LONG-TERM DYNAMICS AND MANAGEMENT REQUIREMENTS OF SANDCAPPED FAIRWAYS

A THESIS

by

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ABSTRACT

As golf course irrigation water quality continues to decline, sand-capping of golf course fairways is increasing. Capping of degraded golf course fairways with a layer of sand to promote better turfgrass health, performance, and playability is becoming a common practice where irrigation water is of poor quality, usually high in sodium. Benefits of sand-capping include improved surface drainage and increased infiltration rates, greater rooting depth, improved traffic tolerance and playing conditions, alleviated compaction, enhanced ability to flush salts from the upper root zone, and improved soil structure (White, 2013). However, over time, unique management challenges may arise, including organic matter accumulation, surface hydrophobicity, and subsoil permeability issues, especially where irrigation water contains elevated levels of sodium. Our results indicate that capping depth plays a critical role in turfgrass quality, volumetric water content, sorptivity, percent green cover, sodium adsorption ratio, hydrophobicity of the surface, organic matter content, and thatch depth with the shallower capping depths often outperforming the deeper capping depths. Our results indicate that gypsum applications are affective at reducing sodium adsorption ratio (SAR) in sand-capped systems and that while wetting agent applications are important, they may only be necessary in deeper capping systems. Our results indicate that the more aggressive cultural practices lead to a short-term reduction in turfgrass quality but provide a greater turfgrass quality later into the season. Our results suggest that moisture is potentially a key factor in how these capping depths perform regarding the parameters measured. The research-based information learned from this study will help turfgrass professionals best

manage their sand-cap systems in the future and will be utilized when constructing future/renovating established turfgrass systems.

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NOMENCLATURE

ET_o	Evapotranspiration
%GC	Percent Green Cover
NDVI	Normalized Difference Vegetation Index
OM	Organic Matter
pH	-log [Hydrogen ion concentration]
SAR	Sodium Adsorption Ratio
SF	Surface Firmness
U	Infiltration Rate
Tc	Turfgrass warm season crop coefficient
TD	Thatch Depth
TD 5	Topdressed 5
TQ	Turfgrass Quality
USGA	United States Golf Association
VWC	Volumetric Water Content
WDPT	Water Drop Penetration Time
+WA	Wetting Agent
-WA	No Wetting Agent
+WP	Worm Power
-WP	No Worm Power

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

The golf industry is an 84-billion-dollar industry that continues to expand as the game progresses. Roughly, 24 million people play golf each year in the United States totaling over 400 million rounds played annually (National Golf Foundation, 2019). Golf's estimated outreach, defined as anyone who plays, watches, or reads about golf, is 107 million, roughly 1 of every 3 Americans (National Golf Foundation, 2019). The turfgrass industry in the United States also accounts for approximately 500,000 jobs (Haydu et al., 2008). As the game adapts to accommodate the number of golfers and the desires of golfers to have ideal course conditions, there is a greater demand to provide exceptional playing conditions from golf course superintendents. The United States Golf Association understands the needs for the game and has funded more than 40 billion dollars, dating back to 1920, towards projects to provide research-based information for golf course superintendents to utilize in their turfgrass management programs (USGA.org).

Golf course superintendents face a number of agronomic challenges when trying to manage their course, but arguably one of the greatest is providing high quality turfgrass when using poor irrigation water quality. As water becomes more limiting the need to irrigate with reclaimed water is rapidly increasing (Carrow et al., 2008). Reclaimed water often contains high levels of sodium and bicarbonates along with many other undesirable components (Carrow and Duncan, 1998). Sodic soils have poor structure due to dispersion of soil particles, caused by attached sodium ions, leading to restricted water intake and drainage (Davis et al., 2003). Sand-capping of golf course fairways with a layer of sand to promote better turfgrass health, performance, and playability is becoming a common practice where irrigation water is of poor quality, usually high in sodium. Sand-capping is defined as placing a defined layer of sand atop the existing soil. Sand-capping may also be referred to as plating and originated in the 1990's in the Northwestern United States to aid in playability following high rainfall events. Benefits of sand-capping include improved surface drainage and increased infiltration rates, greater rooting depth, improved traffic tolerance and playing conditions, alleviated compaction, enhanced ability to flush salts, and improved soil structure (White, 2013). However, over time, unique management challenges may arise, including organic matter accumulation, surface hydrophobicity, and declining permeability of the subsoil, especially where irrigation water contains elevated levels of sodium.

Irrigation Water Quality

As watering restrictions become more common, there is a need for an alternative water source for golf course irrigation (Carrow et al., 2008). Reclaimed water use for golf course irrigation has increased substantially in recent years. Currently, approximately 35% of irrigation water used on golf courses in the Southeast and Southwest United States is reclaimed water (GCSAA, 2015). Reclaimed water often contains high levels of salts, particularly sodium and bicarbonates, which can have a detrimental effect on turfgrass health. The accumulation of sodium over time can lead to sodium toxicity, nutrient deficiencies, and high pH; all of which can make plant growth challenging (Carrow and Duncan, 1998). Sodium can displace beneficial cations on soil particles leading them to disperse and lose their structure. Loss of soil structure can lead to many agronomic issues such as reduced permeability of subsoil, restricted rooting, reduced drainage, and anaerobic conditions (Carrow and Duncan, 1998). One common metrics used to measure sodium concentrations in soil is Sodium Adsorption Ratio (SAR) (Davis et al., 2003). Sodium adsorption ratio is simply the ratio of sodium (Na) ions to calcium (Ca) and magnesium (Mg) ions in a saturated soil paste. As sodium increases, overall SAR increases. An SAR greater than 9 in irrigation water can lead to problematic uses regarding permeability. An SAR greater than 13 in soil can lead to loss of soil structure and reduce water infiltration (Davis et al., 2003). When bicarbonate and carbonate levels are high, adjusted SAR may be used when determining sodium hazard. The formula for SAR can be seen below:

$$SAR = \frac{Na}{\frac{\sqrt{Ca + Mg}}{2}}$$

Leaching of salts is more attainable in sand-based, rather than clay, systems due to greater macropore space (Carrow and Duncan, 1998). Therefore, sand-capping is a plausible solution to help flush salts through the rootzone.

Managing Sodic Soils

There is limited research-based information on managing sodicity in turfgrass systems irrigated with recycle water (Mancino and Kopec, 1989). When managing sodic soils, there are typically three options to choose from. The first option is changing the plant species to a more salt tolerant species (Davis et al., 2003). While this is an effective approach, it is not suitable for turfgrass environments when a certain plant species is needed in order to provide the necessary playing conditions desired. The second option is changing the variety to a more salt tolerant variety (Davis et al., 2003). This option is a potential option for turfgrass managers as there are some grass varieties, such as seashore paspalum, that are more salt tolerant. The problem with this approach is that the new variety may not provide the desired playing conditions and is not economically feasible for most golf courses removing it from consideration. The third option is amending or changing the soil with calcium (Mancino and Kopec, 1989). This option is the most commonly used approach when managing sodic soils but is deemed the most challenging as well. When attempting to change the soil, the idea is replace the Na ions attached to soil particles with Ca (Mancino and Kopec, 1989). Following displacement, sodium can be leached from the system from irrigation or rainfall. There are two common options when attempting to displace sodium with calcium. The first option is to dissolve any calcium carbonate ($CaCO_3$) or gypsum ($CaSO_4$) that already exist in the soil with application of sulfur or sulfuric acid. The second option is to add calcium in the form of gypsum (Snyder, 2017). After applying gypsum, there must be sufficient irrigation and time to dissolve the gypsum and leach the sodium out of the profile.

Organic Matter Accumulation - Wetting Agents

Another area of concern in sand-capped turfgrass systems is the rapid development of OM leading to hydrophobic conditions in the thatch layer resulting in reduced water infiltration and overall poor turfgrass quality. Hydrophobicity develops when organic compounds with water repellent properties buildup on and between soil particles (Dekker et al., 2009). One solution to managing hydrophobic conditions is the use of wetting agents. Studies have shown wetting agents play a critical role in many golf course superintendent's management plans with 87% of superintendents using wetting agents on a routine basis in their maintenance program with another 11% using them under certain conditions (Karnok et al., 2004). Wetting agents are used for managing localized dry spots, improving infiltration and drainage, moving pesticides through the profile, reducing dew accumulation, improving irrigation efficiency, reducing compacted soils, and reducing damage from fungal diseases such as fairy ring (Karnok et al., 2004; Kaminski and Han et al., 2010). Wetting agents fall under the surfactant's category meaning they cause a physical change at the liquid's surface by reducing the surface tension of the liquid (Karnok et al., 2004). Reducing the surface tension allows the liquid to spread and penetrate easier. There are several different surfactant chemistries including anionic and blends with anionics, nonionic surfactants, and cationic surfactants (Zontek and Kostka, 2012). Most wetting agents used in turfgrass are nonionic surfactants (Karnok et al., 2004). Wetting agents help bond water molecules with the organic coating that is present on the soil particle allowing the soil to become wet essentially "bridging" the gap between the hydrophobic organic compounds and water molecule (Karnok et al., 2004). OARS PS is a common nonionic surfactant used in golf course management that aids in soil water repellency, enhances moisture uniformity, improves water management efficiency, and increases water penetration into the soil profile (Aqua-Aid Solutions, Rocky Mount, NC).

Organic Matter Accumulation - Cultivation

Another concern with the rapid accumulation of organic matter is the buildup of the thatch layer. Thatch is a mixed layer of living and dead tissue that builds up between the grass blade and soil surface. Thatch builds up due to an imbalance of growth and breakdown of organic material (Murray and Juska, 1977). There are several factors that affect organic matter buildup including grass species, plant growth and decay rate, biological activity, cultivation practices, and environmental conditions (Gaussoin et al., 2013). Thatch provides benefits to turfgrass systems, but excess can be problematic. Beneficial aspects of thatch include soil temperature moderation by acting as a buffer, reducing weed populations, and increasing traffic tolerance (Beard, 1973; Butler, 1965). Problems resulting from excessive thatch buildup include reduction in aesthetics of the turf, increased pest problems, and reduction of water infiltration (Murray and Juska, 1977). Increased accumulation of organic matter can also lead to reduced surface firmness, resulting in a spongy thatch layer leading to soft playing conditions that reduce ball bounce and roll which affect playability (White, 2013).

There are a variety of cultural practices that are used in turfgrass systems to aid in the reduction of thatch. Examples of common methods to control thatch are routine topdressing with sand, core aerification with removal of plugs and replacement with sand backfill, and verticutting (Beard, 1973). Topdressing is essentially making applications of sand and grooming it into the canopy over time. Topdressing aids in smoothness for ball roll, thatch dilution, turfgrass recovery, increased firmness, and improved root zones (Lowe, 2015). Topdressing has been reported to be the most effective method but can be quite expensive, so it is not always an option for turfgrass managers (Murray and Juska, 1977). Due to this, thatch management programs often use core aerification, verticutting, and combinations of the two practices. Core aerification and verticutting have been used since the 1940s and are still staple practices in management plans today (Turgeon and Fidanza, 2007). Verticutting and core aerification have been reported to both significantly reduce organic matter content in the thatch layer by 23% and 12%, respectively (Snyder, 2017). Core aerification involves removing soil cores from the turfgrass system. Core aerification enhances gas flow to and from the soil, increases water infiltration, stimulates root and shoot growth, aids in thatch dilution, and improves drainage (Turgeon and Fidanza, 2007). Verticutting is mowing with vertical blades that slice into the turfgrass canopy. Verticutting aids in thatch removal, increases turfgrass density by creating new points of growth, increases firmness, enhances gas flow, and increases water infiltration rates (Trenholm et al., 2000). Turfgrass managers use combinations of core aerification and verticutting extensively today. Reports have shown that the best thatch removal programs consist of verticutting and core aerating immediately following verticutting (Foy, 1991). These aggressive management practices often injure the turf substantially but within three weeks often provide an excellent healthy turfgrass surface. Hybrid bermudagrasses, such as Tifway

419, require intensive cultural management practices for the best overall turfgrass health and playability (Foy, 1991). Verticutting twice annually has been reported to reduce thatch levels by 8% in Tifway Bermudagrass (Carrow et al., 1987).

Soil Amendments - Vermicompost

There are many soil amendments used in turfgrass management today for a variety of purposes, including vermicompost (Gardner et al., 2004). Vermicompost is derived from earthworm castings and is applied to increase soil organic matter, enhance soil structure, and enhance cation exchange capacity (Tajbakhsh et al., 2011). Vermicompost has also been shown to enhance turfgrass quality (Gardner et al., 2004). As the negative public perception of chemicals used in agriculture increases, organic amendments are gaining interest (Tajbakhsh et al., 2011). Worm Power is a vermicompost product used in the turfgrass industry. Proposed benefits of Worm Power include improved soil health, enhanced microbial communities, enhanced plant growth, enhanced uptake of nutrients, and enhanced water-holding capacity (Aqua-Aid Solutions, Rocky Mount, NC). Worm Power has been shown to increase Normalized Difference Vegetation Index (NDVI) values, which is often used as an additional measure of turfgrass quality. Worm Power has been shown to have sufficient microbial activity within the product that is similar to what is found in natural turfgrass systems (Aqua-Aid Solutions, Rocky Mount, NC).

The United States Golf Association has recommendations for sand-based root systems for putting greens, but they do not have recommendations for sand-capping of golf course fairways, roughs, or tees (United States Golf Association, 2004). Currently, soil physical testing laboratories use assumptions from the USGA putting green recommendations, particle size analyses, and moisture release curves to recommend the proper depth required for a particular sand. A previous sand-capping study showed that the recommended depth for a given particle size is not always accurate and can actually do more harm than good (Dyer, 2017). Due to its short history of existence, there are not many publications to aid in providing the best long-term management practices for sand-capped golf course fairways. Our goal is to provide research-based information for golf course superintendents to utilize when managing their sand-capped turf systems. Areas of importance from an agronomic research standpoint could include 1) Determining the efficacy of gypsum application regimes on subsoil sodicity (SAR) levels under a high-Na irrigation source across four sand-cap depths (TD 5, 5, 10, and 20 cm), 2) Determining the efficacy of monthly wetting agents on surface hydrophobicity, 3) determining the efficacy of individual and combined treatments on turfgrass performance (TQ, %GC, %VWC, sand-cap SAR, subsoil SAR, infiltration rate, and WDPT, 4) Determining the effects of monthly Worm Power applications on surface organic matter accumulation and thatch management, 5) determining the efficacy of secondary cultural practices (untreated, verticutting, core aerification, and verticutting + core aerification) on surface organic matter accumulation and thatch depth, 6) Determine the efficacy of individual and combined treatments on turfgrass performance (TQ, SF, %GC, infiltration rate, TD, and %OM).

CHAPTER II

SODICITY AND HYDROPHOBICITY MANAGEMENT IN SANDCAPPED FAIRWAYS

Overview

Sand-capping of golf courses and sports fields is becoming a common practice, especially where irrigation water contains elevated levels of sodium that have degraded native soils over time. Reported benefits of sand-capping include improved drainage and increased infiltration rates, improved root development, improved playing conditions, alleviated compaction, enhanced ability to flush salts, and improved soil structure. Over time, management issues may develop in sand-capped systems, two of which include loss of subsoil permeability due to Na, as well as accumulation of surface organic matter and hydrophobic conditions, which restrict water movement into the soil profile. The objectives of this study were to evaluate the individual and combined effects of gypsum and wetting agent application programs on mitigation of long-term surface hydrophobicity and subsoil sodicity issues in sand-capped ‘Tifway’ Bermudagrass (*Cynodon dactylon x C. transvalensis* Burt. Davy) systems. Studies were conducted over two-years on sand-capped plots ranging in depth from 5 to 20 cm. Results demonstrate that capping depth plays a critical role in overall turfgrass quality, percent green cover, soil water relations, and development of surface hydrophobicity, with shallower capping depths (5 and 10 cm) outperforming deeper capping depths (20 cm) for almost all parameters. While wetting agent applications help to increase surface soil moisture, they appear to only be necessary for deeper capping depths, as little to no hydrophobicity was observed with shallower capping depths. Results also showed that a single yearly application of a high rate (490 g m^{-2}) of annual gypsum rate is most effective at reducing SAR under high Na-irrigation water.

Introduction

Sand-capping, also referred to as ‘plating’, is defined as placing a defined layer of sand atop the existing subsoil. The concept originated in the 1990’s in the Northwestern United States to combat poor golf course playing conditions created by high annual rainfall, including compacted soils, poor aeration, slow drainage, and saturated soils (White, 2013). Ultimately, poor playability due to frequent rainfall events results in fewer rounds of golf played and less revenue for golf courses.

Sand-capping can be accomplished through a heavy topdressing over time or through initial construction/renovation (White, 2013). Typically, money is the driving factor behind which option is chosen for sand-capping. Sand-capping an 18-hole golf course through initial construction or renovation can cost over $1 million dollars depending on the quantity and quality of sand used. Due to this heavy upfront cost, many golf courses opt to use sub-optimal amounts of sand, producing a shallower than often recommended sand-cap (White, 2013). However, there is concern that this may lead to agronomic problems over time. Another approach that is taken by many golf course superintendents is to build up a sand-capped layer over time through topdressing, which may be more economically feasible on a per-year basis.

More recently, sand-capping has been proposed as a construction/renovation technique for combatting effects of poor-quality irrigation water. Elevated salinity, sodium, and bicarbonate levels are common concerns when poor quality water is used for managing turfgrass (Carrow et al., 2008). Over time, native soils irrigated with water sources high in sodium can become degraded and difficult to manage due to loss of permeability. Sand-capping of sodium-degraded golf course fairways to promote improved turfgrass health, performance, and playability has also become a fairly common practice, especially in regions of the country utilizing recycled wastewater. Benefits of sand-capping include improved drainage and increased infiltration rates, greater rooting depth, improved traffic tolerance and playing conditions, alleviated compaction, enhanced ability to flush salts, and improved soil structure (White, 2013). However, over time, unique management challenges may arise in sand-capped turfgrass systems, including organic matter accumulation, surface hydrophobicity, and subsoil permeability issues resulting from elevated levels of sodium in irrigation (White, 2013).

Sodic soils are primarily characterized by poor structure due to dispersion, caused by sodium ions attached to the soil particles, which lead to restricted water intake and drainage (Davis et al., 2003). Plants grown on sodic soils may also experience sodium toxicity, nutrient imbalance/deficiencies, and high pH, all of which can make plant growth for turfgrass challenging. As a result, when managing sodic soils, it is important to incorporate amendments that displace sodium from soil particles and replace it with calcium. This can be achieved through applying gypsum ($CaSO_4$) (Cisar and Snyder, 2003). While potentially costly, gypsum applications can help to mitigate Na effects in sand-capped systems, especially within the subsoil, that arise due to constant use of sodium-laden irrigation water.

The use of wetting agents to combat hydrophobic soils and to aid in water infiltration and moisture retention has become another common practice in managed turfgrass systems such as golf courses and athletic fields (Laha et al., 2009). Turfgrass soils can become hydrophobic over time due to decomposition of organic matter, and often times sandy soils are more prone to water repellency (Karnok et al., 2004). Hydrophobicity develops when organic compounds with water repellent properties accumulate on and between soil particles (Dekker et al., 2009). Wetting agents help reduce surface tension of liquids allowing them to spread and penetrate easier.

Along with alleviating hydrophobicity, it has been suggested that wetting agents may also aid in the movement of products such as fungicides or insecticides down into the soil profile, and this has led to many turfgrass managers applying wetting agents just before or in combination with fungicide applications (Latin and Ou, 2018). However, recent studies suggest that wetting agents have little to no effect on fungicide distribution (Latin and Ou, 2018; Ou, 2018). There is currently limited research on whether wetting agents could aid in the movement of soil amendments such as gypsum, deeper into the soil profile to help eliminate sodicity challenges. This information could be important to understand sand-capped systems, especially since the underlying subsoil is often more prone to permeability loss from Na than the sand-capped layer itself (Obear and Soldat, 2014).

While the United States Golf Association has developed recommendations for sand-based root zones, currently there are no recommendations for sand-capping of golf course fairways, roughs, or tees (United States Golf Association, 2004). Soil physical testing laboratories use assumptions from the USGA putting green recommendations, particle size analyses, and moisture release curves to recommend the proper depth required for a particular sand. Due to its short history of existence, there are limited publications to aid in the long-term management of sand-capped systems for golf course fairways, tee, and roughs. A research-based approach to addressing long-term management challenges of sand-capped turfgrass systems is therefore needed at this time.

The objectives of this study were to evaluate the individual and combined effects of gypsum and wetting agent application programs on mitigation of long-term surface hydrophobicity and subsoil sodicity issues in sand-capped ‘Tifway’ Bermudagrass (*Cynodon dactylon x C. transvalensis* Burt. Davy) fairway systems.

Material and Methods

Study Design and Treatment Layout

This research was conducted at the Scotts Miracle-Gro Facility for Lawn and Garden Research at Texas A&M University in College Station, TX from June 2018 to November 2019. The roughly 9,300 m^2 sand-cap research facility was constructed and established to Tifway bermudagrass (*Cynodon dactylon x C. transvalensis* Burt. Davy) in 2014 along a north-south running 1-2% slope. This study was conducted on the south half of the facility, which is sand-capped atop a Boonville fine sandy loam (fine, smectitic, thermic, Chromic Vertic Albaqualf) with pH 8.1 and containing 15% clay, 20% silt, and 65% sand in the surface 30 cm that lies atop clay. The subsoil was graded so that it exhibited a 1.5% east-to-west slope to aid in drainage away from the facility. This enhanced drainage across the facility by directing the water to drainage ditches that were installed.

The study was arranged in a split plot design with 3 replicate plots. Sand-cap depth including topdressed 5 (TD 5= topdressed 2.54 cm/year over 2 years), 5, 10, and 20 cm as the whole plot factor. Whole plots (3.7 m x 15.2 m) were then split into subplots (3.7 m x 7.6 m) receiving wetting agent (OARS PS, Aqua-Aid Solutions, Rocky Mount, NC) applied at 0 and 0.002 L m^{-2} $month^{-1}$ from April through November. Wetting agent was applied to plots using a spray hawk calibrated to deliver 0.08 L m^{-2}. Subplots were further divided into sub-subplots (1.2 m x 7.6 m) receiving 3 gypsum treatments using Verdecal G (Aqua-Aid Solutions, Rocky Mount, NC) applied at 0 g m^{-2} monthly = untreated, 49 g m^{-2} monthly (totaling 490 g m^{-2}), and 490 g m^{-2} applied once annually during early spring. The pelletized gypsum was applied with a drop spreader just prior to a regularly scheduled irrigation event.

Irrigation Practices

Plots received irrigation from April through November, at levels needed to supply warm-season crop coefficient ($Tc=0.6 \times ET_o$), based on historical ET_o from the Texas ET Network for College Station, TX. Precipitation volumes were recorded and irrigation was adjusted to ensure the turfgrass was receiving the desired amount of water. Effective rainfall was calculated based on the method recommended by Texas A&M AgriLife Extension (2015), which assumed the first 25 mm of rainfall in an event to be 100% effective, subsequent rainfall <50 mm to be 67% effective, and rainfall >50mm to be 0% effective. Irrigation water at the site originates from a municipal groundwater source with high levels of sodium and bicarbonates (pH 8.1, Na 300 mg kg^{-1}, HCO_3^- 500 mg kg^{-1}, SARadj = 23 meq L^{-1}).

Cultural Management Practices

Plots were mowed 2-3 times weekly at a 1.3 cm height of cut using a Toro Reelmaster mower with clippings were left on the plots. Nitrogen was applied at a 4.9 g m^{-2} every 6 weeks from May through September across all plots using a 21-7-14 fertilizer which contained 25% sulfur urea (American Plant Food Corp., Galena Park, TX). No other micronutrients were applied as soil analyses indicated levels were sufficient. Plots were verticut once in August of both years at roughly 0.6 cm depth using a Jacobsen walk behind verticutting unit with 2.5 cm spacing. After verticutting was finished, debris was blown off the plots using a backpack blower. Immediately following verticutting, plots were core aerated with a walk behind John Deere aerification unit removing 2.5 cm plugs using 1 cm tines at 3.2 cm spacing. A backpack blower was used to remove any debris that had accumulated on the surface of the plots.

Evaluations of Turfgrass Quality and Percent Cover

Turfgrass Quality was assessed in all plots biweekly throughout the growing season in 2018 and 2019 using a visual quantitative measuring system with a scale from 1-9 for turfgrass quality (Morris and Shearman, 1998). A minimum score of 6 was used to indicate acceptable turfgrass quality. Light box images were taken for all plots biweekly throughout the growing season in 2018 and 2019. Turf Analyzer software (Green Research Services, LLC, Fayetteville, AR) was used to identify percent green cover through digital image analysis (Karcher and Richardson, 2013; Karcher et al., 2017). A minimum of 75 percent green cover was used to indicate acceptable percent green cover.

Soil Moisture

Volumetric Water Content measurements for the 0-5 cm depth, were taken for all plots biweekly throughout the growing season in 2018 and 2019 using a Dynamax TH_2O Portable Soil Moisture Meter (Dynamax Inc., Houston, TX) containing a Theta Probe (Delta-T Devices, Cambridge, England) (Miller and Gaskin, 1999). Two measurements were taken per plot on the day prior to irrigation, with the average recorded.

Sand-Cap and Subsoil Sodium Adsorption Ratio

Samples for both the sand-cap layer (mixture of the entire layer) and the upper 2.5 cm of the subsoil beneath were taken bimonthly in 2018 and 2019 for determination of sodium adsorption ratio (SAR) within the 10 and 20 cm capping depth plots. Samples were submitted to the Texas A&M Agrilife Extension Service Soil, Water and Forage Testing Laboratory for SAR analysis (Rhoades and Clark, 1978).

Measurement of Infiltration Rate

Infiltration rates were measured bimonthly throughout the growing season in 2018 and 2019 using the double-ring Turf-Tec Infiltrometer (Turf-Tec International, Tallahassee, FL). The inner and outer ring diameter of the Infiltrometer is 6 cm and 10.8 cm, respectively. The Infiltrometer penetrated 5 cm into the surface. Measurements were obtained within the plots capped with 10 and 20 cm sand. Both rings of the Turf-Tec Infiltrometer were completely filled with water. A stopwatch was then used to determine the time required for 25.4, 50.8, and 76.2 mm (1, 2, 3 inch) cumulative depth of water to infiltrate, and those times were recorded. Two measurements were obtained per plot and averaged.

