeping bentgrass health and rooting characteristics under abiotic stress. *International Turfgrass Society Research Journal*, 14(1), 893-901.

Schiavon, M., & Serena, M. (2023). Advances in irrigation and water management of turfgrass. In Fidanza, M. (Ed.), *Achieving sustainable turfgrass management* (pp. 157-196). Burleigh Dodds Science Publishing. Cambridge, UK.

Schiavon, M., Shaddox, T.W., Williams, K.E., Gallo, S., Boeri, P.A., Unruh, J.B., Kruse, J., & Kenworthy, K. (2023). Nitrogen requirements for deficit-irrigated bermudagrass (*Cynodon* spp.) fairways in South Florida. *Journal of Agronomy and Crop Science,* 209(1), 1-11.

Shahrokhi, M., Tehranifar, A., Hadizadeh, H., & Selahvarzi, Y. (2011). Effect of drought stress and paclobutrazol-treated seeds on physiological response of Festuca arundinacea L. Master and Lolium perenne L. Barrage. *Journal of Biological and Environmental Sciences,* 5(14).

Shekoofa, A., Rosas-Anderson, P., Carley, D.S., Sinclair, T.R., & Rufty, T.W. (2016). Limited transpiration under high vapor pressure deficits of creeping bentgrass by application of Daconil-Action. *Planta,* 243, 421-427.

Thompson, C., Guertal, E., McGroary, P., Soldat, D., & Hopkins, B.G. (2023). Considerations with soil testing in turfgrass. In M. Fidanza (Ed.), *Achieving sustainable turfgrass management* (pp. 625-646). Burleigh Dodds Science Publishing. Cambridge, UK.

Throssell, C. (2005). GCSAA-USGA Wetting Agent Evaluation. *Golf Course Management,* 73(4), 52–91.

Trenholm, L.E., Lickfeldt, D.W., & Crow, W.T. (2005). Use of 1, 3-dichloropropene to reduce irrigation requirements of sting nematode-infested bermudagrass. *HortScience,* 40(5), 1543-1548.

United States Golf Association (USGA) Staff. (2018). Understanding Wetting Agents: USGA Green Section Collection. *USGA Green Section Record,* 56(9), 1-66.

Vaughn, S. F., Dinelli, F. D., Jackson, M. A., Vaughan, M. M., & Peterson, S. C. (2018). Biochar-organic amendment mixtures added to simulated golf greens under reduced chemical fertilization increase creeping bentgrass growth. *Industrial crops and products,* 111, 667-672.

Younas, A., Rashid, M., & Fiaz, S. (2021). Role of nanotechnology for climate resilient agriculture. In *Engineering Tolerance in Crop Plants Against Abiotic Stress* (pp. 101-124). CRC Press.