Infiltration rates slowed over time and can be modeled with the equation of $I=Ut^{0.70}$. The decline in infiltration rate is attributed to be due to the general decline over time in porous media (Phillip, 1957) or due to the measurements being made with a declining head of water (Nimmo et al., 2009). The value of U was determined by regressing I on $t^{0.70}$, with an intercept set to 0. U can be used as in indicator of infiltration rate and can be used to estimate the amount of time needed for a known amount of water to infiltrate (i.e., $t=(I/U)^{1/0.70}$). At initiation of the measurement there is 76.2 mm head of water which decreases over time to 0 mm. For example, the amount of time required to infiltrate 25.4, 50.8, and 76.2 mm water given U=3.50mm·$s^{-0.70}$ would be 8, 15, and 22 s, respectively. For example, the amount of time required to infiltrate 25.4, 50.8, and 76.2 mm water given U=0.56mm·s$^{-0.70}$ would be 48, 94, and 132 s, respectively. An example of a high U value (3.498) is located on the left side of the figure below while a slow U value (0.560) is located on the right side of the figure (Figure 2.0).

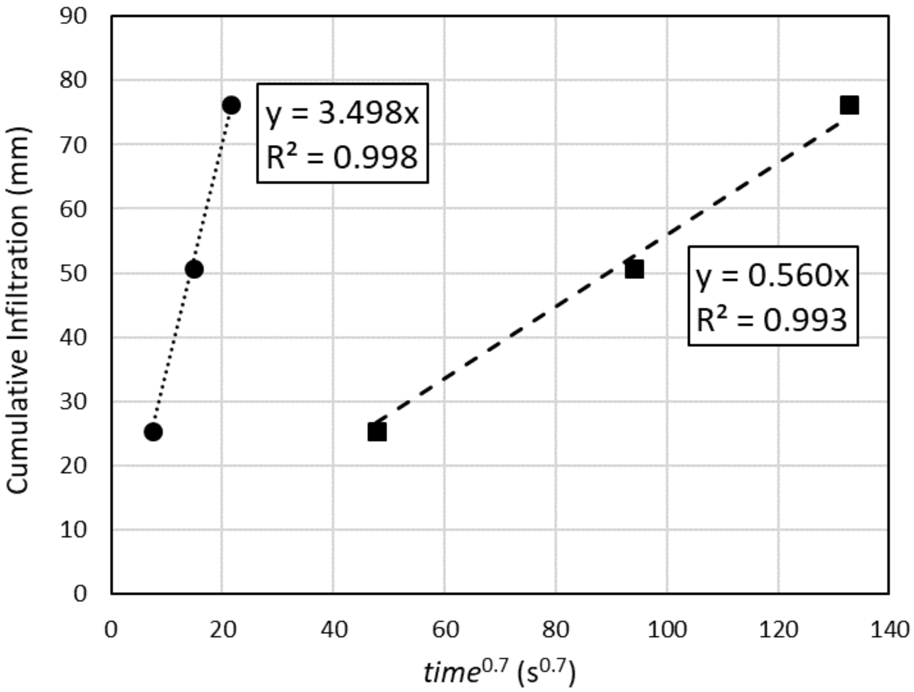


Figure 2.0 (above). Cumulative infiltration (mm) plotted over time (s$^{0.7}$).

U will be used to reference short-term infiltration rate, since the rates decreased similarly over time regardless of treatment.

Sand-Cap Hydrophobicity Testing

Water Droplet Penetration Time tests were conducted for all plots monthly throughout the growing season in 2018 and 2019 to determine the degree of hydrophobicity (Dekker et al., 2009). Measurements were obtained within all plots at depths of 1.3 cm, 3.8 cm, and 7.5 cm. Using a soil core sampler, three 2.5 cm diameter cores were removed from each plot. Following removal, a dropper was used to place a drop of distilled water at each of the three depths. A stopwatch was used to record the length of time it took for the drop to infiltrate at each depth the sample. Three cores were removed from each plot with all readings averaged to determine relative hydrophobicity at each depth.

Data Analysis

At the conclusion of the project, all data were subjected to analysis of variance (ANOVA) procedures using the general linear procedures of SPSS (IBM, Armonk, NY). Where significant treatment x year interactions were detected, data were presented separately by year. Where appropriate, means were compared using Fishers LSD test ($P \leq 0.05$).

Results

Site Environmental Conditions

Rainfall at the site was high in 2018, exceeding 1278 mm compared to the historical average of 1016 mm. The month of August produced the least amount of rain only totaling 5.1 mm (Table 2.1). Rainfall was the highest during October, with 355.3 mm of precipitation (Table 2.1). Coinciding with low precipitation, August also produced the highest reference evapotranspiration rates, averaging 6.4 mm per day (Table 2.1). August was also the hottest month, producing an average high temperature of 34.7 °C (Table 2.1).

Rainfall at the site was lower than usual in 2019, at 857 mm compared to the historical average of 1016 mm (Table 2.2). The month of July produced the least amount of rain, totaling only 12.4 mm (Table 2.2). Rainfall was the highest during May, with 200.2 mm of precipitation (Table 2.2). Coinciding with low precipitation, July also produced the highest evapotranspiration rates averaging 6.1 mm per day (Table 2.2). August was the hottest month of 2019, with average high temperature of 35.2 ℃ (Table 2.2).

Table 2. 1 Weather data for 2018 at the Texas A&M Turfgrass Field Laboratory, College Station, TX. An on-site weather station was used to obtain all data and is a part of the Texas ET Network. Data are presented for January 2018 through December 2018.

Month	**Total ET_0**	**Daily ET_0**	**Total Precipitation**	**Average Temperature**			**Avg. Relative Humidity**	**Avg. Windspeed**
				Mean	**Low**	**High**		
		mm			**°C**		**%**	**m/s**
January	72.3	2.3	28.2	7.3	2.4	13.9	56.2	2.4
February	58.1	2.1	43.2	12.1	9.0	16.8	78.9	2.7
March	131.1	4.2	148.1	17.3	12.3	23.2	59.2	2.8
April	136.0	4.5	43.2	17.2	12.2	23.6	60.5	2.6
May	169.9	5.5	60.2	24.7	20.4	30.4	64.6	2.2
June	180.4	6.2	62.0	27.6	23.8	32.7	66.1	2.7
July	197.0	6.4	44.5	28.3	24.0	34.4	60.7	1.9
August	199.2	6.4	5.1	28.4	23.9	34.7	59.1	2.2
September	105.4	3.5	157.5	24.9	22.6	29.3	75.3	1.6
October	89.4	2.9	355.3	19.7	16.6	24.7	75.8	2.0
November	67.8	2.3	101.9	12.1	8.2	17.5	68.4	2.1
December	65.0	2.2	228.6	10.6	6.9	15.4	65.5	2.5

Table 2. 2 Weather data for 2019 at the Texas A&M Turfgrass Field Laboratory, College Station, TX. An on-site weather station was used to obtain all data and is a part of the Texas ET Network. Data are presented for January 2019 through December 2019.

Month	**Total ET_0**	**Daily ET_0**	**Total Precipitation**	**Average Temperature**			**Avg. Relative Humidity**	**Avg. Windspeed**
				Mean	**Low**	**High**		
		mm			**°C**		**%**	**m/s**
January	65.3	2.1	113.5	9.1	5.3	14.6	66.9	2.4
February	64.2	2.3	50.0	11.7	8.8	16.4	74.2	2.7
March	107.2	3.5	26.9	14.1	10.0	19.4	62.1	2.8
April	127.9	4.4	143.5	18.6	14.0	24.5	66.6	2.8
May	130.8	4.8	200.2	23.8	20.6	28.2	74.8	2.7
June	160.4	5.4	119.4	26.0	21.4	31.0	71.7	2.5
July	189.5	6.1	12.4	27.6	23.7	32.9	63.5	2.3
August	183.3	5.9	25.1	29.1	25.0	35.2	61.7	1.6
September	148.1	5.0	47.5	27.3	23.3	33.2	63.2	1.7
October	114.2	4.9	71.4	19.6	14.9	26.2	63.1	2.0
November	70.0	2.3	35.6	12.9	7.6	19.5	66.6	2.0
December	64.6	2.2	11.7	11.2	6.1	18.1	62.6	1.9

Table 2. 3 Analysis of variance for measured parameters for the sandy loam subsoil study.

	TQ		**% GC**	**VWC**		**U**	**Sand SAR**	**Clay SAR**	**WDPT 1.3 cm**	**WDPT 3.8 cm**	
	2018	**2019**		**2018**	**2019**					**2018**	**2019**
Capping Depth (CD)	***	***	***	***	***	***	NS	**	***	***	***
Wetting Agent (WA)	NS	**	NS	*	*	*	NS	*	***	**	***
Gypsum (G)	NS	NS	NS	NS	*	NS	**	***	NS	NS	NS
Date (D)	***	***	***	***	***	***	***	***	***	**	***
CD x WA	*	***	NS	***	***	***	**	**	***	***	***
CD x G	NS	NS	NS	NS	NS	NS	NS	*	*	NS	NS
CD x D	***	***	***	***	***	***	NS	NS	***	***	***
WA x G	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
WA x D	NS	NS	NS	NS	NS	NS	NS	NS	***	**	***
G x D	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CD x WA x G	NS	*	NS	NS	NS	NS	NS	NS	*	NS	NS
CD x WA x D	NS	**	*	NS	NS	NS	NS	NS	***	***	***
CD x G x D	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
WA x G x D	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CD x WA x G x D	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS, *, **, *** Nonsignificant or significant at P = 0.05, 0.01, or 0.001

Turfgrass Quality

Based on ANOVA, there was a significant capping depth main effect on turfgrass quality in 2018 and 2019 (Table 2.3, Figures 2.1 and 2.2). In 2018, the topdressed 5 cm and 5 cm capping depths had the highest mean turfgrass quality followed by the 10 cm capping depth and lastly the 20 cm capping depth, respectively. Turfgrass quality ranged from 6.3 to 7.0, with all capping depths maintaining at or above the minimum acceptable turfgrass quality of 6.0.

In 2019, topdressed 5 cm (TD 5), 5 cm, and 10 cm capping depths showed significantly higher turfgrass quality than the 20 cm capping depths. Turfgrass quality ranged from 5.9 to 7.1 and the 20 cm capping depth failed to meet the minimum acceptable turfgrass quality of 6.0.

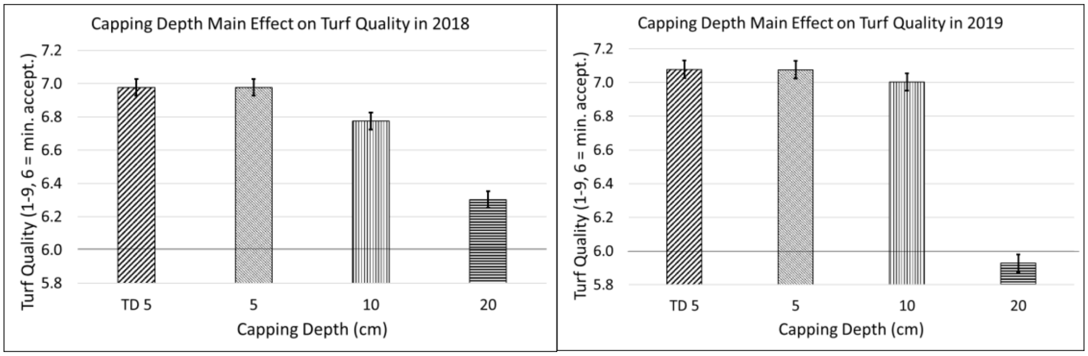


Figure 2.1 (left) and 2.2 (right). Turfgrass quality during 2018 and 2019 as affected by capping depth. Data are pooled across wetting agent and gypsum treatment. Turfgrass quality was evaluated using the NTEP visual 1-9 scale. Error bars indicate Fisher's LSD at P ≤ 0.05 centered on the means. A minimum acceptable turfgrass quality of 6.0 indicated by the horizontal line.

Based on ANOVA, there was a significant capping depth x date interaction on turfgrass quality in 2018 (Table 2.3; Figure 2.3). In 2018, nine of ten dates showed a significant capping depth effect on mean turfgrass quality. The TD 5 and 5 cm capping depths had the highest turfgrass quality, followed by the 10 and 20 cm capping depths. The 20 cm capping depth was the only depth that fell below the minimum acceptable turfgrass quality of 6.0, and did so on three different rating dates.

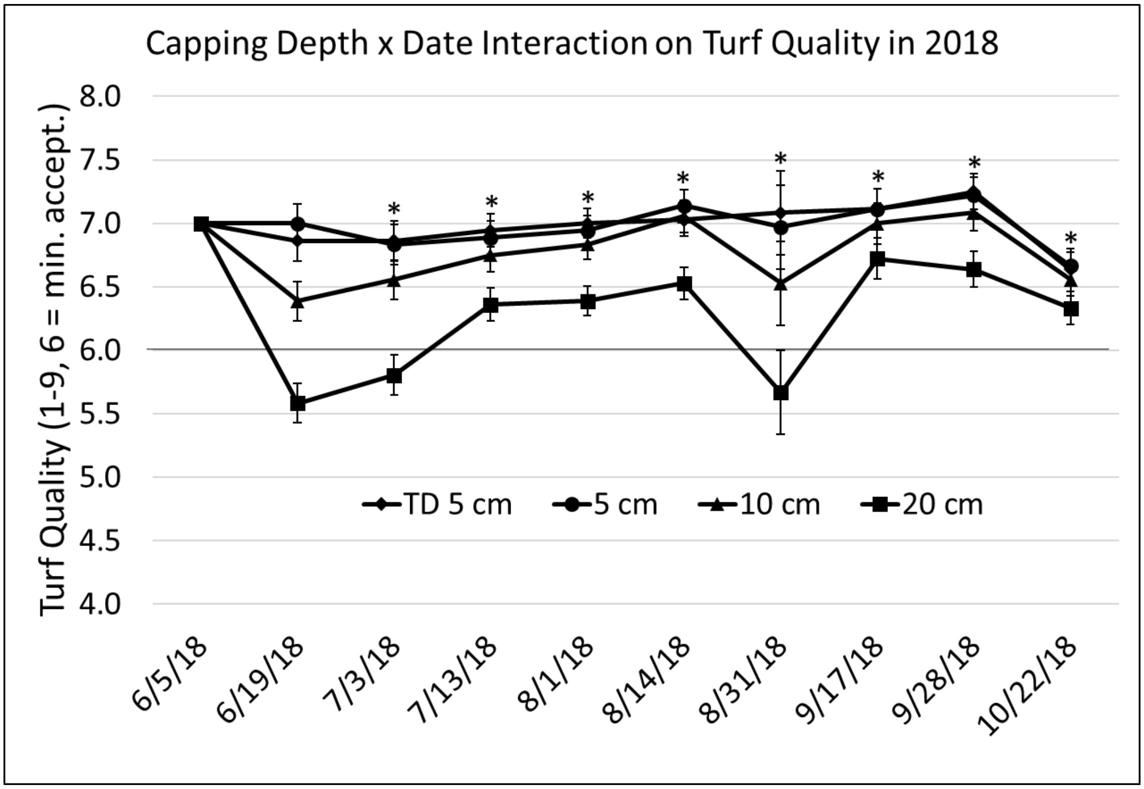


Figure 2.3. Turfgrass quality during 2018 as affected by capping depth x date interaction. Data are pooled across wetting agent and gypsum treatment. Turfgrass quality was evaluated using the NTEP visual 1-9 scale. Error bars indicate Fisher's LSD at $P \leq 0.05$. * indicates significant dates.

The ANOVA detected a significant wetting agent main effect on mean turfgrass quality in 2019 (Table 2.3; Figure 2.4). Plots that received wetting agent had significantly higher turfgrass quality than plots not receiving wetting agent. Both wetting agent treatments produced turfgrass quality that met the minimum acceptable turfgrass quality of 6.0.

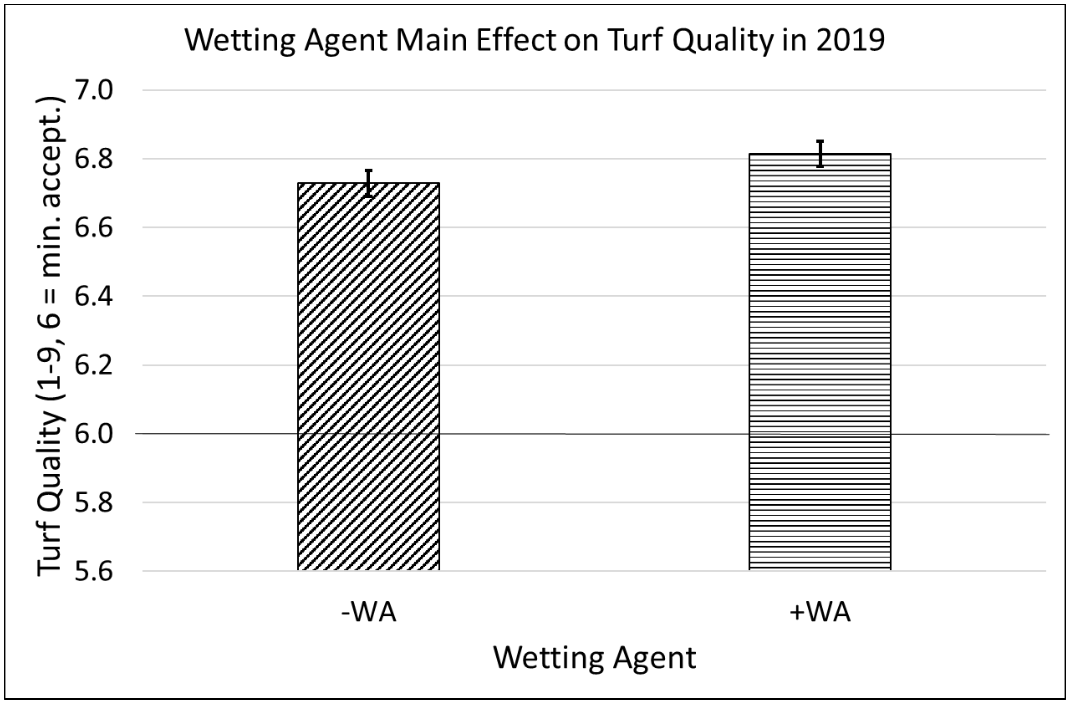


Figure 2.4. Turfgrass quality during 2019 as affected by wetting agent (WA). Data are pooled across capping depth and gypsum treatment. Turfgrass quality was evaluated using the NTEP visual 1-9 scale. Error bars indicate significant differences based on Fisher's LSD at $P \leq 0.05$. A minimum acceptable turfgrass quality of 6.0 indicated by the horizontal line.

The ANOVA detected a significant capping depth x wetting agent x date interaction on turfgrass quality in 2019 (Table 2.3; Figures 2.5, 2.6, 2.7 and 2.8). There was no significant capping depth x wetting agent x date interaction at the TD 5 cm, 5 cm, or 10 cm capping depths. At the 20 cm capping depth in 2019, plots that received wetting agent application had a significantly higher mean turfgrass quality than plots that did not receive a wetting agent application on four of ten rating dates. Plots receiving wetting agent application fell below the minimum acceptable turfgrass quality of 6.0 on only three of ten dates, while plots that did not receive wetting agent application fell below the minimum acceptable turfgrass quality on eight of ten dates.

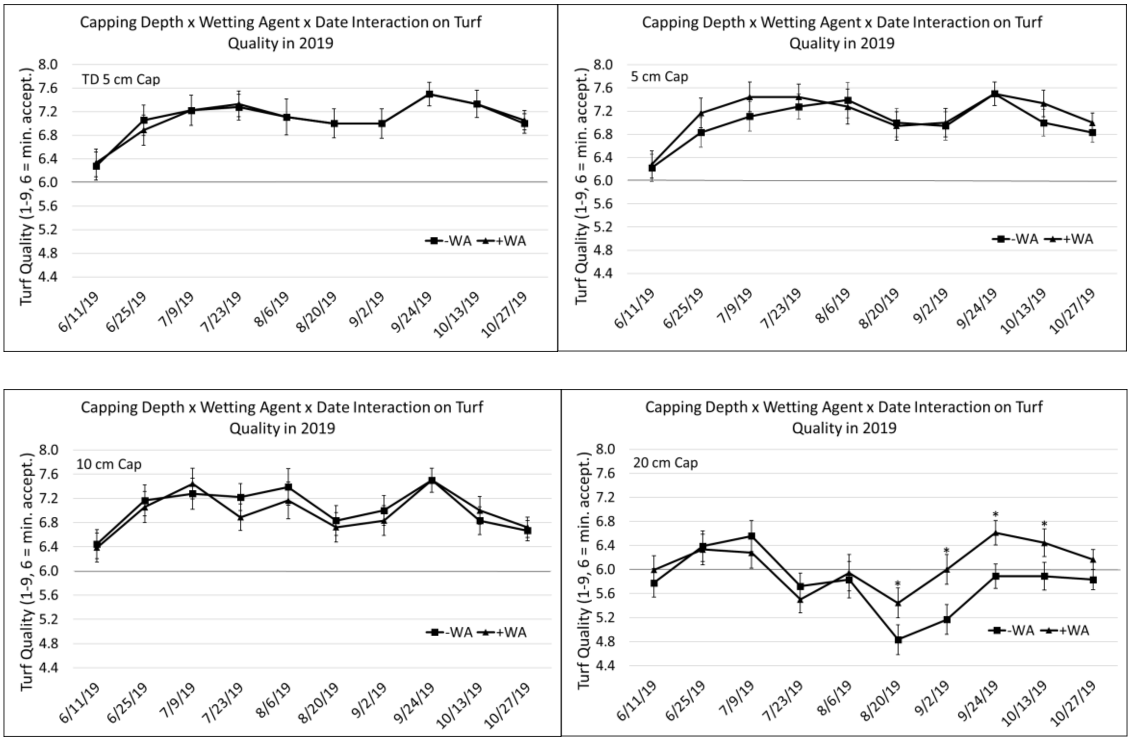


Figure 2.5 (upper left), 2.6 (upper right), 2.7 (lower left), and 2.8 (lower right). Data are pooled across gypsum treatment. Turfgrass quality during 2019 as affected by capping depth x wetting agent x date interaction. Turfgrass quality was evaluated using the NTEP visual 1-9 scale. Error bars indicate Fisher's LSD at P ≤ 0.05. * indicates significant dates.

Based on ANOVA, there was a significant capping depth x wetting agent x gypsum interaction on turfgrass quality in 2019 (Table 2.3; Figures 2.9, 2.10, 2.11, and 2.12). At the 20 cm capping depth in 2019, plots that did not receive a gypsum application but received wetting agent had significantly higher mean turfgrass quality than plots not receiving gypsum application or wetting agent application. Plots that did not receive a gypsum or wetting agent produced mean turfgrass quality below the minimum acceptable turfgrass quality of 6.0. This same general trend was also observed in plots that received the monthly gypsum applications, but was not significant.

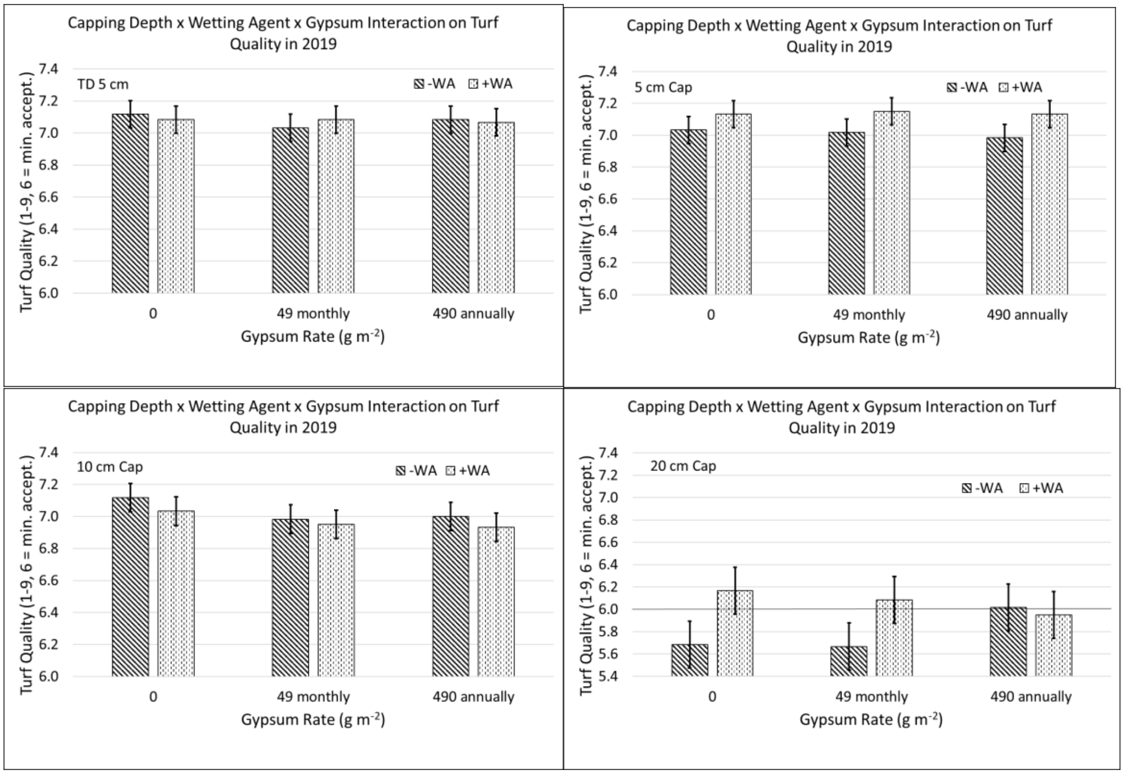


Figure 2.9 (upper left), 2.10 (upper right), 2.11 (lower left), and 2.12 (lower right). Turfgrass quality during 2019 as affected by capping depth x wetting agent x gypsum interaction. Turfgrass quality was evaluated using the NTEP visual 1-9 scale. Error bars indicate Fisher's LSD at $P \leq 0.05$. A minimum acceptable turfgrass quality of 6.0 indicated by the horizontal line.

Percent Green Cover

When pooled across years, wetting agent, and gypsum treatments, ANOVA showed a significant capping depth main effect on percent green cover (Table 2.3; Figure 2.13). The TD 5 cm capping depth treatment had the highest mean percent green cover followed by the 5 and 10 cm capping depth plots. The 20 cm capping depth plots held the lowest overall percent green cover. Percent green cover ranged from 70 to 79 percent, with the 20 cm capping depth being the only capping depth failing to meet the minimum acceptable percent green cover level of 75 percent.

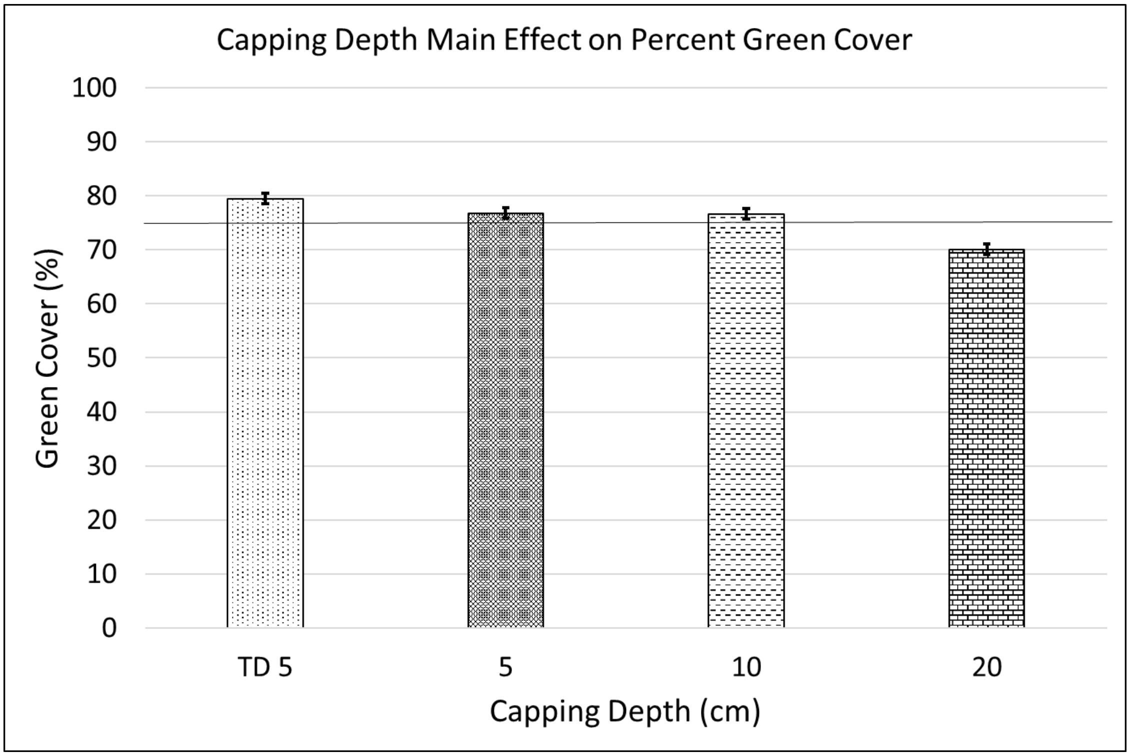
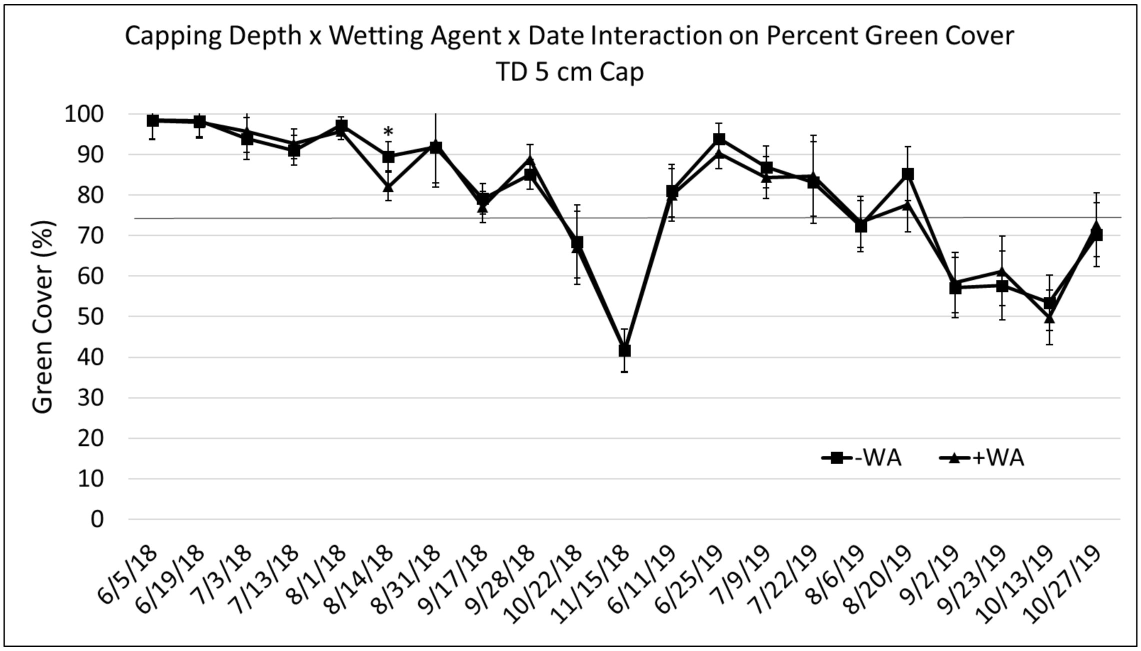


Figure 2.13. Percent green cover as affected by capping depth. Data are pooled across wetting agent, gypsum treatment, and year. Error bars indicate Fisher's LSD at P ≤ 0.05. The horizontal line indicates a minimum acceptable percent green cover of 75%.

The ANOVA showed a capping depth x wetting agent x date interaction for percent green cover during both years (Table 2.3; Figures 2.14, 2.15, 2,16, and 2.17). On 20 of 21 rating dates, the TD 5 cm capping plots that did not receive wetting agent had similar levels of percent green cover as plots receiving wetting agent. For 14 of 21 dates, mean percent green cover was above the minimum acceptable percent green cover of 75 percent, regardless of wetting agent treatment.

At the 5 cm capping depth, for 13 of 21 dates, mean percent green cover was above the minimum acceptable percent green cover of 75 percent, regardless of the application of wetting agent. At the 10 cm capping depth, mean percent green cover was above the minimum acceptable percent green cover of 75 percent on 15 of 21 rating dates, regardless of wetting agent treatment.

At the 20 cm capping depth, there were significant differences in percent green cover due to wetting agent treatment on four of 21 dates. For three of these dates, plots not receiving wetting agent showed higher percent green cover compared to plots receiving wetting agent. For 11 of 21 dates, plots not receiving a wetting agent showed percent green cover that was below the minimum acceptable level of 75 percent. For ten of 21 dates, plots receiving wetting agent exhibited mean percent green cover that was below the minimum acceptable percent green cover of 75 percent.



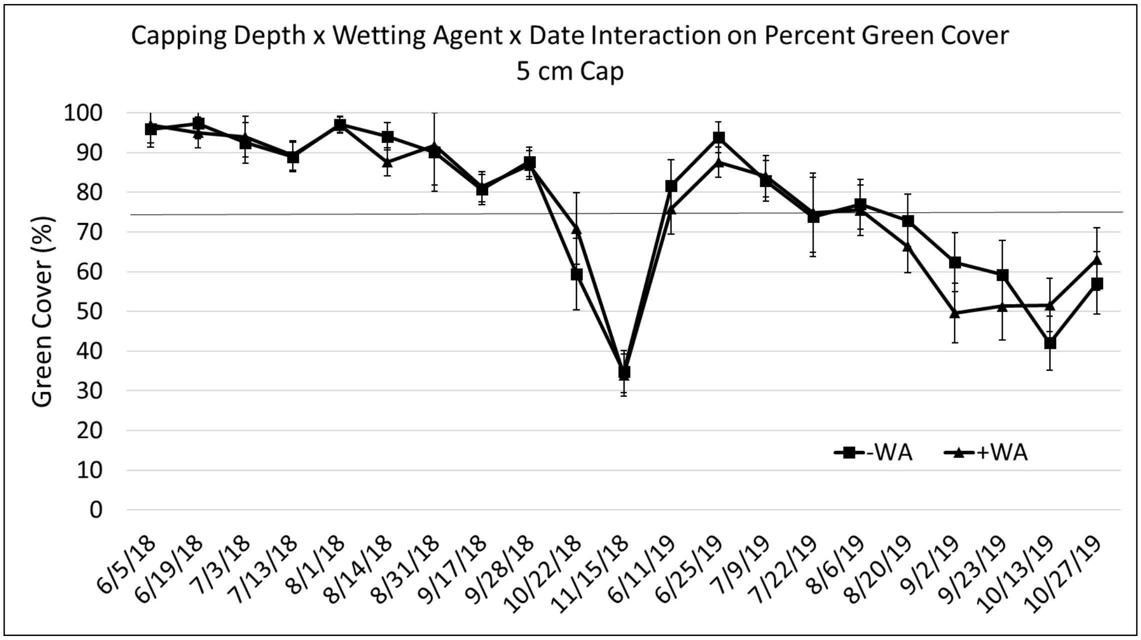
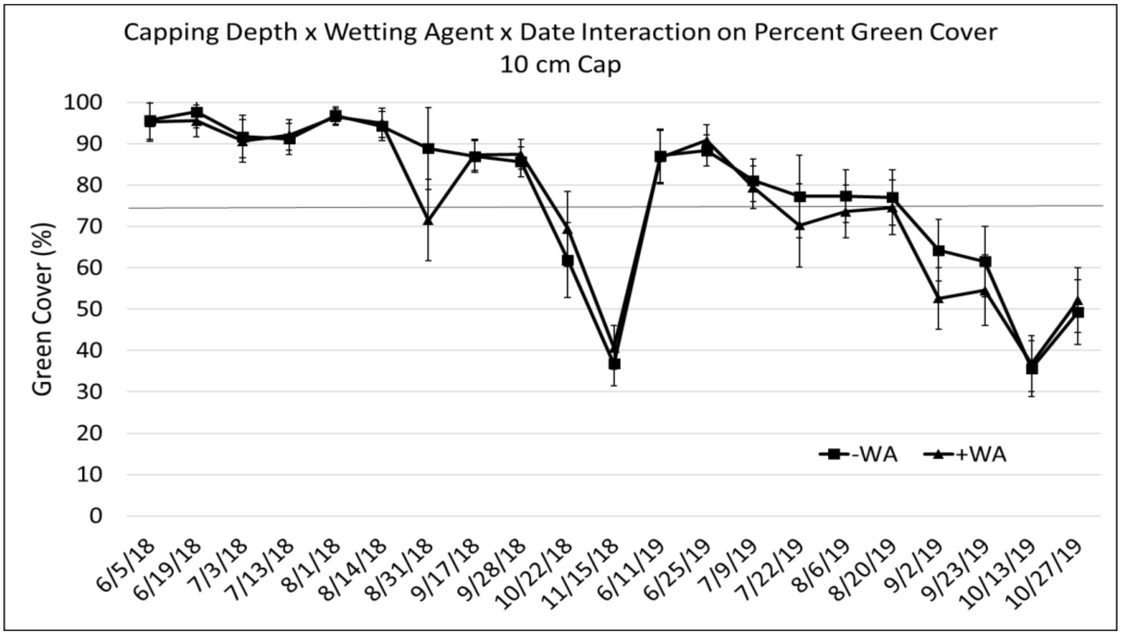


Figure 2.14 (upper) and 2.15 (lower). Percent green cover for the TD 5 cm (upper) and 5 cm (lower) capping depths as affected by wetting agent x date interaction over both years. Data are pooled across gypsum treatment. Error bars indicate Fisher's LSD at P ≤ 0.05. * indicates significant dates.



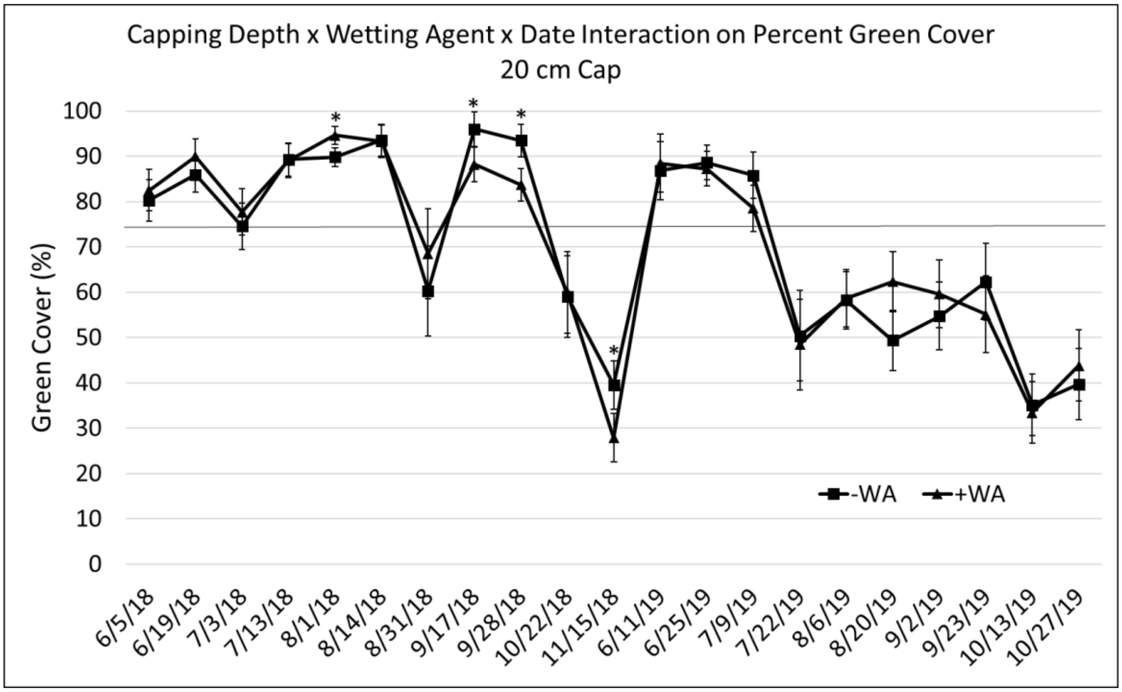


Figure 2.16 (upper) and 2.17 (lower). Percent green cover for the 10 cm (upper) and 20 cm (lower) capping depths as affected by capping depth x wetting agent x date interaction across both years. Data are pooled across gypsum treatment. Error bars indicate Fisher's LSD at P ≤ 0.05. * indicates significant dates.

Volumetric Water Content

ANOVA detected a significant capping depth main effect on volumetric water content (VWC) in both 2018 and 2019 (Table 2.3; Figures 2.18 and 2.19). In 2018, VWC at the 0-5 cm depth ranged from 12 to 26%. The topdressed 5 cm capping depth plots had the significantly highest mean VWC followed by the 5 cm, 10 cm, and lastly 20 cm capping depths. In 2019, VWC ranged from 13 to 32%. The TD 5 cm capping depth plots had the highest mean VWC, followed by the 5 and 10 cm capping depths. The 20 cm capping depth held the lowest mean VWC, averaging 13% across rating dates.

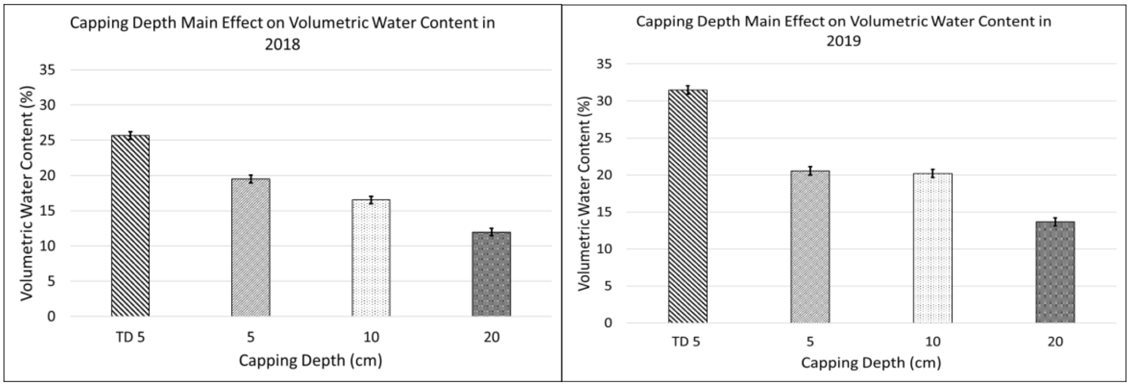


Figure 2.18 (left) and 2.19 (right). Volumetric water content at the 0-5 cm depth during 2018 and 2019 as affected by capping depth. Data are pooled across wetting agent and gypsum treatments. Error bars indicate Fisher's LSD at $P \leq 0.05$.

The ANOVA detected a significant capping depth x wetting agent interaction on VWC in 2018 and 2019 (Table 2.3; Figures 2.20 and 2.21). In 2018, there was no significance detected between treatments for VWC within the TD 5 cm or 5 cm capping depths, regardless of wetting agent treatment. Somewhat surprisingly, at the 10 cm capping depth in 2018, plots receiving no wetting agent had higher VWC than plots receiving wetting agent. The opposite was observed at the 20 cm capping depth in 2018, as plots that received wetting agent had significantly higher VWC than plots not receiving wetting agent. Plots that received wetting agent had VWC nearly 3 percent higher than plots not receiving wetting agent application. In 2019, there were no significance differences detected in VWC between TD 5 cm, 5 cm, and 10 cm capping depths, regardless of wetting agent treatment. At the 20 cm capping depth in 2019, plots that received a wetting agent application had significantly higher VWC than plots not receiving wetting agent. Plots that received wetting agent had VWC levels nearly 3 percent higher than plots not receiving wetting agent.

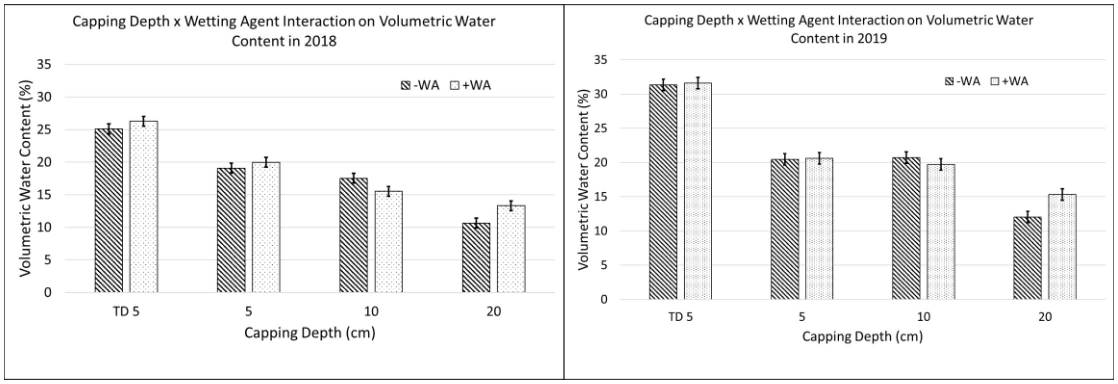


Figure 2.20 (left) and 2.21 (right). Volumetric water content in 2018 and 2019 as affected by capping depth x wetting agent interaction. Data are pooled across gypsum treatments. Error bars indicate Fisher's LSD at P ≤ 0.05.

ANOVA detected a significant capping depth x date interaction on VWC in both 2018 and 2019 (Table 2.3; Figures 2.22 and 2.23). In 2018 and 2019, all dates showed a significant capping depth effect on VWC. The general trend for both years was that the TD 5 cm capping depth plots had the highest VWC followed by the 5 cm, 10 cm, and 20 cm plots. In 2019, the 5 cm and 10 cm caps alternated back and forth regarding VWC but when referring back to the capping depth main effect (Figure 2.19), the 5 cm cap had a slightly higher VWC than the 10 cm cap.

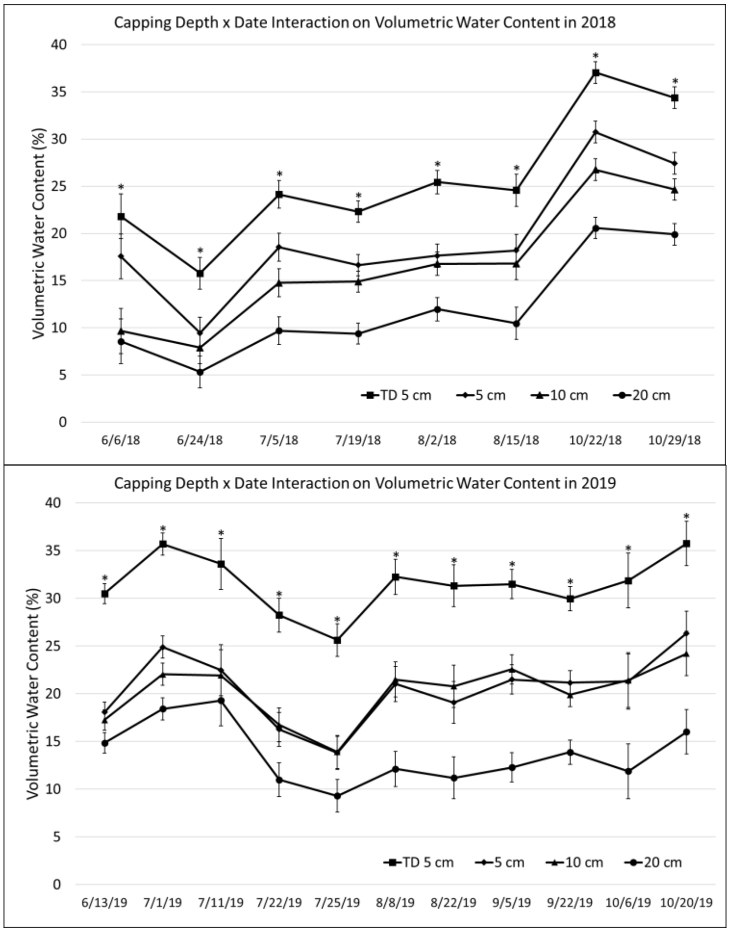


Figure 2.22 (upper) and 2.23 (lower) Volumetric water content at the 0-5 cm depth in 2018 and 2019 as affected by capping depth x date interaction. Data are pooled across wetting agent and gypsum treatments. Error bars indicate Fisher's LSD at $P \leq 0.05$. * indicates significant dates.

The ANOVA detected a significant wetting agent x gypsum interaction on VWC in 2019 (Table 2.3; Figure 2.24). Within plots that received wetting agent, split-plots that received the monthly gypsum applications had significantly higher VWC than untreated plots. There were no significant differences detected in VWC of plots not receiving wetting agent, regardless of gypsum treatment.

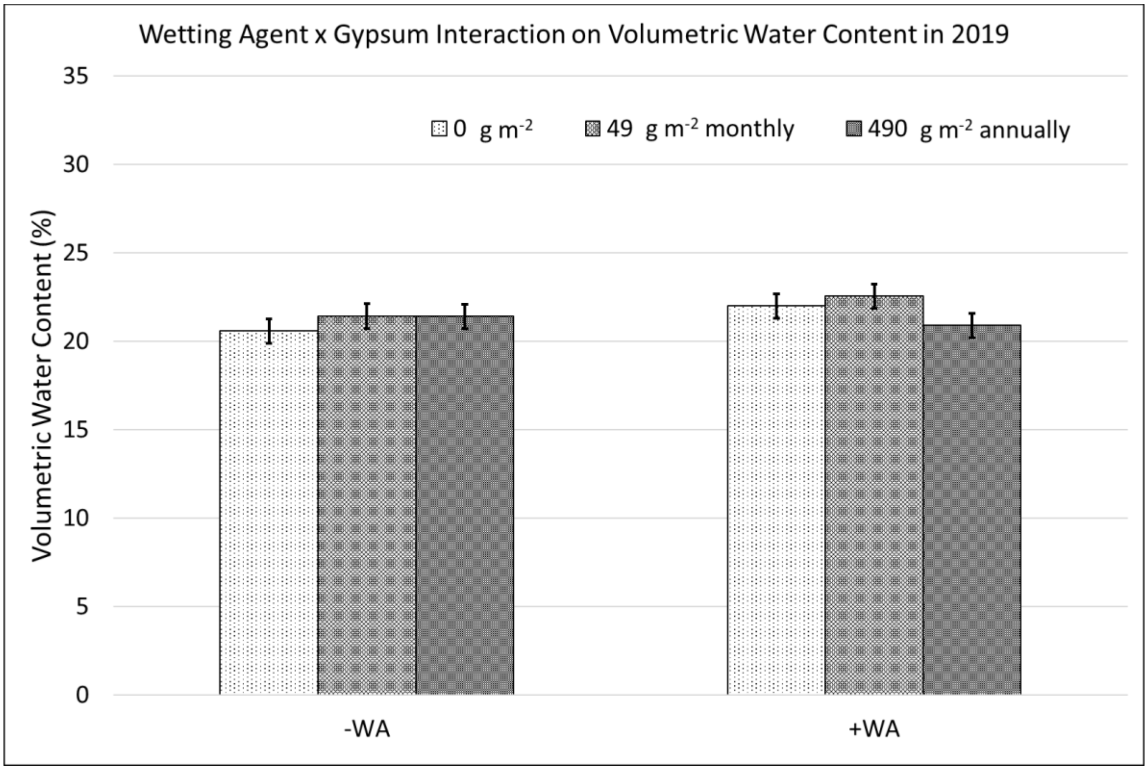


Figure 2.24. Volumetric water content in 2019 as affected by wetting agent x gypsum interaction. Data are pooled across capping depth. Error bars indicate Fisher's LSD at $P \leq 0.05$.

Infiltration Rates

The ANOVA detected a significant capping depth main effect on infiltration rate (Table 2.3; Figure 2.25). The 20 cm capping depth plots had significantly higher mean infiltration rates than 10 cm capping depth plots. When pooling across all wetting agent and gypsum treatments, infiltration rates for the 20 cm capping depth plots was 3.0 mm $s^{-0.70}$ compared with 2.4 mm $s^{-0.70}$ for the 10 cm capping depth plots.

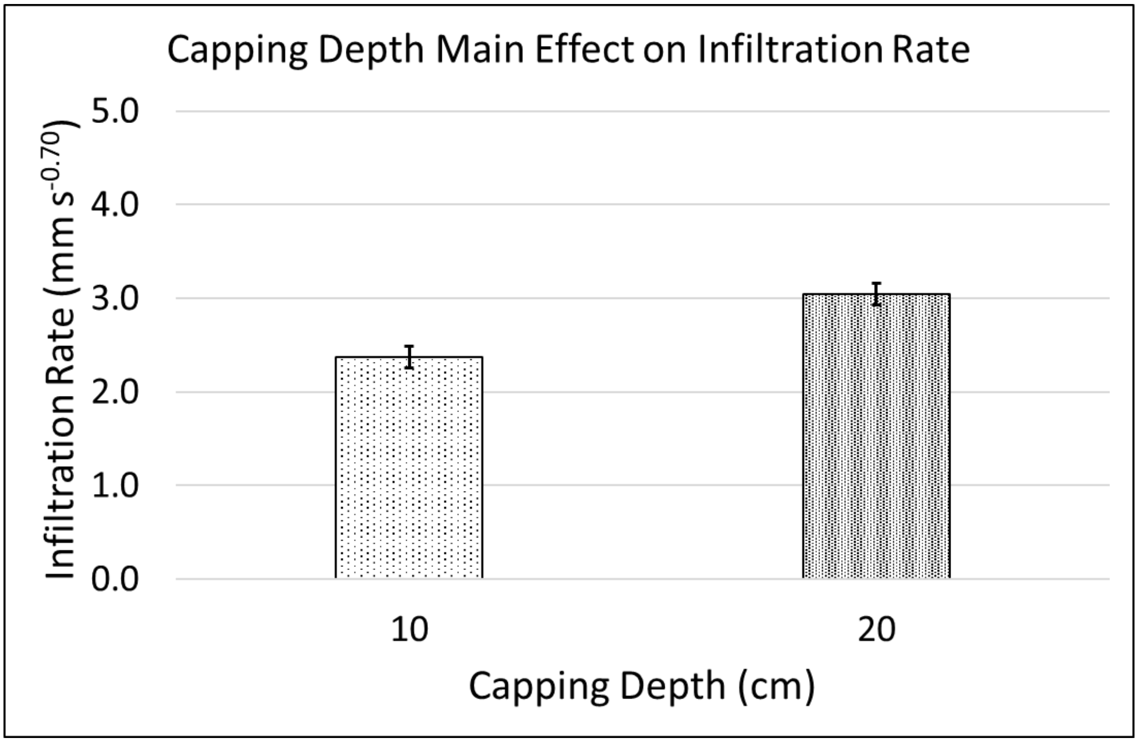


Figure 2.25. Infiltration rate as affected by capping depth. Data are pooled across years, wetting agent, and gypsum treatment. Error bars indicate Fisher's LSD at $P \leq 0.05$.

The ANOVA also detected a significant capping depth x wetting agent interaction on infiltration rate over both years (Table 2.3; Figure 2.26). At the 20 cm capping depth, plots receiving wetting agent had significantly lower infiltration rate than plots not receiving wetting agent application. When pooling across gypsum treatment and years, infiltration rate at the 20 cm cap in plots that received wetting agent was 2.7 mm $s^{-0.70}$ compared with 3.4 mm $s^{-0.70}$ for plots that did not receive wetting agent.

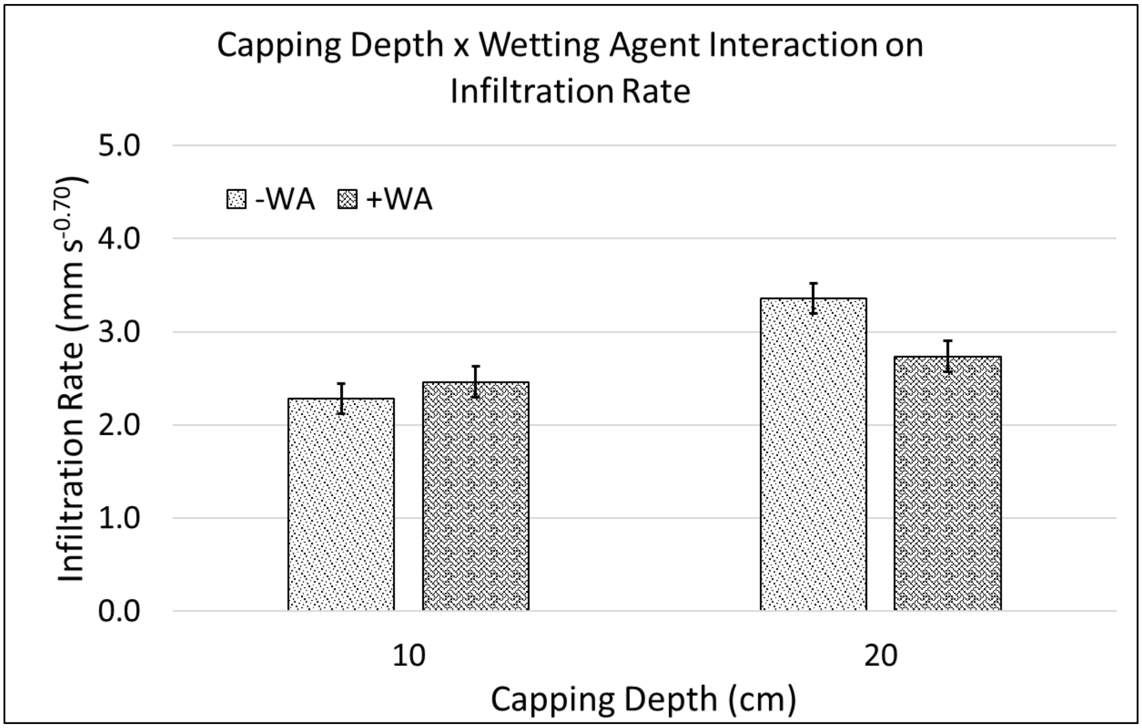


Figure 2.26. Infiltration rate as affected by capping depth x wetting agent interaction. Data are pooled across gypsum treatment and years. Error bars indicate Fisher's LSD at $P \leq 0.05$.

ANOVA detected a significant capping depth x date interaction on infiltration rate during both years (Table 2.3; Figure 2.27). Pooling data across both years, three of six dates showed a significant capping depth effect on infiltration rate, where the rate was significantly higher in the 20 cm capping depth plots compared to 10 cm capping depth plots.

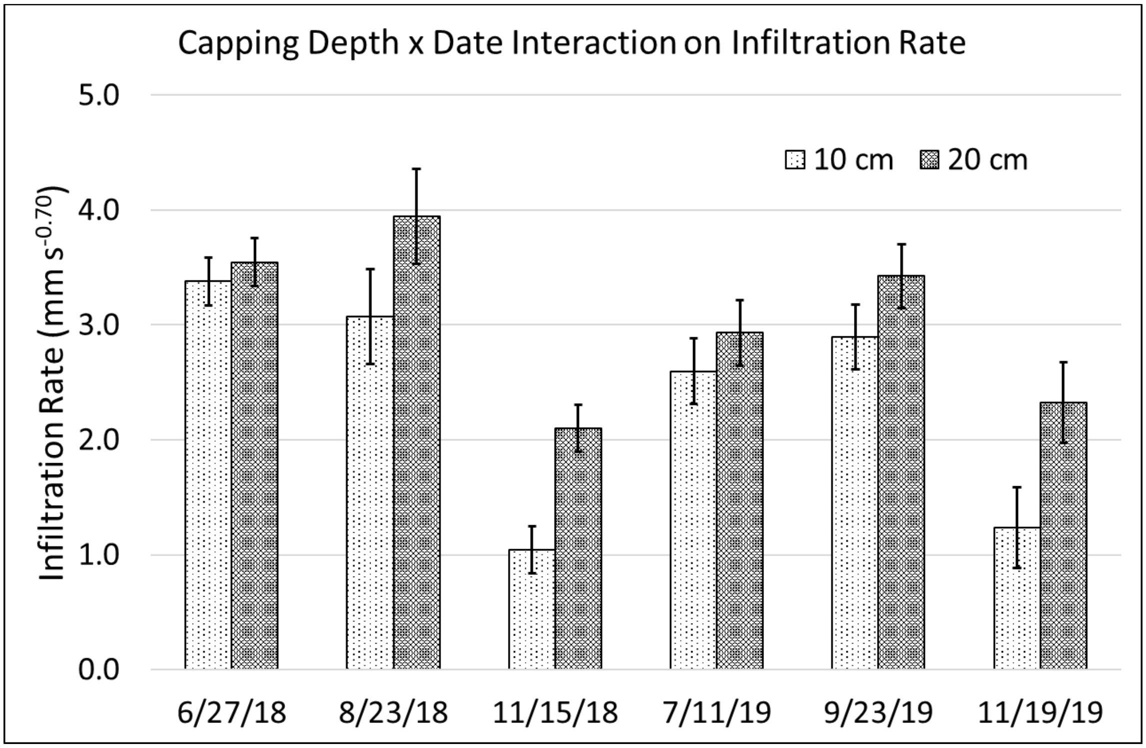


Figure 2.27. Infiltration rate as affected by capping depth x date interaction. Data are pooled across gypsum, wetting agent, and years. Error bars indicate significant differences based on Fisher’s LSD at $P \leq 0.05$. * indicates significant dates.

Sand-Cap Sodium Adsorption Ratio

Based on ANOVA, there was a significant gypsum main effect on sand-cap sodium adsorption ratio (SAR), when pooled across years (Table 2.3; Figure 2.28). Plots receiving the 490 g m^{-2} annual gypsum rate had significantly lower sand-cap SAR compared to plots that did not receive any gypsum applications. SAR was highest in untreated plots (4.0), followed by plots receiving monthly gypsum applications (3.4), and plots receiving the single annual application of gypsum 490 g m^{-2} (3.1).

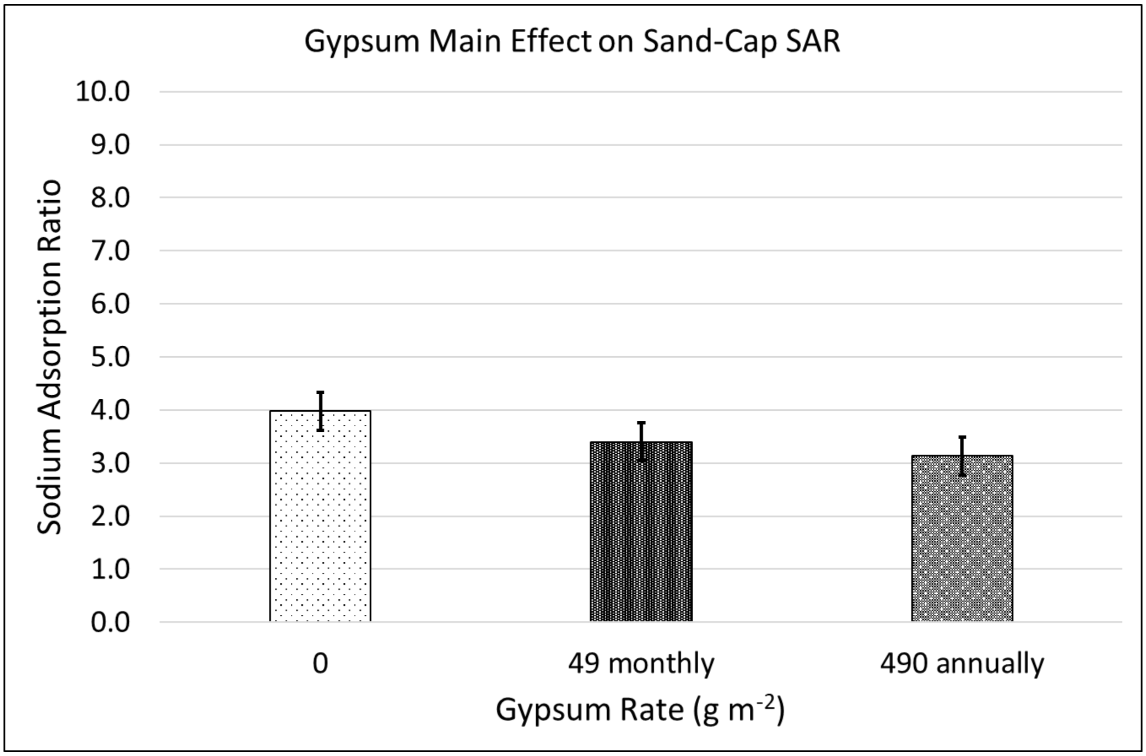


Figure 2.28. Sand-cap SAR as affected by gypsum treatment. Data are pooled across wetting agent treatment, capping depth, and years. Error bars indicate significant differences based on Fisher's LSD at P ≤ 0.05.

The ANOVA showed a capping depth x wetting agent interaction on sand-cap SAR, when pooled across years (Table 2.3; Figure 2.29). At the 20 cm capping depth, plots that received wetting agent application had significantly higher sand-cap SAR than plots not receiving wetting agent application. At the 20 cm capping depth, SAR in plots receiving wetting agent was nearly 4.0, compared to SAR of 3.1 in plots not receiving wetting agent application.

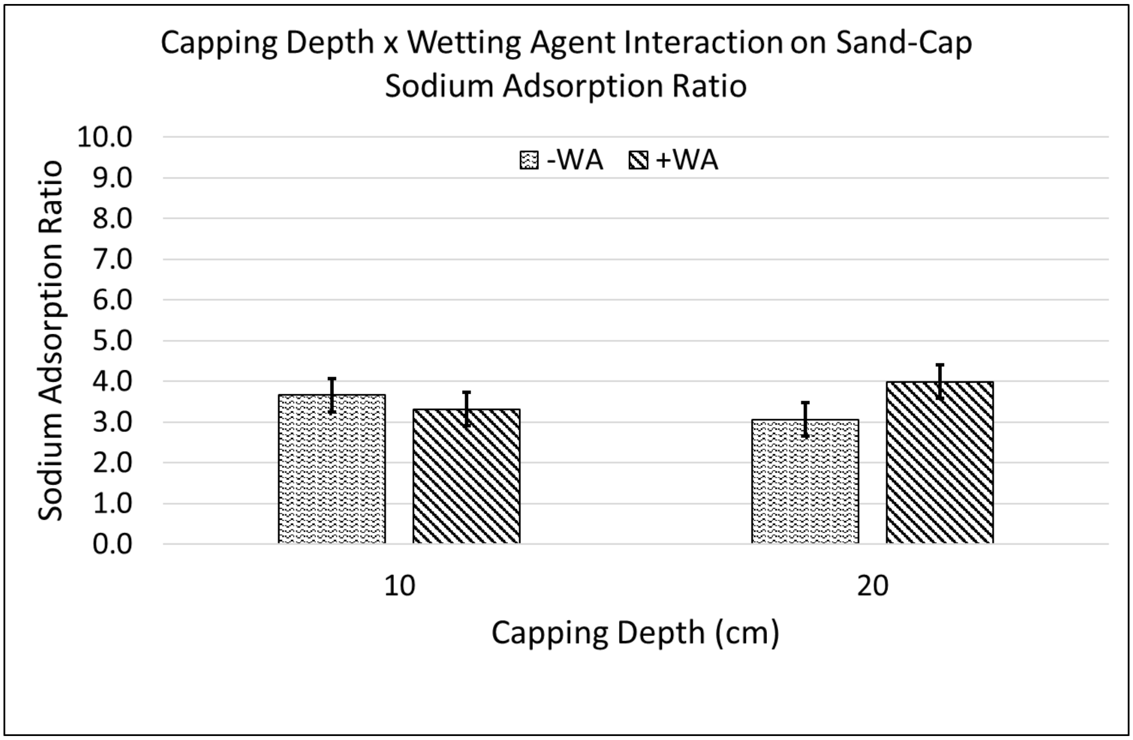


Figure 2.29. Sand-cap SAR as affected by capping depth x wetting agent interaction. Data are pooled across gypsum and years. Error bars indicate significant differences based on LSD at P ≤ 0.05.

Subsoil Sodium Adsorption Ratio

Based on ANOVA, there was a significant capping depth main effect on subsoil SAR over both years (Table 2.3; Figure 2.30). Subsoil SAR for the 10 cm capping depth was significantly higher than the 20 cm capping depth. The mean subsoil SAR at the 10 cm capping depth was 8.7 compared to a mean subsoil SAR of 7.6 at the 20 cm capping depth.

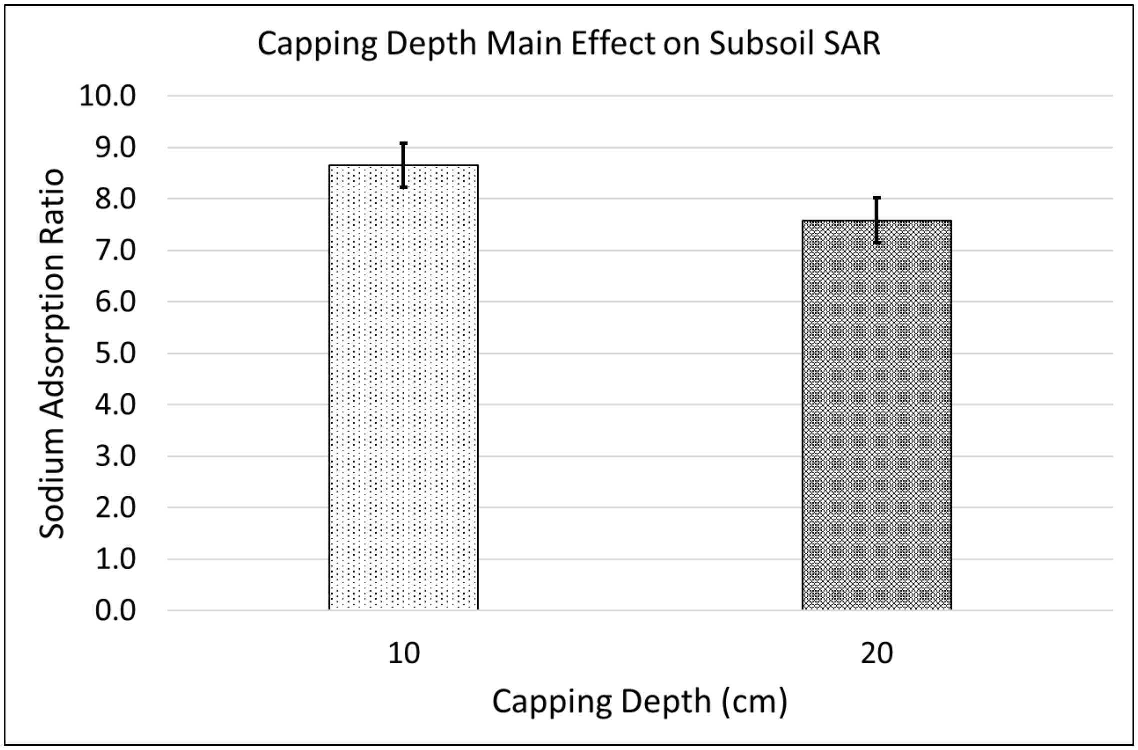


Figure 2.30. Subsoil SAR as affected by capping depth. Data are pooled across wetting agent, gypsum rate, and year. Error bars indicate Fisher's LSD at $P \leq 0.05$.

ANOVA showed a gypsum main effect on subsoil SAR, when pooling across both years (Table 2.3; Figure 2.31). Subsoil SAR in plots not receiving gypsum treatments were significantly higher than both plots receiving monthly gypsum applications as well as the one time annual gypsum application. When averaged across all rating dates, subsoil SAR was highest in untreated plots (9.1), followed by monthly gypsum (7.9) and annual gypsum treatment plots (7.4).

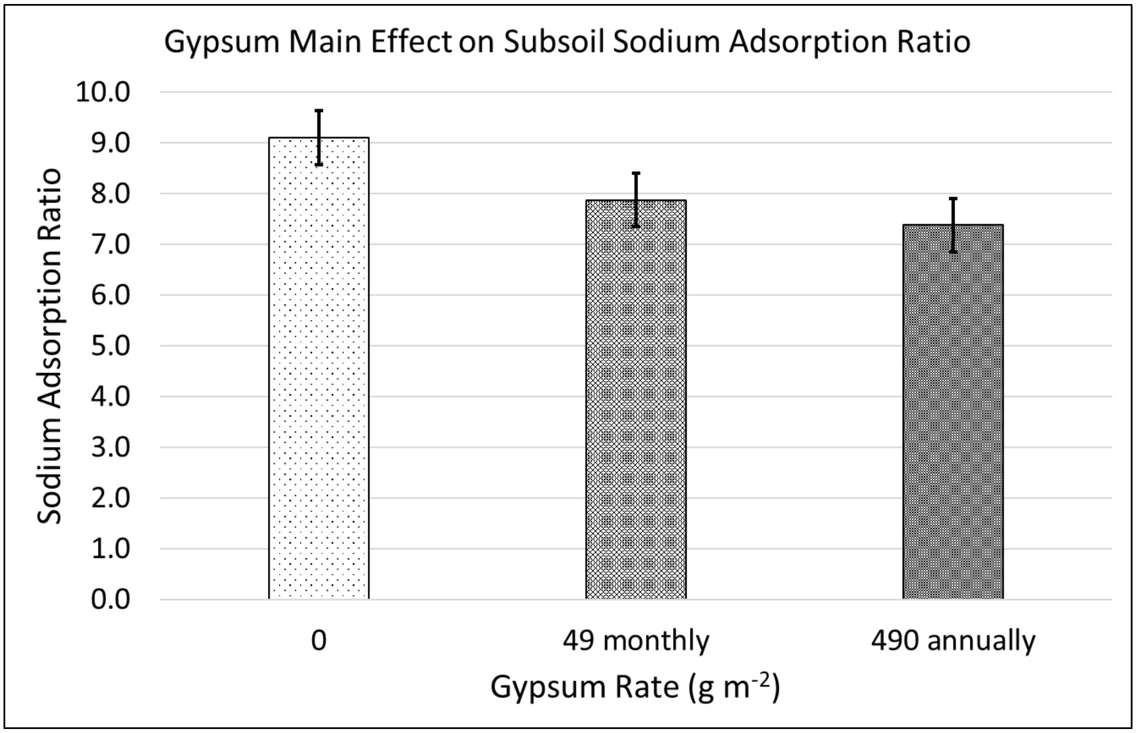


Figure 2.31. Subsoil SAR as affected by gypsum treatments. Data are pooled across wetting agent treatments, capping depths, and years. Error bars indicate Fisher's LSD at P ≤ 0.05.

When pooling across both years, ANOVA detected a capping depth x wetting agent interaction on subsoil SAR (Table 2.3; Figure 2.32). At the 20 cm capping depth, plots that received wetting agent showed significantly higher subsoil SAR than plots not receiving wetting agent application. Subsoil SAR of plots receiving wetting agent was 8.5, while mean subsoil SAR for untreated plots was 6.7.

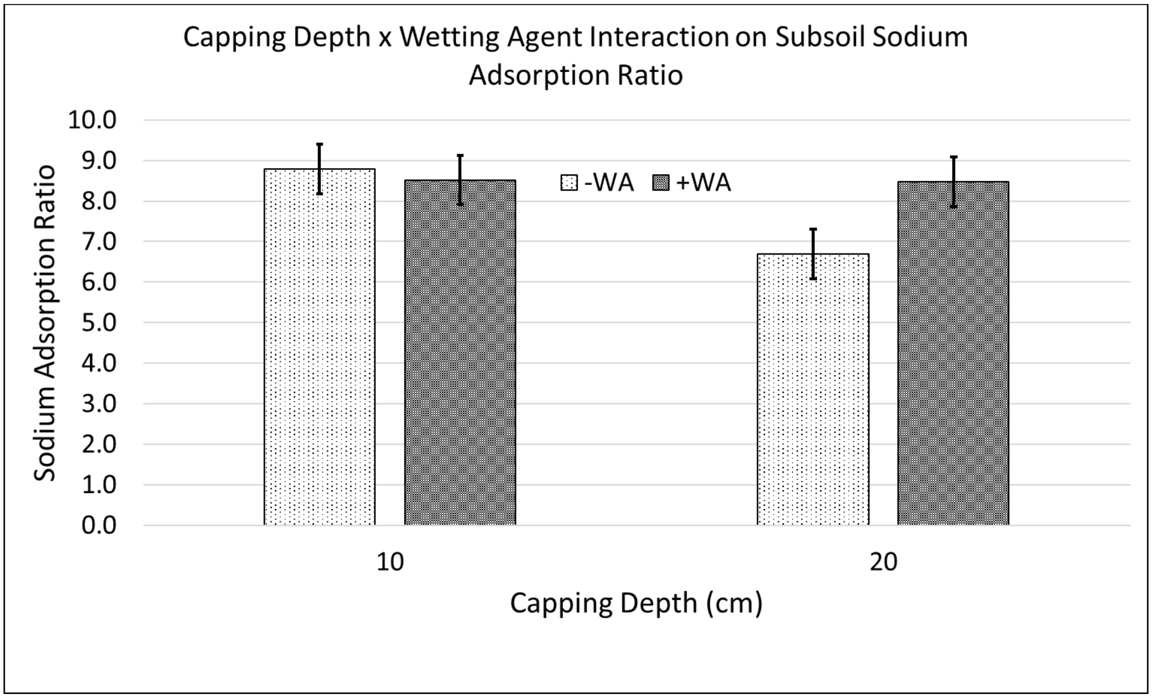


Figure 2.32. Subsoil SAR as affected by capping depth x wetting agent interaction. Data are pooled across year and gypsum treatment. Error bars indicate Fisher's LSD at $P \leq 0.05$.

When pooling across years, ANOVA detected a significant capping depth x gypsum interaction on subsoil SAR (Table 2.3; Figure 2.33). At the 10 cm capping depth, plots receiving the one time annual gypsum application had significantly lower subsoil SAR than untreated plots.

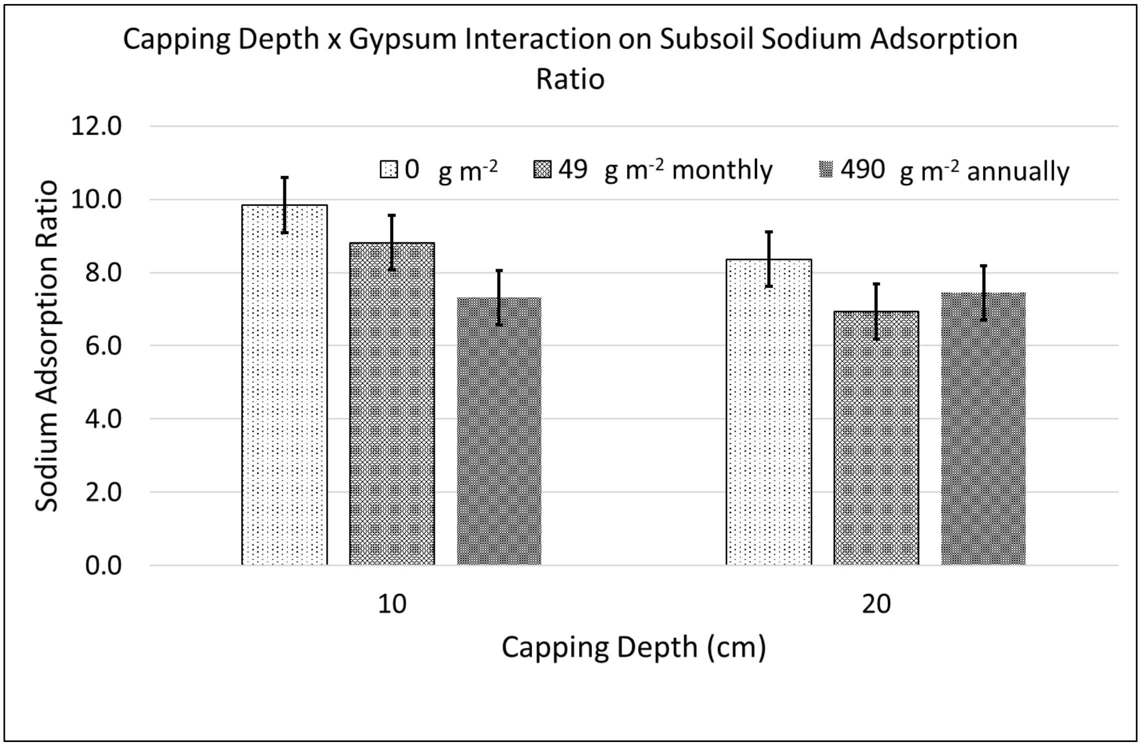


Figure 2.33. Subsoil SAR as affected by capping depth x gypsum interaction. Data are pooled across year and wetting agent treatment. Error bars indicate Fisher's LSD at P ≤ 0.05.

Water Droplet Penetration Time at 1.3 cm Depth

The ANOVA detected a capping depth main effect on WDPT at the 1.3 cm depth, when pooled across years (Table 2.3; Figure 2.34). No hydrophobicity was detected within the TD 5 cm, 5 cm, or 10 cm capping depths placing them in the wettable (0-5 s) category for degree of hydrophobicity. However, the 20 cm capping depth treatments had significantly higher WDPT at the 1.3 cm depth compared to all other capping depth treatments. The WDPT was roughly 21 s in the 20 cm capping depth plots placing them in the slightly water repellant (5-60 s) category for degree of hydrophobicity.

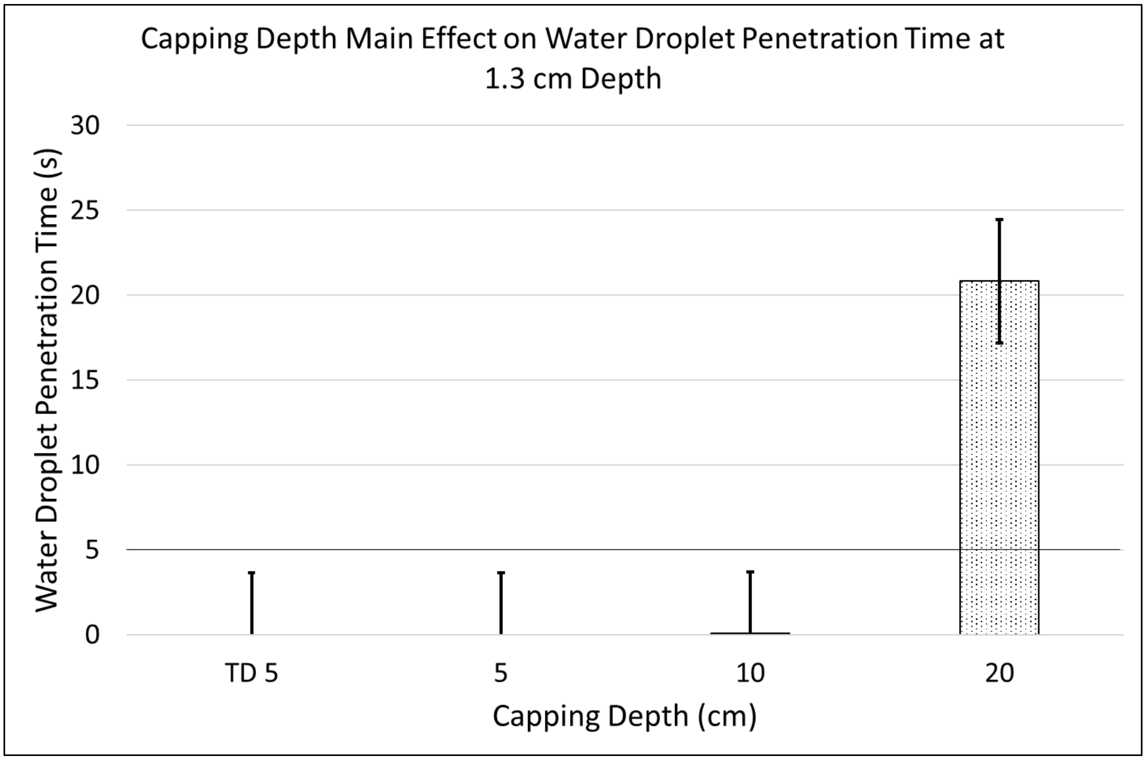


Figure 2.34. WDPT at the 1.3 cm depth as affected by capping depth. Data are pooled across wetting agent, gypsum treatment, and year. Error bars indicate Fisher's LSD at $p \leq 0.05$.

The ANOVA also showed a significant wetting agent main effect for WDPT at the 1.3 cm depth, when pooled across years (Table 2.3; Figure 2.35). Plots not receiving wetting agent had significantly higher mean WDPT compared to plots receiving wetting agent application. Plots that did not receive wetting agent had WDPT of 10 s falling into the slightly water repellant (5-60 s) category regarding hydrophobicity, while plots that received wetting agent had WDPT of 0 s placing them in the wettable (0-5 s) category regarding hydrophobicity.

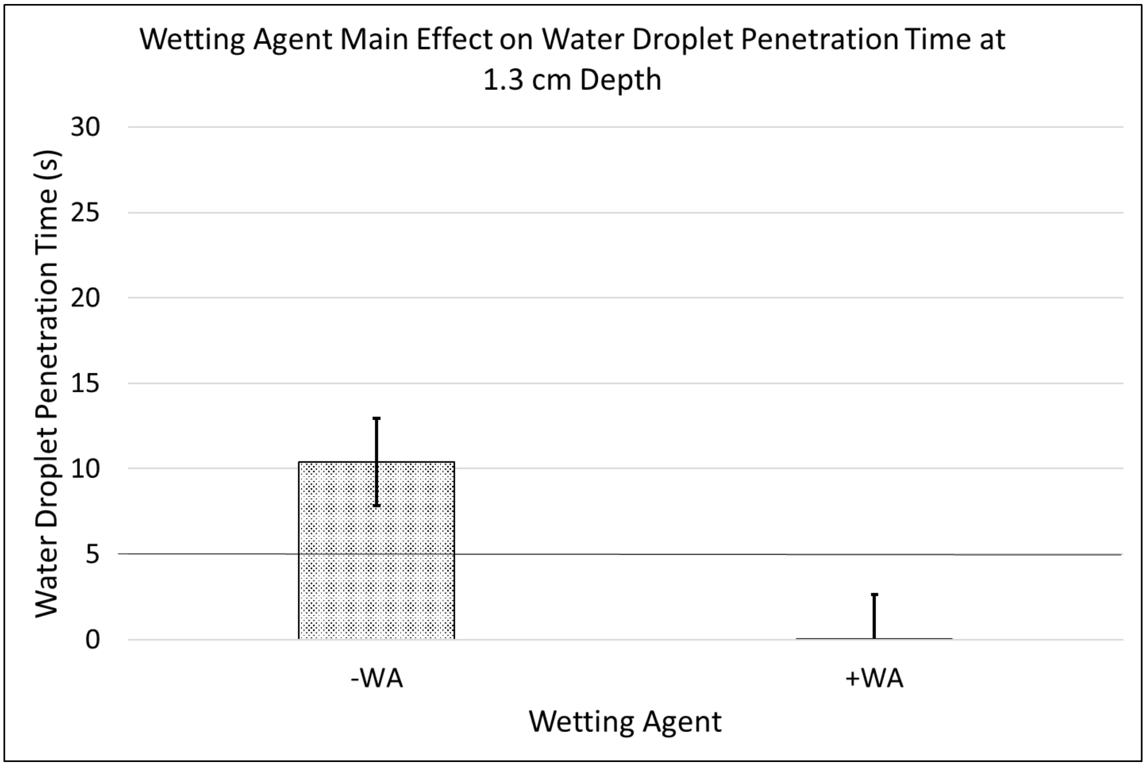


Figure 2.35. WDPT at 1.3 cm depth as affected by wetting agent treatment. Data are pooled over gypsum treatment and year. Error bars indicate Fisher’s LSD at $P \leq 0.05$.

The ANOVA showed a significant capping depth x wetting agent x gypsum interaction on WDPT at the 1.3 cm depth, when pooled across years (Table 2.3; Figure 2.36). At the 20 cm capping depth in plots not receiving wetting agent application, split-plots receiving the one-time annual gypsum application had significantly lower WDPT than both plots that were untreated with gypsum and plots that were treated monthly with gypsum. The WDPT for plots not receiving wetting agent or gypsum was 60 s falling into the slightly water repellent category (5-60 s) for hydrophobicity, and 45 s for those receiving monthly gypsum but no wetting agent falling into the slightly water repellent (5-60 s) category regarding hydrophobicity. Plots that received wetting agent plus the single annual application of gypsum was 20 s falling into the slightly water repellant category (5-60 s). Regardless of gypsum rate, plots receiving a wetting agent experience little to no hydrophobicity placing them into the wettable category (0-5 s).

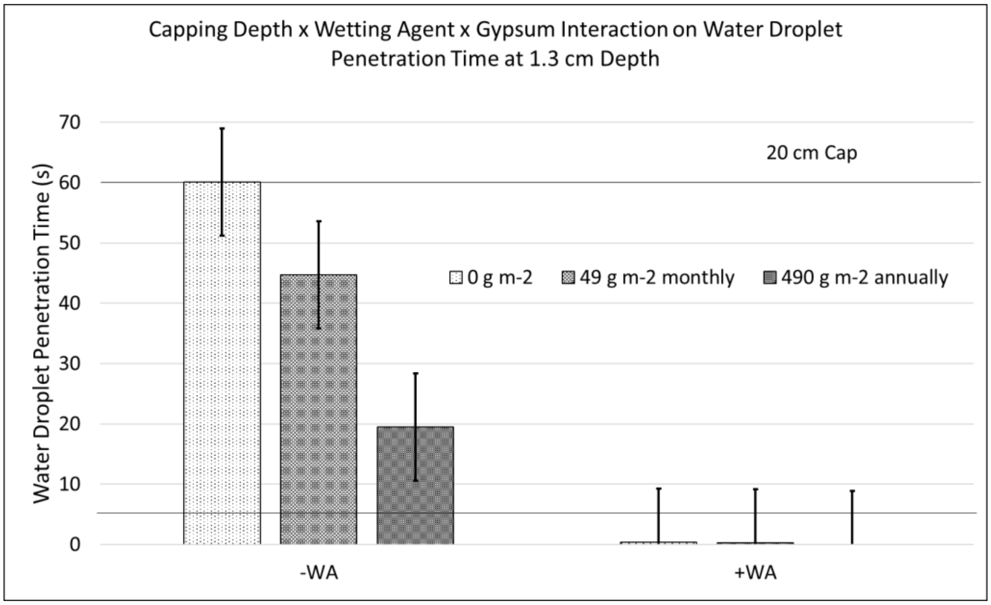


Figure 2.36. WDPT at 1.3 cm depth as affected by capping depth x wetting agent x gypsum interaction. Data are pooled across years. Error bars indicate Fisher’s LSD at P ≤ 0.05.

The ANOVA also detected a significant capping depth x wetting agent x date interaction on WDPT at the 1.3 cm depth during both years (Table 2.3; Figure 2.37). Across 2018 and 2019, on four of ten measurement dates (July and August of each year), there was a significant capping depth x wetting agent x date interaction on WDPT at the 1.3 cm depth. On those four dates at the 20 cm capping depth, plots not receiving wetting agent had significantly higher WDPT at the 1.3 cm depth compared to plots receiving wetting agent application. The WDPT of plots not receiving wetting agent application at the 20 cm capping depth approached 135 s, while approaching only 0 to 2 s for plots receiving wetting agent.

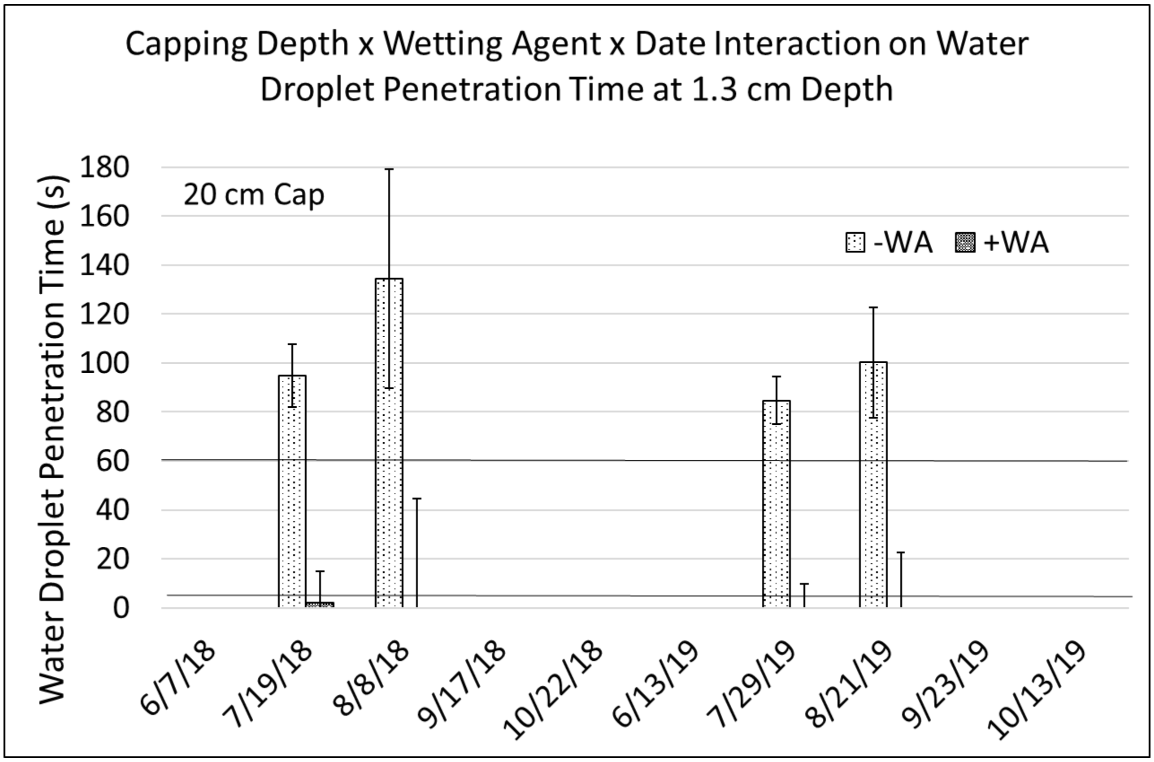


Figure 2.37. WDPT for the 1.3 cm depth as affected by capping depth x wetting agent x date interaction during 2018 and 2019. Data are pooled across gypsum treatment and years. Error bars indicate Fisher’s LSD at P ≤ 0.05. * indicates significant dates.

Water Droplet Penetration Test 3.8 cm Depth

Based on ANOVA, there was a significant capping depth main effect on WDPT at the 3.8 cm depth in 2018 and 2019 (Table 2.3; Figures 2.38 and 2.39). In 2018, the 20 cm capping depth plots had WDPT of 1.8 s, significantly higher than the WDPT of 0 s for all other capping depths. In 2019, the 20 cm capping depth plots had WDPT of 3.3 s, which was significantly higher than WDPT of 0 s for all other capping depths. All capping depths, regardless of year, fell into the wettable (0-5 s) category regarding hydrophobicity.

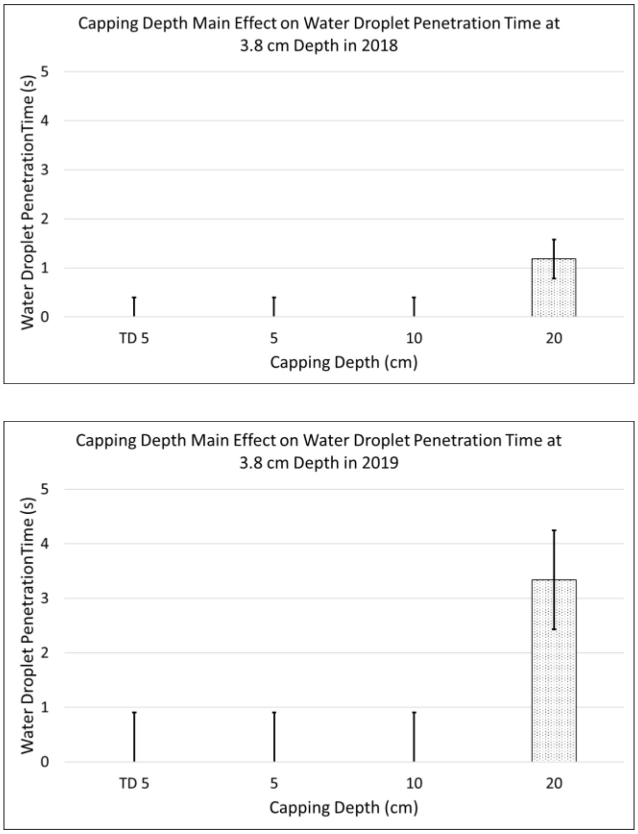
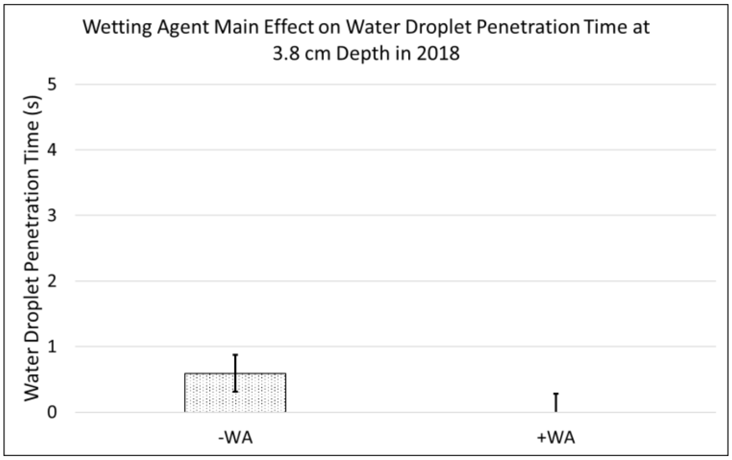


Figure 2.38 (upper) and 2.39 (lower) WDPT at 3.8 cm depth for 2018 (upper) and 2019 (lower) as affected by capping depth. Data are pooled across wetting agent and gypsum treatments. Error bars indicate Fisher’s LSD at $P \leq 0.05$.

The ANOVA detected a wetting agent main effect on WDPT at the 3.8 cm depth for both 2018 and 2019 (Table 2.3; Figure 2.40 and 2.41). In 2018, plots not receiving wetting agent application had WDPT of 0.6 s, which was significantly higher than WDPT of 0 s for plots receiving wetting agent application. In 2019, plots not receiving wetting agent application had WDPT of 1.7 seconds, which was significantly higher than that for plots receiving wetting agent application (0 s). All capping depths, regardless of year, fell into the wettable (0-5 s) category regarding hydrophobicity.



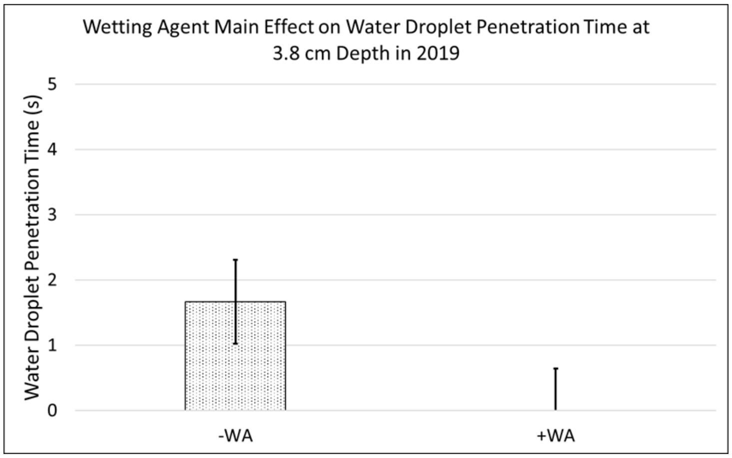


Figure 2.40 (upper) and 2.41 (lower) WDPT at 3.8 cm depth as affected by wetting agent treatment during 2018 and 2019. Data are pooled across gypsum treatment and capping depth. Error bars indicate Fisher's LSD at P ≤ 0.05.

For both 2018 and 2019, ANOVA detected a significant capping depth x wetting agent x date interaction on WDPT at the 3.8 cm depth (Table 2.3; Figures 2.42 and 2.43). In 2018 at the 20 cm capping depth, plots not receiving wetting agent application had a significantly higher WDPT than plots receiving wetting agent application on two of five rating dates. Mean WDPT for plots not receiving wetting agent ranged from 4.3 to 7.5 s, compared to 0 s for plots receiving wetting agent application. In 2019 at the 20 cm capping depth, plots not receiving wetting agent application again had significantly higher WDPT compared to plots receiving wetting agent application on two of five rating dates. Mean WDPT for plots not receiving wetting agent application ranged from 9 to 25 s, compared to 0 s for plots receiving wetting agent application.

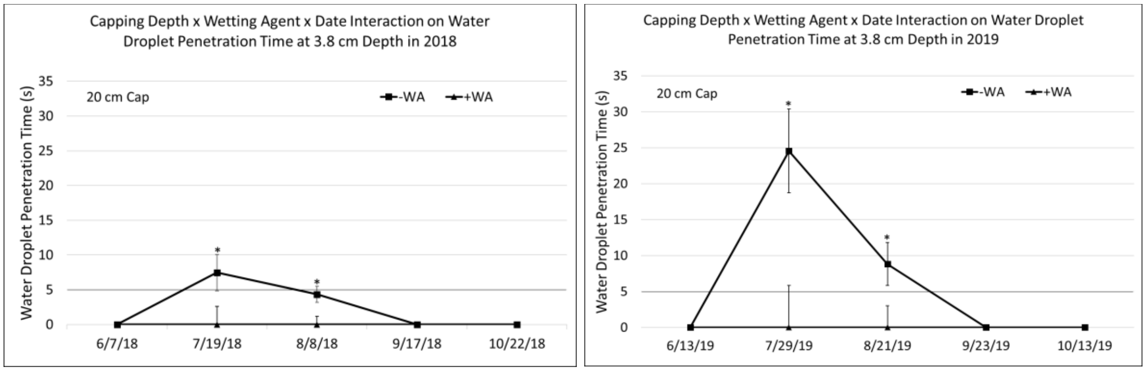


Figure 2.42 (left) and 2.43 (right). WDPT at 3.8 cm depth as affected by capping depth x wetting agent x date interaction during 2018 and 2019. Data are pooled across gypsum treatments. Error bars indicate Fisher’s LSD at P≤ 0.05. * indicates significant dates.

Discussion

Wetting Agents

Plots that received applications of a wetting agent had a significantly higher turfgrass quality and volumetric water content than plots that did not receive them. Similar findings were observed regarding turfgrass quality in a previous study (Karnok and Tucker, 2001). However, significant differences were only observed at the 20 cm capping depth suggesting that wetting agents may not be necessary at shallower capping depths. Hydrophobic conditions only existed at the 20 cm capping depth but wetting agent at that depth alleviated surface hydrophobicity suggesting they may be a necessary management practice in deeper capping systems. Similar results regarding the use of wetting agents to alleviate hydrophobicity were observed in a previous study (Leinauer et al., 2007). While wetting agent applications enhanced TQ and VWC, while also alleviating hydrophobicity, they increased both sand-cap and subsoil SAR significantly suggesting that the wetting agent aided in the infiltration of sodic water. Similar findings regarding the use of wetting agents to aid in infiltration were found in a prior study (Pelishek et al., 1962). This suggest that wetting agents may be more effective when irrigating with non-sodic water. In conclusion, the results suggest that application of a wetting agent may only be necessary at deeper capping depths.

Gypsum

While applications of gypsum were effective at reducing subsoil SAR compared to the untreated plots, all gypsum treatments, including the untreated, produced SARs that were lower than the problematic threshold of 13. Similar findings regarding the use of gypsum in turfgrass systems to reduce SAR when irrigating with high-sodic water were observed in a previous study (Mancino, 1989). The untreated plots SAR was only 1.7 higher than the heavy gypsum rate SAR suggesting that the benefits, while positive, may not outweigh costs and time. It is also important to note how the label rate performed under irrigation with high-sodic water suggesting that the rate may need to be increased. The same trend was observed with the sand-cap layer SAR as well with even lower SAR values thus indicating that the reduction in SAR may not be significant enough to justify the application. Similar findings regarding the use of gypsum in turfgrass to reduce sodium levels were found in a prior study (Mancino, 1989). Rates of 0, 2,240, 4,480, and 8,960 kg ha^{-1} per year (0, 1, 2, and 4 tons/acre per year) were applied yearly on a golf course with irrigation water containing a Na level of 800 mg kg^{-1}.

Wetting Agent x Gypsum Interactions

At the 20 cm capping depth, subsoil SAR was significantly higher in plots that received a wetting agent than plots that did not receive a wetting agent. This would suggest that the wetting agent aided in the infiltration of sodic water into the profile at the 20 cm capping depth. Similar findings regarding the use of wetting agents to aid in infiltration were found in a prior study (Pelishek et al., 1962). However, in this study there was no wetting agent main effect on infiltration to support this suggestion. The 20 cm capping depth had a significantly lower subsoil SAR than the 10 cm capping depth. This suggest that potentially the wetting agent, which was more effective at the 20 cm depth, may have aided in the movement of gypsum down to the subsoil. Previous studies have shown wetting agents have aided in the movement of fungicides into the soil profile but there is little to no research in turfgrass on the use of wetting agents to move gypsum (Latin and Ou, 2018). Sand-cap layer SAR was also significantly higher in plots that received applications of a wetting agent at the 20 cm capping depth than plots that did not receive a wetting agent. This suggest that potentially the gypsum moved through the sand-cap layer quickly perhaps with the aid of the wetting agent application in combination with a sandy soil prone to leaching.

Capping Depth

Capping depth plays a critical role in overall turfgrass health and performance as the shallower capping depths outperformed the 20 cm capping depth for TQ, VWC, %GC, and WDPT test. Similar results regarding capping depth performance were found in a previous study on sand-capped fairways (Dyer, 2017). The 20 cm cap was dryer and or poorer quality due to hydrophobic conditions that developed. Moisture retention is believed to be a key factor that drives the shallower capping depths allowing them to outperform the 20 cm cap with higher TQ, VWC, %GC, and reduced hydrophobicity. The 20 cm capping depth did have a greater infiltration rate than the 10 cm capping depth, which could be a desired trait in areas that receive intense rainstorms. The 20 cm capping depth was also more effective at flushing sodium out of the system as it had both lower sand-cap and subsoil SAR than the 10 cm capping depth. However, both capping depths produced SARs that are below the problem threshold of 13 suggesting that capping depth may not be as crucial for managing SAR as believed to be. It is important to note that over time these capping depths may perform differently due to increases in OM.

Summary and Conclusion

As golf course irrigation water quality continues to decline, sand-capping of golf course fairways is increasing. Sand-capping has many agronomic benefits including improved drainage and increased infiltration, greater rooting depth, improved traffic tolerance and playing conditions, alleviated compaction, enhanced ability to flush salts, and improved soil structure (White, 2013). However, over time, unique management challenges may arise, including organic matter accumulation, surface hydrophobicity, and subsoil permeability issues, especially where irrigation water contains elevated levels of sodium. Therefore, it is important to understand how various sand-capping depths in combination with various treatments can remedy these issues and provide a high quality healthy turfgrass stand. Our results indicate that capping depth plays a critical role in TQ, VWC, %GC, and WDPT as the shallower capping depths outperformed the deepest capping depth for all parameters. The 20 cm capping depth was dryer and of poorer quality due to hydrophobic conditions that developed. While wetting agent applications helped increased VWC, our results show that they may only be necessary in deeper rather than shallower capping depths to combat hydrophobicity that is more prevalent in deeper sand-capped systems. Our results indicate that a heavy annual gypsum rate is most effective at reducing SAR compared to the untreated plots. This was a key finding as a monthly gypsum rate is what is currently recommended. While sand-capping originated to combat high annual rainfalls, it is being proven that there are many other benefits it provides to improve turfgrass health and playability. Further research is needed to see how sand-capped systems perform over longer periods of time to truly understand their longevity and the management necessary to reap the agronomic benefits they provide.

CHAPTER III

INFLUENCE OF SECONDARY CULTURAL PRACTICES ON SURFACE ORGANIC MATTER ACCUMULATION

Overview

Sand-capping golf course fairways is becoming a common practice where irrigation water is of extremely poor quality, particularly with regard to elevated sodium. While sand-capping provides many benefits, there are some areas of concern, especially regarding the potential for rapid accumulation of organic matter, that over time may reduce turfgrass performance, health, and playability. The objectives of this research were to determine the individual and combined effects of applications of the biostimulant ‘Worm Power’ and of cultural practices on turfgrass quality and cover, surface firmness, infiltration rates, surface organic matter accumulation, and thatch depth of sand-capped systems of varying construction depth. Results of the study indicate that capping depth has a major influence on all parameters measured, with shallower capping depths outperforming the deepest capping depth in terms of overall turfgrass quality and percent green cover. Results also showed that although causing temporarily reduced quality, verticutting + aeration produced superior turfgrass quality compared to either practice alone during the second half of the season. Our results also showed that deeper capping depths had greater measured thatch depth but lower total organic matter contents relative to shallower capping depths. Collectively, the results suggest that the combining cultural practices aeration + verticutting provides the greatest benefit in terms of reducing organic matter and producing the best playing surface on sand-capped fairways.

Introduction

Sand-capping is defined as placing a defined layer of sand atop the existing subsoil. Sand-capping may also be referred to as plating and originated in the 1990's in the Northwestern United States to combat poor golf course conditions due to excess water (White, 2013). Those poor course conditions included compacted soils, poor aeration, slow drainage, saturated soils leading to unplayable conditions, and salinity/sodicity stresses. All of these undesirable course conditions lead to less rounds of golf being played and ultimately less revenue coming in for golf courses. Capping of degraded golf course fairways with a layer of sand to promote improved turfgrass health, performance, and playability is becoming a common practice where irrigation water is of poor quality and/or high in sodium. Benefits of sand-capping include improved drainage and increased infiltration rates, greater rooting depth, improved traffic tolerance and playing conditions, alleviated compaction, enhanced ability to flush salts, and improved soil structure (White, 2013). However, over time, unique management challenges may arise, including organic matter accumulation, surface hydrophobicity, and subsoil permeability issues, especially where irrigation water contains elevated levels of sodium (White, 2013).

The rapid development of organic matter over the first three years of a previous sand-capping study is concerning, especially due to association with hydrophobicity also noted in the thatch layer (Dyer, 2017). Hydrophobicity develops when organic compounds with water repellent properties buildup on and between soil particles (Dekker et al., 2009). It has been suggested that overly dry conditions result in a coating on soil particles that contain fungal mycelium, which is not present in wet conditions (Wilkinson and Miller, 1978). It was determined that the coating was organic and acidic since washing it with NaOH removed it while HCl did not. The coatings were deemed to be calcium or magnesium soaps of fatty acids (Wilkinson and Miller, 1978). One solution to managing hydrophobic conditions is the use of wetting agents. Studies have shown wetting agents play a critical role in many golf course superintendent's management plans with 87% of superintendents using wetting agents on a routine basis in their maintenance program with another 11% using them under certain conditions (Karnok et al., 2004). Agronomic issues resulting from surface organic matter accumulation may include, among other things, reduced water infiltration, which could lead to overly dry conditions and poor turfgrass quality. Wetting agents are used for managing localized dry spots, improving infiltration and drainage, moving pesticides through the profile, reducing dew accumulation, improving irrigation efficiency, reducing compacted soils, and reducing damage from fungal diseases such as fairy ring (Karnok et al., 2004; Kaminski and Han et al., 2010).

Increased accumulation of organic matter may also lead to reduced surface firmness, resulting in a spongy thatch layer that affects playability by reducing ball bounce and roll (White, 2013). Thatch is a mixed layer of living and dead tissue that builds up between the grass blade and soil surface. Thatch builds up due to an imbalance of growth and breakdown of organic material (Murray and Juska, 1977). There are several factors that affect organic matter buildup including grass species, plant growth and decay rate, biological activity, cultivation practices, and environmental conditions (Gaussoin et al., 2013). Problems resulting from excessive thatch buildup include reduction in aesthetics of the turf, increased pest problems, and reduction of water infiltration (Murray and Juska, 1977). Often times there is a need to remove thatch through cultural practices. . Examples of common cultural practices to manage thatch are topdressing with sand, core aerification, and verticutting (Beard, 1973). Topdressing is essentially making applications of sand and grooming it into the canopy over time. Topdressing aids in smoothness for ball roll, thatch dilution, turfgrass recovery, increased firmness, and improved root zones (Lowe, 2015). Topdressing has been reported to be the most effective method but can be quite expensive, so it is not always an option for turfgrass managers (Murray and Juska, 1977). Due to this, turfgrass managers in their thatch management programs often use core aerification, verticutting, and combinations of the two practices. Core aerification and verticutting have been used since the 1940s and are still staple practices in management plans today (Turgeon and Fidanza, 2007). Verticutting and core aerification have been reported to both significantly reduce organic matter content in the thatch layer by 23% and 12%, respectively (Snyder, 2017). Core aerification involves removing soil cores from the turfgrass system often followed by topdressing to fill in the holes. Core aerification enhances gas flow to and from the soil, increases water infiltration, stimulates root and shoot growth, aids in thatch dilution, and improves drainage (Turgeon and Fidanza, 2007). Verticutting is mowing with vertical blades that slice into the turfgrass canopy.

Verticutting aids in thatch removal, increases turfgrass density by creating new points of growth, increases firmness, enhances gas flow, and increases water infiltration rates (Trenholm et al., 2000). Turfgrass managers use combinations of core aerification and verticutting extensively today. Reports have shown that the best thatch removal programs consist of verticutting and core aerating immediately following verticutting (Foy, 1991). In golf course putting greens organic matter is typically in the 1 to 3% by weight in the initial mix used for construction but often increases rapidly (Carrow, 2001). A 5% by weight organic matter content is enough to plug macropores in the sand and seal them off. The sealing of macropores can lead to agronomic problems, such as reduced gas exchange in the rootzone and reduced water infiltration (Carrow, 2001).

Another common management practices in turfgrass systems is applying soil amendments and there are numerous soil amendments on the market each with a proposed purpose. One soil amendment that is used in turfgrass is vermicompost (Gardner et al., 2004). Vermicompost is derived from earthworm castings and is applied to increase soil organic matter, enhance soil structure, and enhance cation exchange capacity (Tajbakhsh et al., 2011). Vermicompost has also been shown to enhance turfgrass quality (Gardner et al., 2004). Worm Power is a vermicompost product used in the turfgrass industry. Proposed benefits from use of Worm Power include improving soil health, enhancing microbial communities, enhanced plant growth, enhanced uptake of nutrients, and enhanced water holding capacity (Aqua-Aid Solutions, Rocky Mount, NC). Worm Power has been shown to increase Normalized Difference Vegetation Index (NDVI) values, which is often used as an additional measure of quality in turfgrass systems (Aqua-Aid Solutions and NC State, 2016). Worm Power has been shown to have sufficient microbial activity within the product that is similar to what is found in natural turfgrass systems (Aqua-Aid Solutions and NC State, 2016).

Sand-capping is not a new management practice but there is limited research that provides insights on how to best manage these systems long term. Our goal is to provide research-based information for golf course superintendents to utilize when managing their sand-capped turfgrass systems. The objectives of this project was to 1) Determine the effects of monthly applications of Worm Power on surface organic matter accumulation and thatch management on sand capped soil, 2) Determine the effects of secondary cultural practices on surface organic matter accumulation, and 3) Determine the effect of individual and combined treatments on turfgrass performance (turfgrass quality, surface firmness, percent green cover, and surface infiltration).

Materials and Methods

Research site and plot construction

This research was conducted at the Scotts Miracle-Gro Facility for Lawn and Garden Research at Texas A&M University in College Station, TX from June 2018 to November 2019. A 9,300 m^2 sand-cap research facility was installed in 2014 along a south-north running 1.5% slope. On the half of the facility used for this study, the upper 30 cm of the native Boonville fine sandy loam soil (fine, smectitic, thermic, Chromic Vertic Albaqualf) containing 15% clay, 20% silt, and 65% sand was excavated and replaced with a clay loam subsoil containing 38% clay, 35% silt, and 27% sand with a pH of 8.7. The subsoil was graded so that it exhibited a 1.5% east-to-west slope to aid in drainage away from the facility.

Maintenance of the Research Area

Plots were mowed 2-3 times weekly at a 1.3 cm height of cut using a Toro Reelmaster mower with clippings left on the plots. Nitrogen was applied at a 4.9 g m^{-2} every 6 weeks from May through September across all plots using a 21-7-14 (N-P-K) fertilizer which contained 25% N as sulfur-coated urea (American Plant Food Corp., Galena Park, TX). No other micronutrients were applied as soil analyses indicated levels were sufficient.

Plots received irrigation from April through November, at levels needed to supply warm-season crop coefficient ($Tc=0.6 \times ET_o$), based on historical ET_o from the Texas ET Network for College Station, TX. Precipitation volumes were recorded and irrigation was adjusted to ensure the turfgrass was receiving the desired amount of water. Effective rainfall was calculated based on the method recommended by Texas A&M AgriLife Extension (2015), which assumed the first 25 mm of rainfall in an event to be 100% effective, subsequent rainfall <50 mm to be 67% effective, and rainfall >50mm to be 0% effective. Irrigation water at the site originates from a municipal groundwater source with high levels of sodium and bicarbonates (pH 8.1, Na 300 mg kg^{-1}, HCO_3^- 500 mg kg^{-1}, SARadj = 23 meq L^{-1}).

During the study, wetting agent applications were also made across the entire study area from April through November of each year. OARS PS (Aqua-Aid Solutions, Rocky Mount, NC) was applied monthly at the label rate of 0.002 L m^{-2} calibrated to deliver 0.08 L m^{-2}. Applications were made using a spray hawk, with 0.3 cm irrigation applied afterwards to move product into the soil

Cultural Management Treatments

The study was conducted on four-year old Tifway bermudagrass (*Cynodon dactylon x C. transvalensis* Burt. Davy) and arranged in a split-split plot design with three replicates (Dyer, 2017). Whole plots (3.7 m x 15.2 m) consisted of, sand-capping depth treatments of topdressed 5= TD 5 (topdressed 2.54 cm per year over 2 years during 2015 and 2016), 5, 10, and 20 cm.

Whole plots were divided into split plots (3.7 m x 7.6 m) receiving monthly applications of either 0 or 0.005 L m^{-2} rates of Worm Power, which is a vermicompost liquid soil amendment (Aqua-Aid Solutions, Rocky Mount, NC). Worm Power treatments were made using a spray hawk calibrated to deliver 0.08 L m^{-2}. Split-plots were further split into 0.9 m x 7.6 m split-split plots to accommodate four different organic matter cultural management regimes, including untreated, verticutting, core aerification, and verticutting + core aerification.

Organic matter cultural management regimes were imposed twice annually, in June and August of both years. Verticutting was performed to a 0.6 cm depth using a walk behind verticutting unit with 2.5 cm spacing. After the verticutting process was complete, debris was blown off the plots using a backpack blower.

Core aeration treatments were also performed in June and August of both years using a walk behind aerification unit equipped with hollow tines (1 cm diameter x 3.2

cm spacing). Similar to verticutting treatments, a backpack blower was used following aeration to remove any cores and debris that had accumulated on the surface of the plots.

For treatments receiving combined verticutting + aeration, aeration was initially performed, followed by verticutting. Again, a backpack blower was then used to remove debris.

Evaluations of Turfgrass Quality and Percent Green Cover

Turfgrass Quality was assessed in all plots biweekly throughout the growing season in 2018 and 2019 using a visual quantitative measuring system with a scale from 1-9 for Turfgrass quality (Morris and Shearman et al. 1998). A minimum score of 6 was used to indicate acceptable turfgrass quality. Light box pictures were taken for all plots biweekly throughout the growing season in 2018 and 2019. Turf Analyzer was used to identify percent green cover through digital image analysis (Karcher and Richardson, 2013; Karcher et al., 2017).

Evaluation of Surface Firmness

Surface firmness was measured for all plots monthly throughout the growing season in 2018 and 2019 using the FieldScout Trufirm Tester (Spectrum Technologies, Inc., Aurora, IL) (Stowell et al., 2009). Two measurements were taken per plot and the average value was used for analysis.

Evaluation of Thatch Depth and Organic Matter Content

Thatch depth measurements were made at the 10 cm and 20 cm capping depth plots at the beginning of the growing season in 2018. Thereafter, these measurements were then taken in early November of each year, at the end of the growing season. Using a 2.5 cm diameter soil sampler tool (Turf-Tec International, Tallahassee, FL), three 5 cm deep cores were removed from each plot. Following removal, the depth of thatch was measured using the criteria outlined by Callahan et al. (1997). The three values were averaged to determine the mean depth of thatch in each plot. Organic matter content in the surface 0 to 5 cm depth was then estimated for each of these cores by loss on ignition (Schulte and Hopkins, 1996). Briefly, the three core samples were combined into one composite sample. Initial field weight of this sample was then recorded before placing into a drying oven at 105℃ for three days, after which oven dry weights were recorded before further analyses. Once all weights were recorded, samples were separated into three fractions using a 2 mm sieve and tweezers. The three fractions were particles < 2 mm, particles > 2 mm, and plant material. Following separation, entire samples were placed into a muffle furnace for combustion analysis at 550℃ for six hours. Loss on ignition methodology was used to determine organic matter content for all samples . The known weights of the particles > 2mm and plant material were removed from both the dry weight and final weight before determining soil organic matter content.

In addition to the end-of-year measurements, during 2019, organic matter contents for the 0-5 cm depth of untreated control plots were also determined monthly using the previously described methodology with the objective of characterizing dynamics of monthly or seasonal shifts in organic matter fractions.

Measurement of Infiltration Rate

Infiltration rates were measured bimonthly throughout the growing season in 2018 and 2019 using the double-ring Turf-Tec Infiltrometer (Turf-Tec International, Tallahassee, FL). The inner and outer ring diameter of the Infiltrometer is 6 cm and 10.8 cm, respectively. The Infiltrometer penetrated 5 cm into the surface. Measurements were obtained within the plots capped with 10 and 20 cm sand. Both rings of the infiltrometer were completely filled with water. A stopwatch was then used to determine the time required for 25.4, 50.8, and 76.2 mm (1, 2, 3 inch) cumulative depth of water to infiltrate, and those times were recorded. Two measurements were obtained per plot and averaged.

Measured infiltration rates slowed with time and fit an equation of $I=Ut^{0.70}$. Whether the decline of infiltration rate with time is because of the general decline in infiltration rate in porous media with time (Philip, 1957) or because of the fact that the measurements were made with declining head of water in the Infiltrometer (Nimmo et al., 2009) is uncertain. We determined the value of U by regressing I on $t^{0.70}$, setting the intercept to 0. The value of U is an indicator of infiltration rate and can be used to estimate the amount of time required to infiltrate a given depth of water is (i.e., $t=(I/U)^{1/0.70}$), starting with 76.2 mm head of water at the sand cap surface and ending at 0 mm. For example, the amount of time required to infiltrate 25.4, 50.8, and 76.2 mm water given $U=4.57 \mathrm{mm \cdot s^{-0.70}}$ would be 12, 31, and 56 s, respectively. For example, the amount of time required to infiltrate 25.4, 50.8, and 76.2 mm water given $U=0.42 \mathrm{mm \cdot s^{-0.70}}$ would be 354, 952, and 1,698 s, respectively. An example of a high U value (4.571) is located on the left side of the figure below while a slow U value (0.417) is located on the right side of the figure (Figure 2.0).

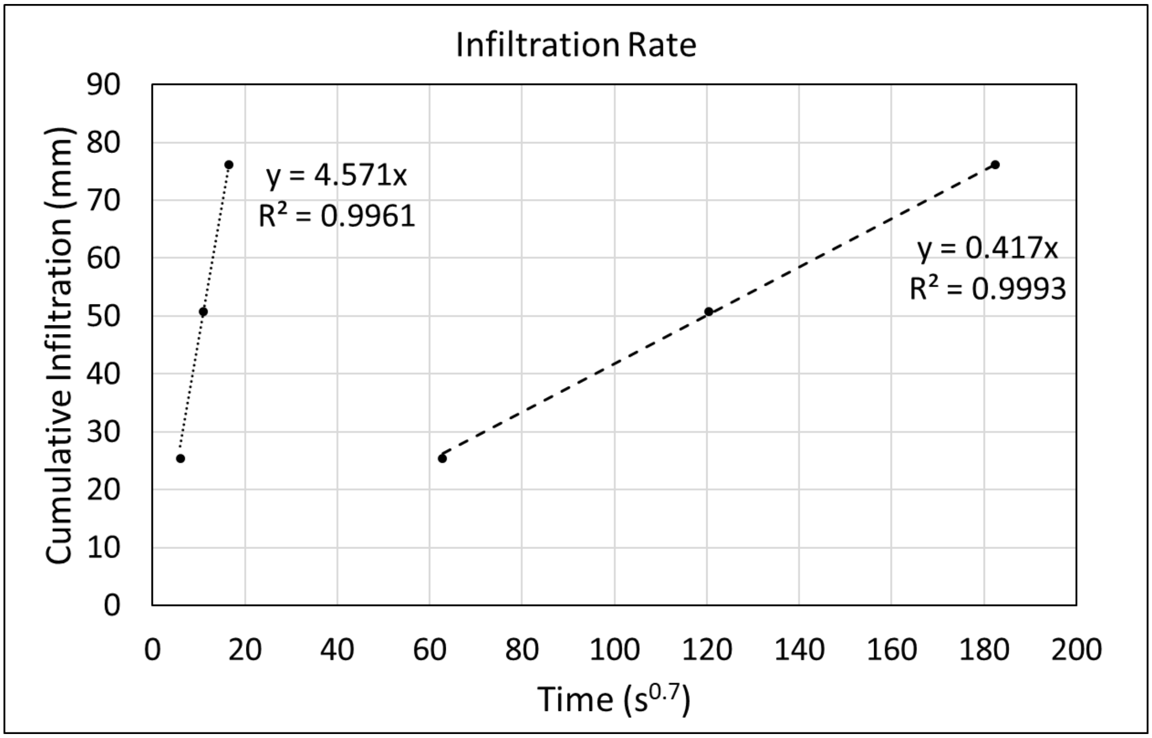


Figure 3.0. Cumulative infiltration (mm) plotted over time (s0.70).

Data Analysis

At the conclusion of the project, all data were subjected to analysis of variance procedures using the general linear procedures of SPSS (IBM, Armonk, NY). Where significant treatment x year interactions were detected, data were presented separately by year. Where appropriate, means were compared using Fisher's LSD ($P \leq 0.05$).

Results

Table 3. 1 Weather data for 2018 at the Texas A&M Turfgrass Field Laboratory, College Station, TX. An on-site weather station was used to obtain all data and is a part of the Texas ET Network. Data are presented for January 2018 through December 2018.

Month	**Total ET_0**	**Daily ET_0**	**Total Precipitation**	**Average Temperature**			**Avg. Relative Humidity**	**Avg. Windspeed**
				Mean	**Low**	**High**		
		mm			**°C**		**%**	**m/s**
January	72.3	2.3	28.2	7.3	2.4	13.9	56.2	2.4
February	58.1	2.1	43.2	12.1	9.0	16.8	78.9	2.7
March	131.1	4.2	148.1	17.3	12.3	23.2	59.2	2.8
April	136.0	4.5	43.2	17.2	12.2	23.6	60.5	2.6
May	169.9	5.5	60.2	24.7	20.4	30.4	64.6	2.2
June	180.4	6.2	62.0	27.6	23.8	32.7	66.1	2.7
July	197.0	6.4	44.5	28.3	24.0	34.4	60.7	1.9
August	199.2	6.4	5.1	28.4	23.9	34.7	59.1	2.2
September	105.4	3.5	157.5	24.9	22.6	29.3	75.3	1.6
October	89.4	2.9	355.3	19.7	16.6	24.7	75.8	2.0
November	67.8	2.3	101.9	12.1	8.2	17.5	68.4	2.1
December	65.0	2.2	228.6	10.6	6.9	15.4	65.5	2.5

Table 3. 2 Weather data for 2019 at the Texas A&M Turfgrass Field Laboratory, College Station, TX. An on-site weather station was used to obtain all data and is a part of the Texas ET Network. Data are presented for January 2019 through December 2019.

Month	**Total ET_0**	**Daily ET_0**	**Total Precipitation**	**Average Temperature**			**Avg. Relative Humidity**	**Avg. Windspeed**
				Mean	**Low**	**High**		
		mm			**°C**		**%**	**m/s**
January	65.3	2.1	113.5	9.1	5.3	14.6	66.9	2.4
February	64.2	2.3	50.0	11.7	8.8	16.4	74.2	2.7
March	107.2	3.5	26.9	14.1	10.0	19.4	62.1	2.8
April	127.9	4.4	143.5	18.6	14.0	24.5	66.6	2.8
May	130.8	4.8	200.2	23.8	20.6	28.2	74.8	2.7
June	160.4	5.4	119.4	26.0	21.4	31.0	71.7	2.5
July	189.5	6.1	12.4	27.6	23.7	32.9	63.5	2.3
August	183.3	5.9	25.1	29.1	25.0	35.2	61.7	1.6
September	148.1	5.0	47.5	27.3	23.3	33.2	63.2	1.7
October	114.2	4.9	71.4	19.6	14.9	26.2	63.1	2.0
November	70.0	2.3	35.6	12.9	7.6	19.5	66.6	2.0
December	64.6	2.2	11.7	11.2	6.1	18.1	62.6	1.9

Table 3. 3 Analysis of variance for measured parameters for the clay loam subsoil study.

	TQ		**% GC**		**SH**		**U**	**TD**	**OM**
	2018	**2019**	**2018**	**2019**	**2018**	**2019**			
Capping Depth (CD)	***	***	***	***	***	***	***	***	***
Worm Power (WP)	NS	NS	NS	NS	NS	NS	NS	NS	*
Cultural Practice (CP)	***	*	**	***	*	NS	NS	NS	NS
Date (D)	***	***	***	***	***	***	***	***	***
CD x WP	**	***	NS	NS	NS	NS	NS	NS	***
CD x CP	NS	*	NS	NS	NS	NS	NS	*	NS
CD x D	***	***	***	***	***	***	NS	NS	NS
WP x CP	NS	**	NS	NS	NS	NS	NS	NS	NS
WP x D	NS	*	**	*	NS	NS	NS	*	NS
CP x D	***	***	***	***	NS	*	NS	NS	NS
CD x WP x CP	NS	NS	NS	NS	NS	**	NS	NS	NS
CD x WP x D	NS	NS	NS	**	NS	NS	NS	NS	***
CD x CP x D	NS	NS	NS	NS	NS	NS	NS	*	NS
WP x CP x D	NS	NS	NS	NS	NS	NS	NS	NS	NS
CD x WP x CP x D	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS, *, **, *** Nonsignificant or significant at P = 0.05, 0.01, or 0.001

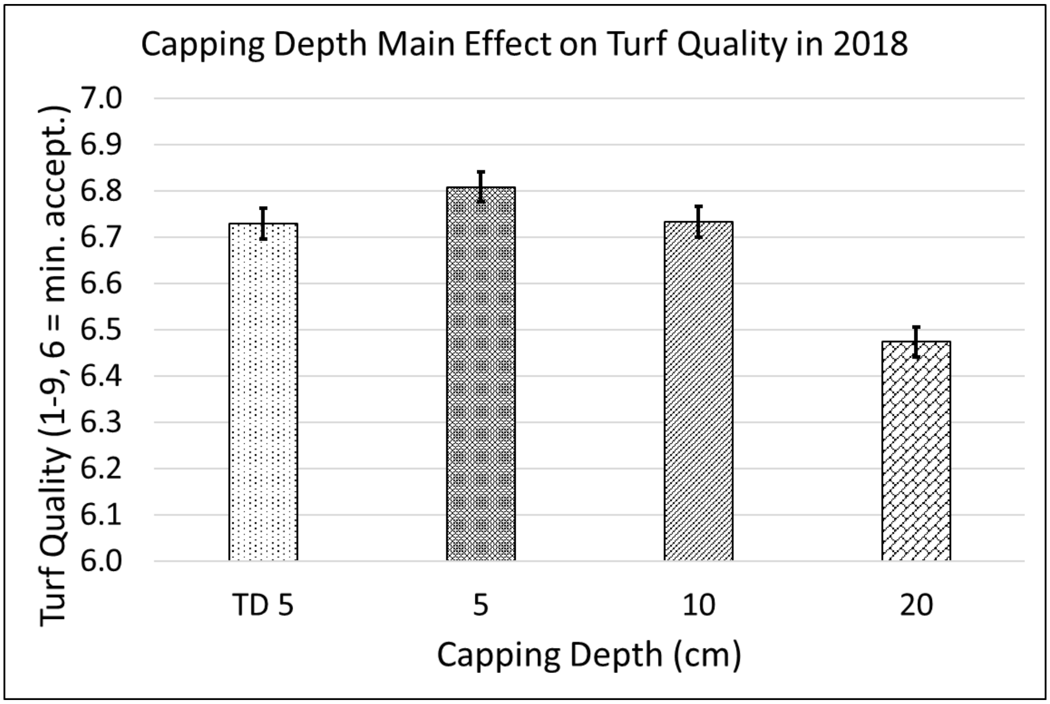
Table 3. 4 Analysis of variance for monthly organic matter content measurements in 2019.

	Organic Matter
Capping Depth (CD)	NS
Worm Power (WP)	*
Date (D)	***
CD x WP	NS
CD x D	NS
WP x D	NS
CD x WP x D	NS

NS, *, **, *** Nonsignificant or significant at P = 0.05, 0.01, or 0.001

Turfgrass Quality

Based on ANOVA, there was a significant capping depth main effect on turfgrass quality in 2018 and 2019 (Table 3.3; Figures 3.1 and 3.2). When pooling across Worm Power and cultural practice, turfgrass quality ranged from 6.4 to 6.8 across capping depths in 2018. The 5 cm capping depth plots had the highest turfgrass quality, followed by the TD 5 cm and 10 cm capping depth plots. The lowest turfgrass quality was observed with the 20 cm capping depth plots. All capping depths produced mean turfgrass quality that was above the minimum acceptable turfgrass quality of 6.0. When pooling across Worm Power and cultural practice in 2019, turfgrass quality ranged from 6.4 to 6.9 across capping depths. The TD 5 cm and 5 cm capping depth plots had the highest turfgrass quality, followed by the 10 cm capping depth plots. Again, the lowest quality was associated with the 20 cm capping depth plots. All capping depth plots supported turfgrass qualities that were above the minimum acceptable turfgrass quality of 6.0.



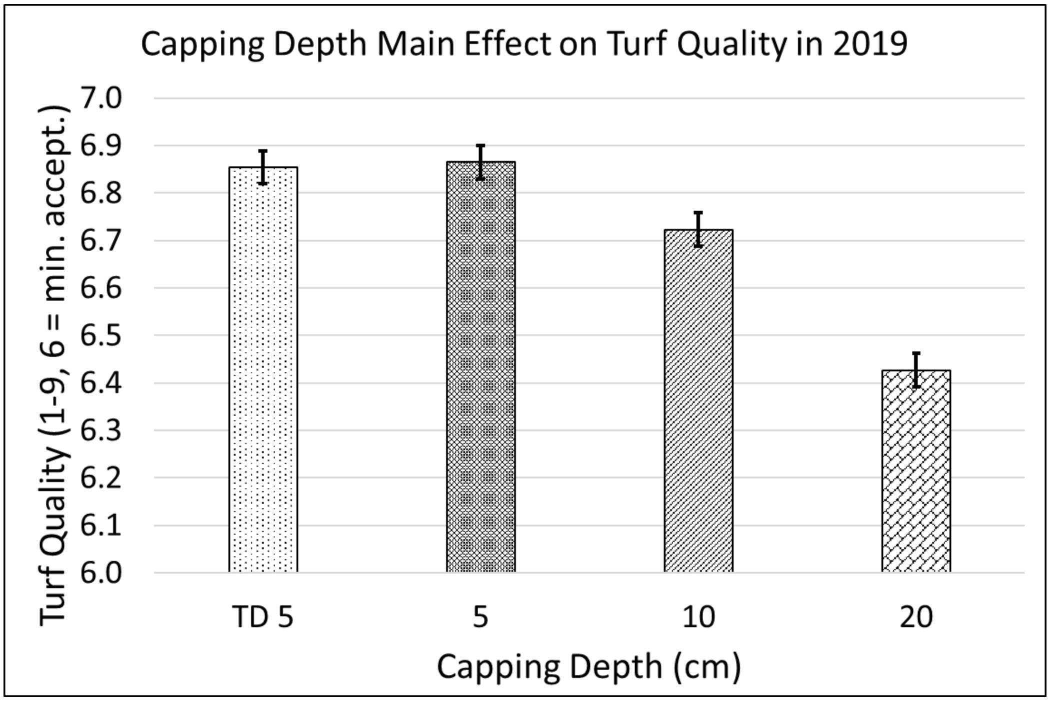


Figure 3.1 (upper) and 3.2 (lower). Turfgrass quality as affected by capping depth for 2018 and 2019. Data are pooled across Worm Power and cultural practice. Error bars indicate Fisher’s LSD at $P \leq 0.05$.

The ANOVA also showed a cultural practice main effect on turfgrass quality in 2018 (Table 3.3, Figure 3.3). Turfgrass quality ranged from 6.6 to 6.8 across cultural practices. The untreated and verticut plots had the highest mean turfgrass quality followed by the core aerated plots and lastly the verticut + core aerated plots. All cultural practice treatments produced turfgrass quality that was well above the minimum acceptable turfgrass quality of 6.0.

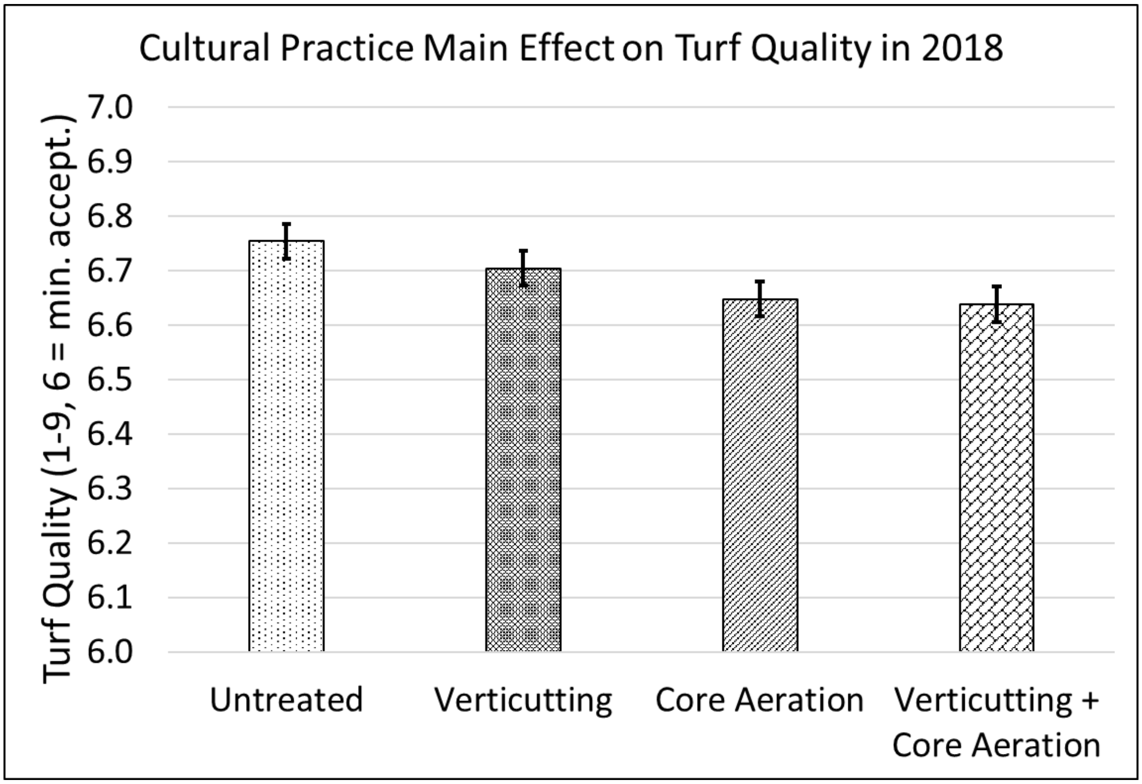
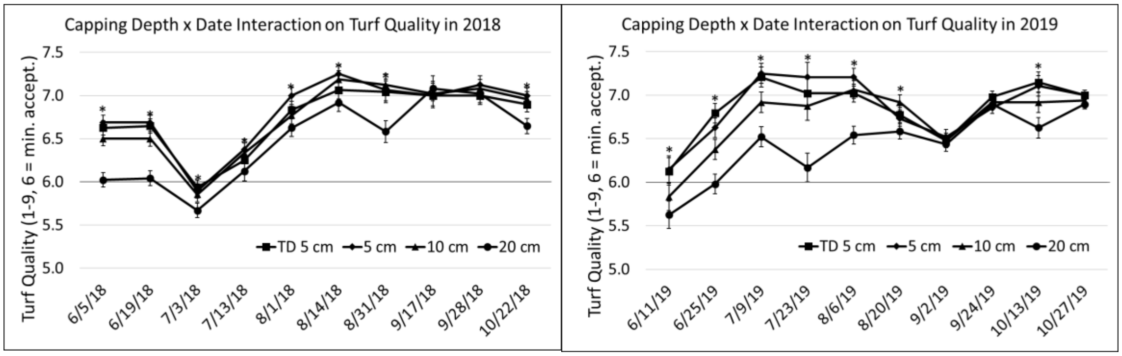


Figure 3.3. Turfgrass quality in 2018 as affected by cultural practice. Data are pooled across capping depths and Worm Power treatments. Error bars indicate Fisher's LSD at $P \leq 0.05$.

The ANOVA also detected a significant capping depth x date interaction on turfgrass quality in 2018 and 2019 (Table 3.3; Figures 3.4 and 3.5). There was a capping depth main effect on turfgrass quality on eight of ten dates in 2018. As such, turfgrass quality was generally highest in the TD 5 cm and 5 cm capping depths and lowest in the 20 cm capping depths, although some dates showed otherwise. On only one of ten rating dates, turfgrass quality fell below the minimum acceptable threshold of 6.0 within all capping depths. In 2019, there was a capping depth main effect on turfgrass quality on seven of ten rating dates. Turfgrass quality was generally highest in the TD 5 cm and 5 cm capping depths, followed by the 10 cm capping depth, and lastly the 20 cm capping depth. Turfgrass quality fell below the minimum acceptable turfgrass quality of 6.0 on only two of 20 dates and only within the10 and 20 cm capping depth treatments.



Figures 3.4 (left) and 3.5 (right). Turfgrass quality as affected by capping depth x date interaction for 2018 and 2019. Data are pooled across cultural practices and Worm Power treatments. Error bars indicate Fisher's LSD at $P \leq 0.05$. * indicates significant dates.

The ANOVA detected a significant capping depth x cultural practice interaction on turfgrass quality in 2019 (Table 3.3; Figure 3.6). When pooling across all 2019 rating dates, untreated, verticutting, and core aeration plots at the 20 cm capping depth, produced higher turfgrass quality levels than the more intensively managed verticutting + core aeration treatments. At the 20 cm capping depth, untreated, verticutting, and core aeration produced mean turfgrass qualities ranging from 6.4 to 6.5, while plots receiving verticutting + core aeration produced mean turfgrass quality of 6.3. All capping depth x cultural practice treatments produced mean turfgrass qualities that were above the minimum acceptable turfgrass quality of 6.0.

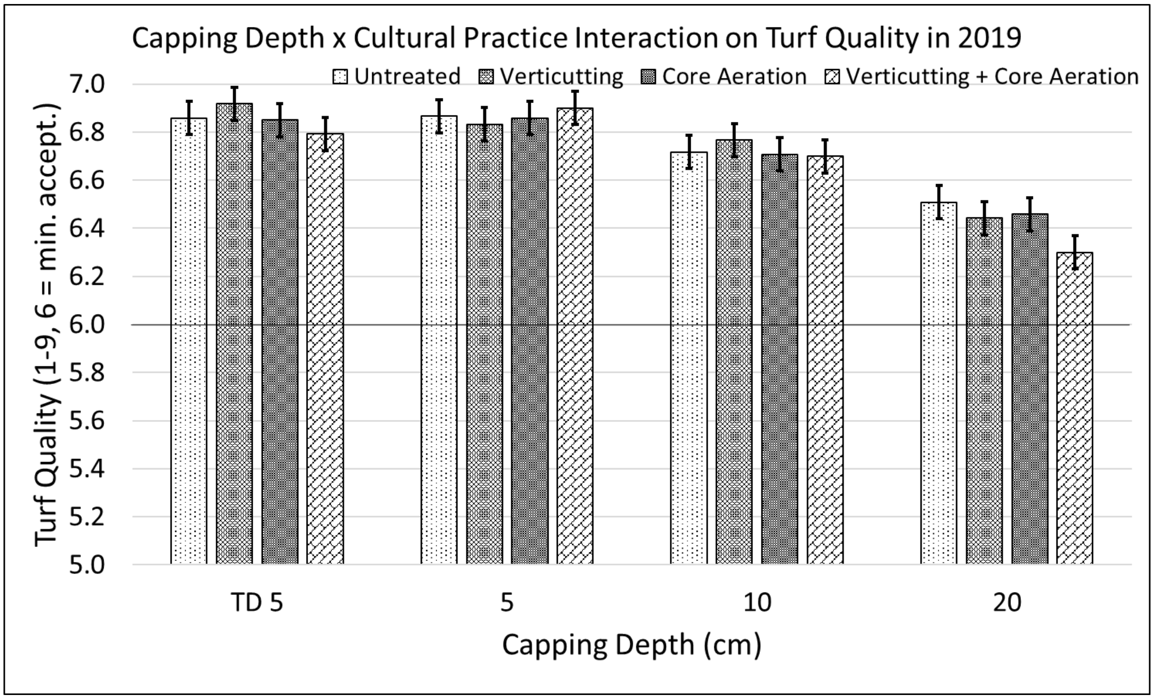


Figure 3.6. Turfgrass quality as affected by capping depth x cultural practice in 2019 interaction. Data are pooled across rating date and Worm Power treatments. Error bars indicate significant differences based on Fisher's LSD at *P* ≤ 0.05.

The ANOVA also detected a significant Worm Power x cultural practice interaction on turfgrass quality in 2019 (Table 3.3, Figure 3.7). In plots receiving core aeration, split-plots that received applications of Worm Power had significantly higher turfgrass quality than plots that did not receive Worm Power. However, there were no other differences due to Worm Power within any other cultural practice treatments in 2019.

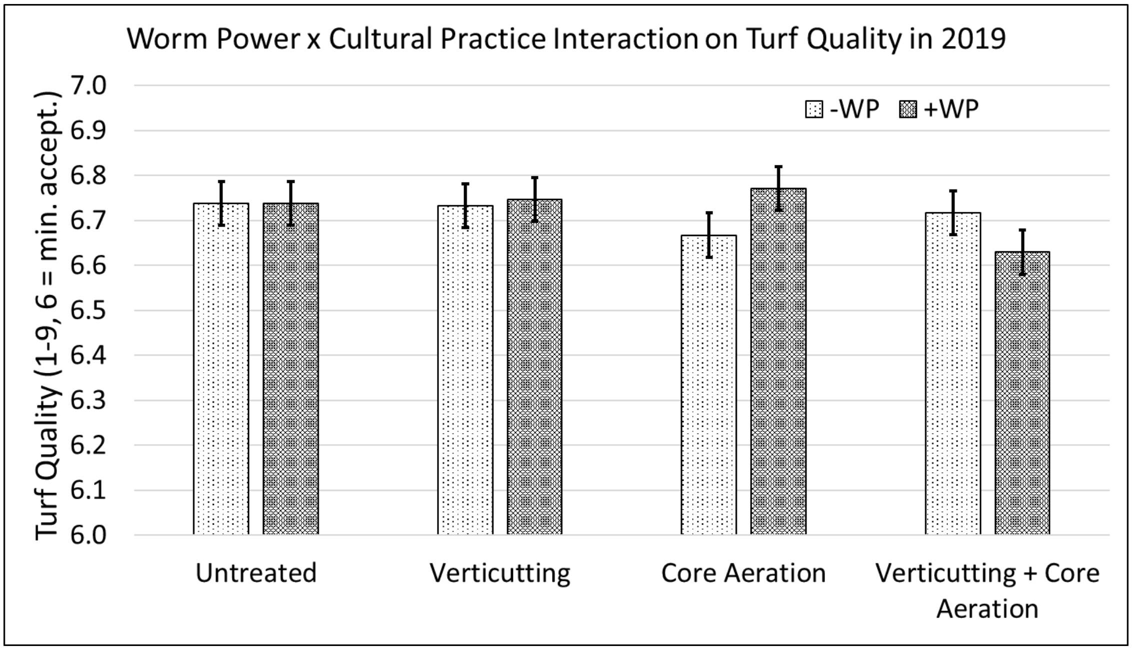


Figure 3.7. Turfgrass quality as affected by Worm Power x cultural practice interaction in 2019. Data are pooled across capping depth. Error bars indicate Fisher's LSD at $P \leq 0.05$.

ANOVA detected a significant Worm Power x date interaction on turfgrass quality in 2019 (Table 3.3; Figure 3.8). As such, plots that received Worm Power had significantly higher turfgrass quality than plots that did not receive Worm Power on one of ten rating dates. On July 6th, 2019 plots that received Worm Power had turfgrass quality of 7.0, compared to plots not receiving Worm Power, which showed mean turfgrass quality of 6.9. On only one of ten dates, turfgrass quality fell below the minimum acceptable turfgrass quality of 6.0, regardless of Worm Power treatment.

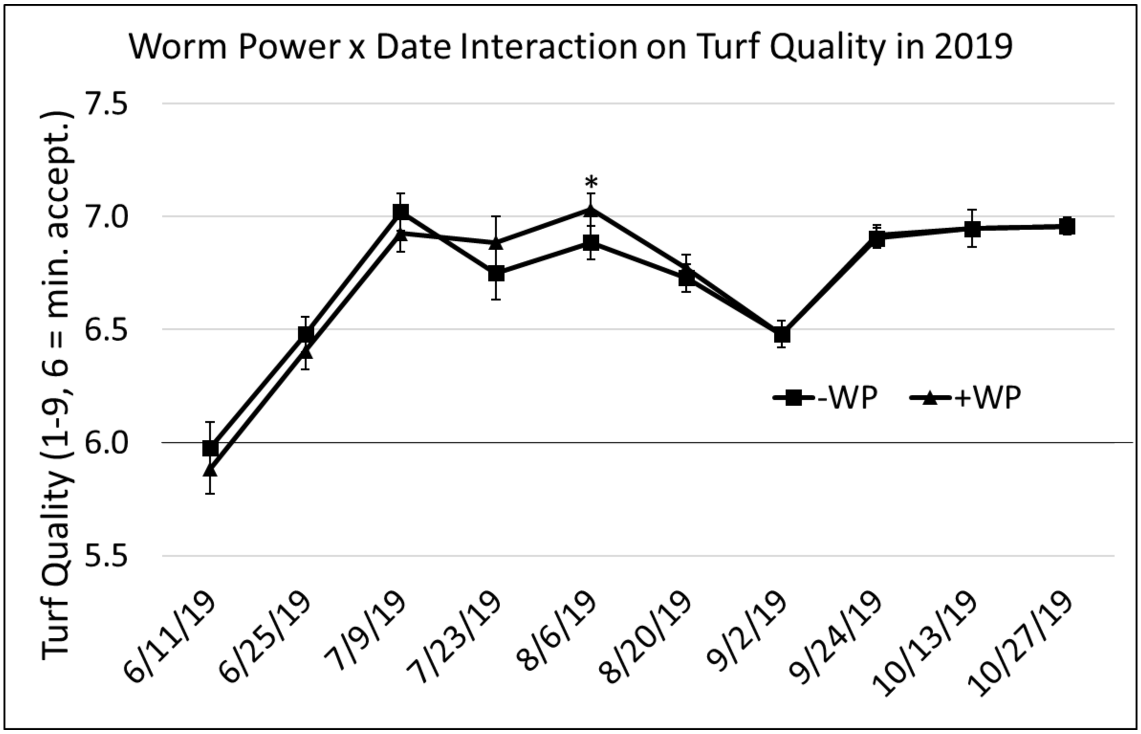


Figure 3.8. Turfgrass quality as affected by Worm Power during 2019. Data are pooled across cultural practice and capping depth. Error bars indicate significant differences based on Fisher's LSD at $P \leq 0.05$. * indicates significant dates.

ANOVA detected a significant cultural practice x date interaction on turfgrass quality in 2018 (Table 3.3; Figure 3.9). Three out of ten dates showed a significant cultural practice x date interaction on turfgrass quality. At the beginning of the season, plots that were untreated or verticut had higher mean turfgrass qualities, but by the end of the season plots receiving combined verticutting + aeration produced the highest turfgrass quality of all cultural practice treatments. ANOVA detected a significant cultural practice x date interaction on turfgrass quality in 2019 (Table 3.3; Figure 3.10). Five out of ten dates showed a significant cultural practice effect on turfgrass quality. At the beginning of the season, plots that were untreated or verticut had higher mean turfgrass qualities, but by the end of the season plots receiving combined verticutting + aeration produced the highest turfgrass quality of all cultural practice treatments.

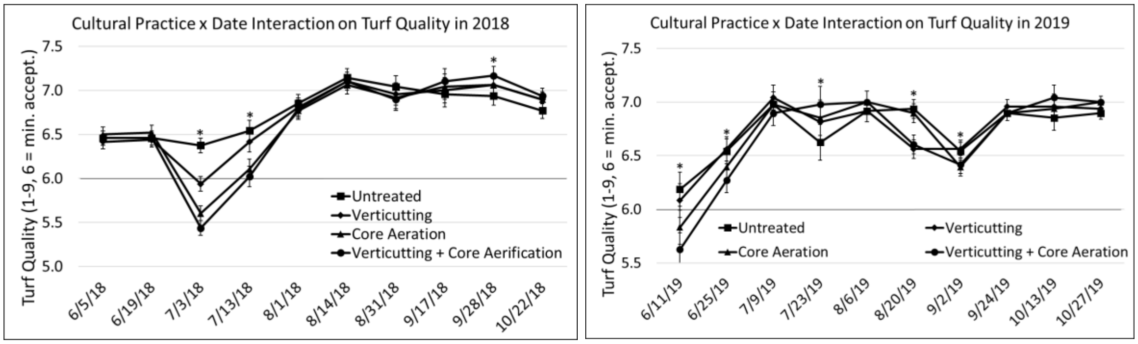
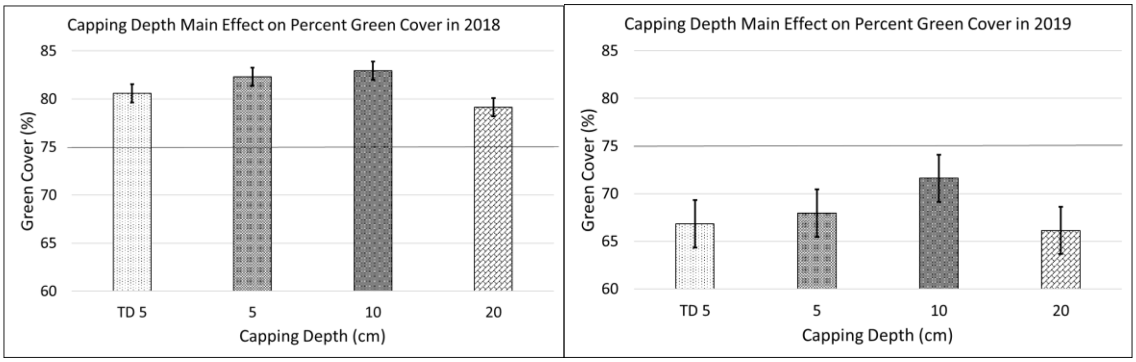


Figure 3.9 (left) and 3.10 (right). Turfgrass quality as affected by cultural practice x date interaction in 2018 and 2019. Data are pooled across Worm Power treatments. Error bars indicate significant differences based on Fisher’s LSD at $P \leq 0.05$. * indicates significant dates.

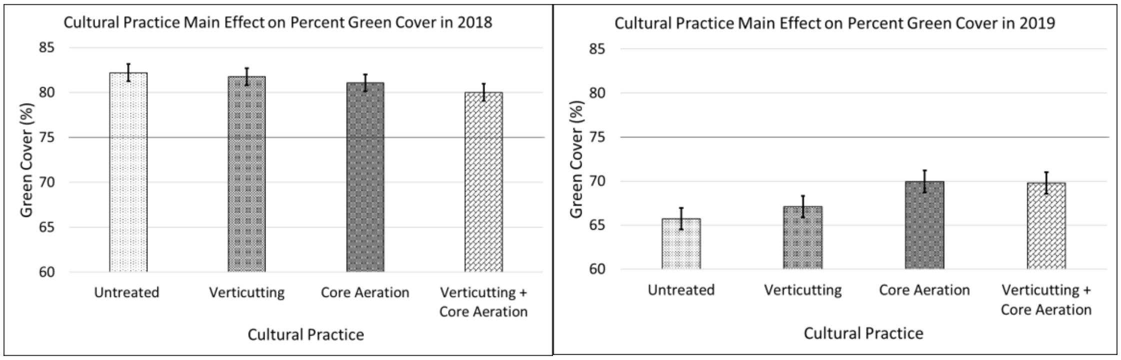
Percent Green Cover

Based on ANOVA, there was a significant capping depth main effect on percent green cover in 2018 and 2019 (Table 3.3; Figures 3.11 and 3.12). In 2018, percent green cover ranged from 79 to almost 83 percent across capping depths. The 10 cm capping depth had the greatest percent green cover, followed by the 5 cm, TD 5 cm, and 20 cm capping depths. The 10 cm capping depth had significantly higher mean percent green cover than the TD 5 cm and 20 cm capping depths. The 5 cm capping depth had significantly higher mean percent green cover than the 20 cm capping depth. In 2019, mean percent green cover ranged from 66 to 72 percent across capping depths. The 10 cm capping depth had the greatest percent green cover followed by the 5 cm, topdressed 5 cm, and 20 cm capping depths. The 10 cm capping depth had significantly higher percent green cover than the 20 cm capping depth. All capping depths in 2019 produced percent green cover levels below 75 percent.



Figures 3.11 (left) and 3.12 (right). Percent green cover as affected by capping depth in 2018 and 2019. Data are pooled across cultural practices and Worm Power treatments. Error bars indicate Fisher's LSD at $P \leq 0.05$.

ANOVA detected a significant cultural practice main effect on percent green cover in both 2018 and 2019 (Table 3.3; Figures 3.13 and 3.14). In 2018, percent green cover ranged from 80 to 83 percent, when pooled across all cultural practice treatment. Untreated plots had a significantly higher percent green cover than plots that were verticut + core aerated. In 2019, percent green cover ranged from 66 to 70 percent across all cultural practices. Plots that were core aerated or verticut + core aerated had a significantly higher percent green cover than plots that were verticut and plots that were untreated.



Figures 3.13 (left) and 3.14 (right). Percent green cover in 2018 and 2019 as affected by cultural practice. Data are pooled across Worm Power. Error bars indicate Fisher's LSD at $p \leq 0.05$.

ANOVA detected a significant capping depth x date interaction on percent green cover in 2018 (Table 3.3; Figure 3.15). On six of 11 dates in 2018, there was a significant capping depth effect on percent green cover, when pooling across cultural practice and Worm Power treatments. Percent green cover ranged from 40 to 98 throughout the season across all capping depths. The TD 5 cm, 5 cm, and 10 cm capping depths generally outperformed the 20 cm capping depth during the summer months, but this trend reversed from September through November. A noticeable decline in percent green cover, particularly for the 20 cm capping depth occurred following the cultural practice treatments in June and August.

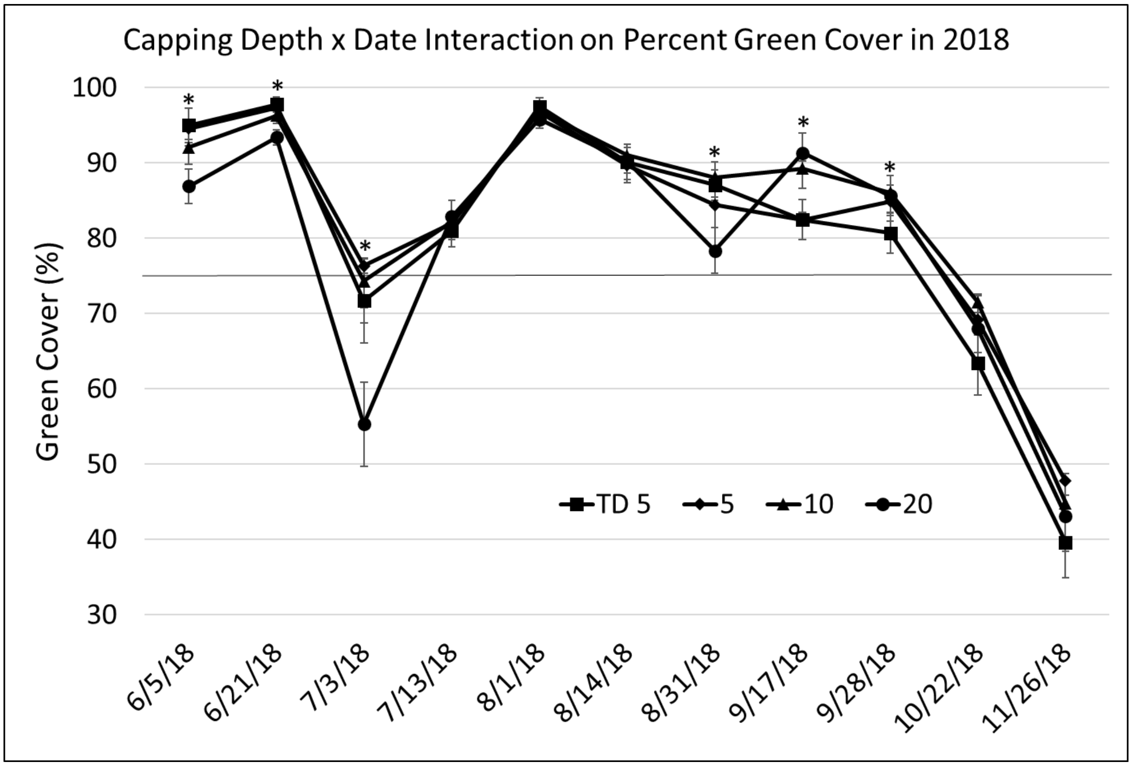
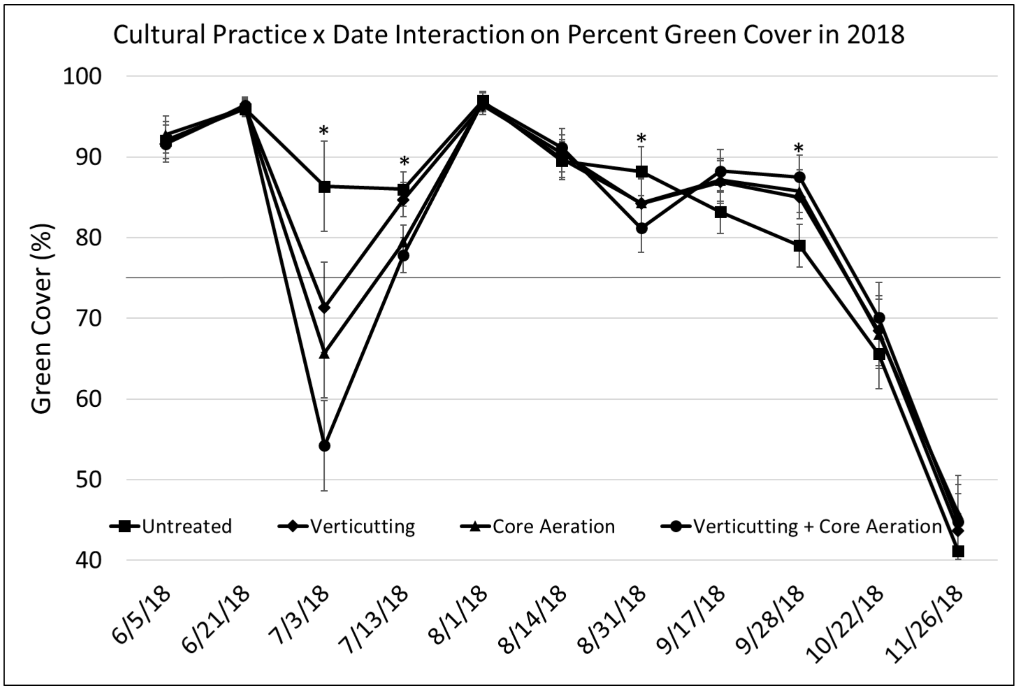
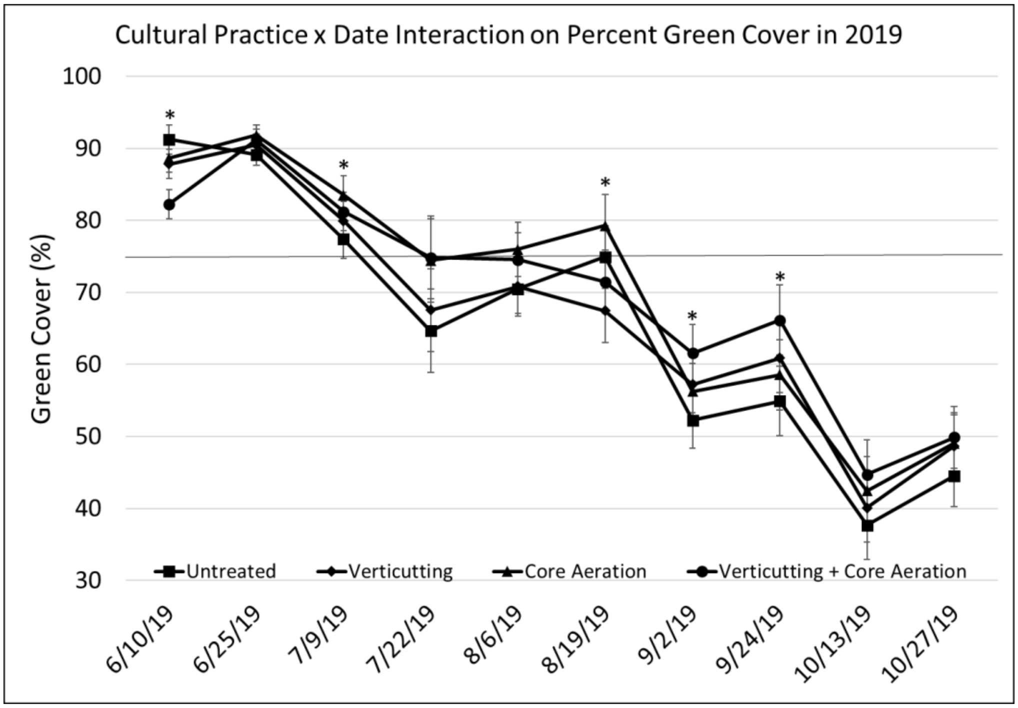


Figure 3.15. Percent green cover as affected by capping depth x date interaction in 2018. Data are pooled across cultural practice and Worm Power treatments. Error bars indicate significant differences based on Fisher's LSD at $P \leq 0.05$. * indicates significant dates.

ANOVA detected a significant cultural practice x date interaction for percent green cover in both 2018 and 2019 (Table 3.3; Figure 3.16 and 3.17). In 2018, there was a significant cultural practice effect on percent green cover on four of 11 dates. Percent green cover ranged from 41 to 97 throughout the season across all cultural practices. Early in the season, the untreated, verticut, and core-aerated plots generally outperformed the verticutting + core aeration plots for percent green cover. However, by the end of the season, verticutting + core aeration treatments had the highest percent green cover. Only three of 11 dates produced percent green covers that were below the 75 percent.

In 2019, there were significant cultural practice main effects on percent green cover on five of ten rating dates (Table 3.3; Figure 3.17). Percent green cover ranged from 38 to 91 throughout the season when taking into account all cultural practices. Early in the season. There was no clear trend in terms of treatment effects on percent green cover. However, by the end of the season, the plots receiving verticutting + core aeration had the highest percent green cover. Percent green cover fell below 75% on seven of ten rating dates during the 2019 season.





Figures 3.16 (upper) and 3.17 (lower). Percent green cover in 2018 and 2019 as affected by cultural practice x date interaction. Data are pooled across Worm Power. Error bars indicate significant differences based on LSD at p≤ 0.05. * indicates significant dates.

The ANOVA showed a significant capping depth x Worm Power x date interaction on percent green cover in 2019 (Table 3.3; Figure 3.18). At the 10 cm capping depth, percent green cover was significantly higher for plots not receiving Worm Power applications than for plots receiving Worm Power applications on one of ten dates. On December 27th, 2019 plots that did not receive Worm Power applications had percent green cover of 57 while plots that received Worm Power had mean percent green cover of 41.

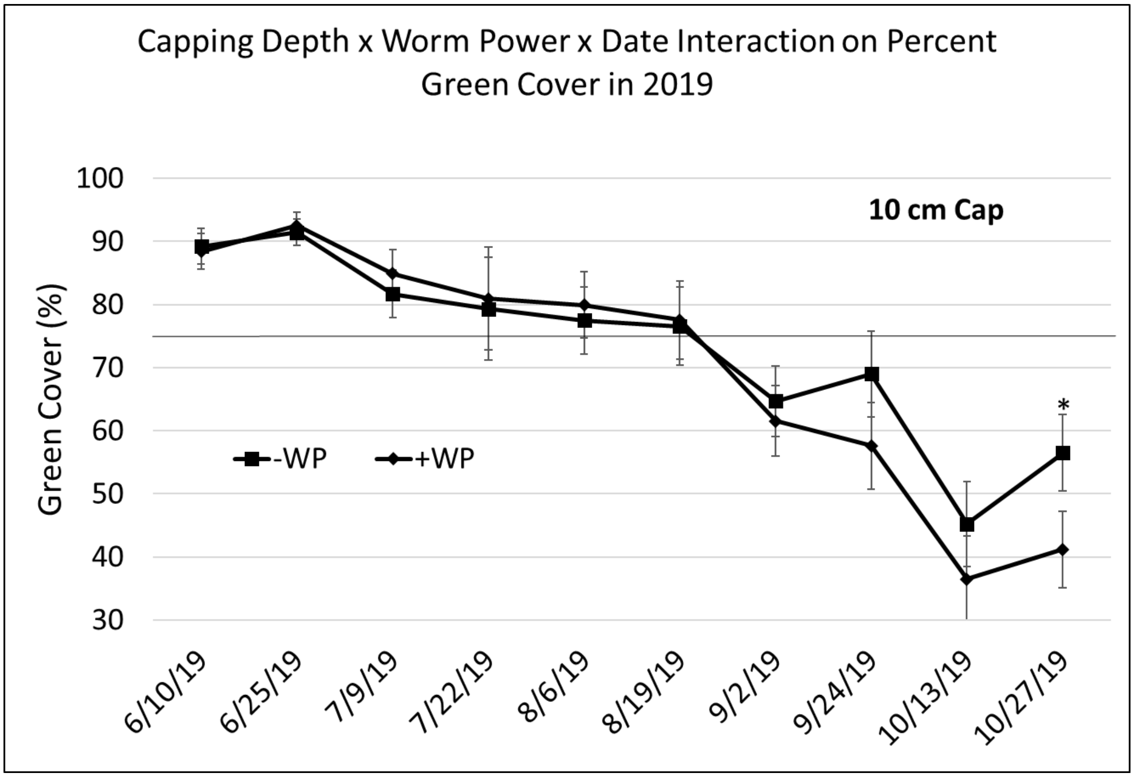
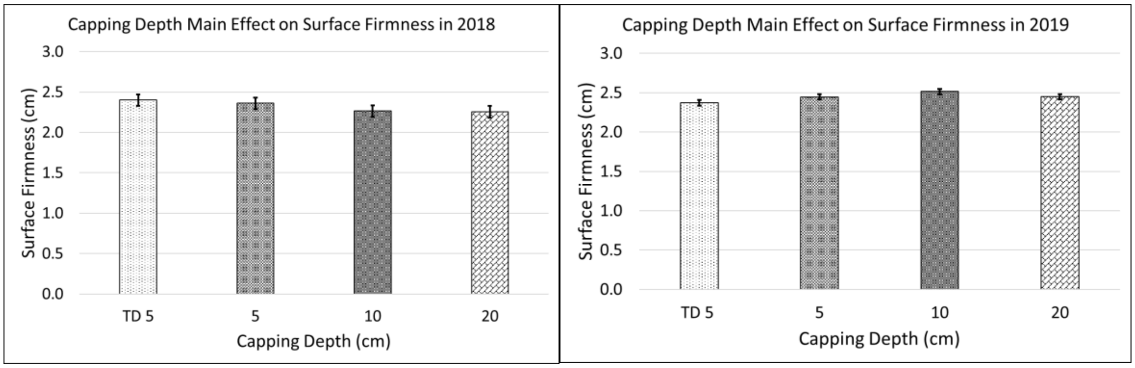


Figure 3.18. Percent green cover in 2019 as affected by capping depth x Worm Power x date interaction. Data are pooled across cultural practice. Error bars indicate Fisher's LSD at $P \leq 0.05$. * indicates significant dates.

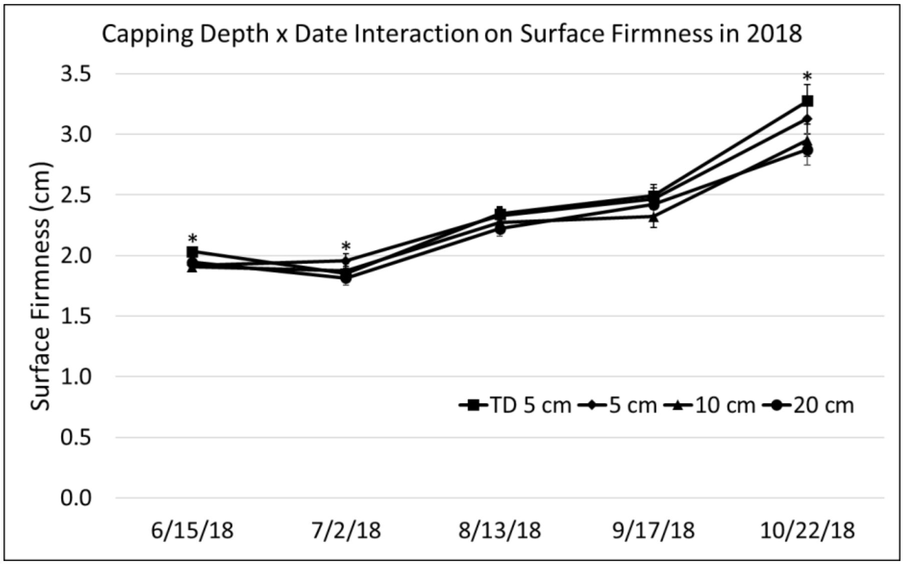
Surface Firmness

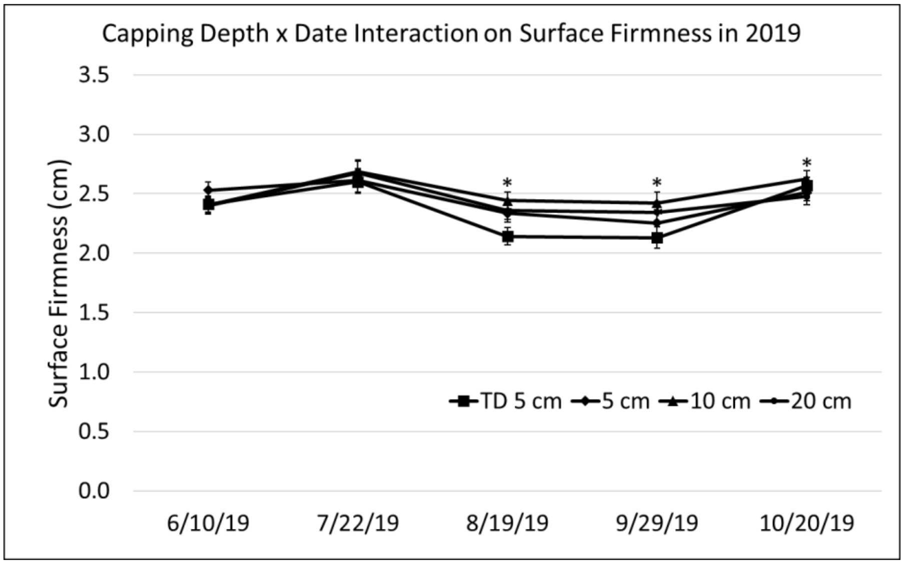
Based on ANOVA, there was a significant capping depth main effect on surface firmness in both 2018 and 2019 (Table 3.3; Figures 3.19 and 3.20). In 2018, when pooling across cultural practices and Worm Power treatments, surface firmness ranged from 2.26 to 2.40 cm. As such, the 10 and 20 cm capping depth plots were slightly but significantly firmer than both the TD 5 and 5 cm capping depth plots. In 2019, surface firmness ranged from 2.37 to 2.52 cm, but the trends were reversed somewhat. The TD 5 cm capping depth plots were significantly firmer (lower values for cm depth of ball penetration) than the 5, 10, and 20 cm capping depth plots.



Figures 3.19 (left) and 3.20 (right). Surface firmness as affected by capping depth in 2018 and 2019. Data are pooled across cultural practice treatments and Worm Power. Lower values represent greater surface firmness. Error bars indicate Fisher’s LSD at $P \leq 0.05$.

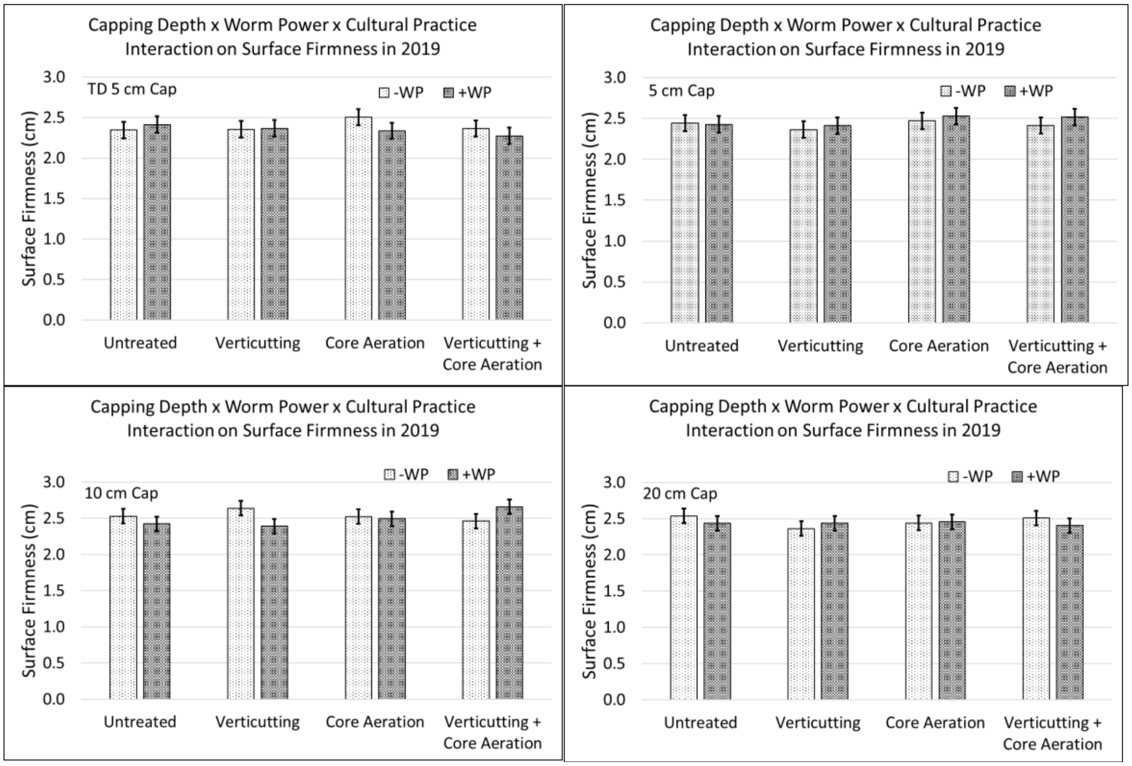
The ANOVA detected a significant capping depth x date interaction on surface firmness in 2018 and 2019 (Table 3.3; Figures 3.21 and 3.22). On three of five dates in 2018, there was a capping depth effect on surface firmness. Surface firmness ranged from 1.81 to 3.28 cm. The TD 5 cm and 5 cm capping depths were the least firm throughout most of the season. By the end of the season, the 10 and 20 cm capping depths were the firmest of all treatments. On three of five dates during 2019, there was a significant capping depth effect on surface firmness. Surface firmness ranged from 2.13 to 2.68 cm. Surface firmness was the least firm in the 10 cm capping depth plots and the firmest in the TD 5 cm capping depth plots.





Figures 3.21 (upper) and 3.22 (lower). Surface firmness as affected by capping depth x date interaction in 2018 and 2019. Data are pooled across cultural practice and Worm Power treatments. Lower values represent greater surface firmness. Error bars indicate Fisher's LSD at $P \leq 0.05$. * indicates significant dates.

The ANOVA detected a significant three-way capping depth x Worm Power x cultural practice interaction on surface firmness in 2019 (Table 3.3; Figures 3.23, 3.24, 3.25, and 3.26). At the 10 cm capping depth in plots that were verticut, split plots that received Worm Power were significantly firmer than plots that did not receive a Worm Power. Plots at the 10 cm capping depth that received Worm Power applications had a mean surface firmness of 2.39 cm while plots that did not receive Worm Power applications had a mean surface firmness of 2.64 cm.



Figures 3.23 (upper left), 3.24 (upper right), 3.25 (bottom left), and 3.26 (bottom right). Surface firmness as affected by capping depth x Worm Power x cultural practice interaction in 2019. Lower values represent greater surface firmness. Error bars indicate Fisher's LSD at $P \leq 0.05$.

The ANOVA also detected a significant cultural practice x date interaction on surface firmness in 2019 (Table 3.3; Figure 3.27). For three of five rating dates in 2019, there was a significant cultural practice effect on surface firmness. Surface firmness ranged from 2.17 to 2.68 cm throughout the season. In June of 2019, plots that received verticutting + core aeration were significantly firmer than untreated plots. In August and September of 2019, plots that received verticutting only or were untreated were significantly firmer than the treatments that received aeration.

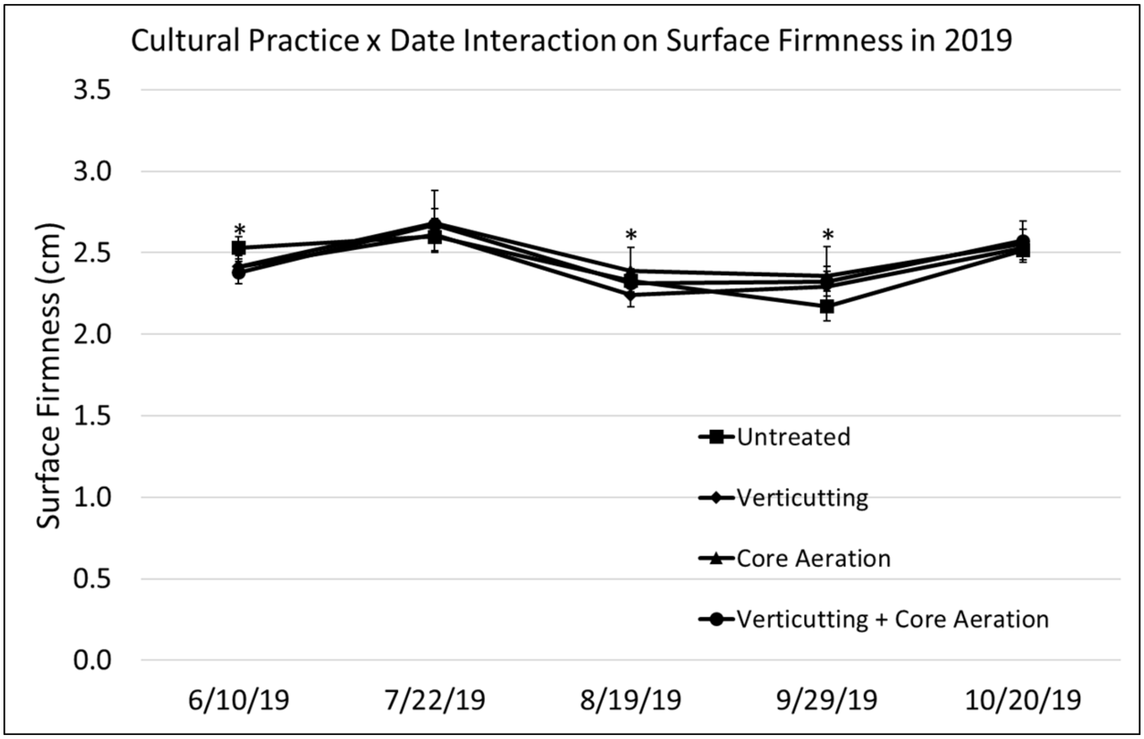


Figure 3.27. Surface firmness in 2019 as affected by cultural practice x date interaction. Lower values represent greater surface firmness. Data are pooled across capping depth and Worm Power treatments. Error bars indicate Fisher’s LSD at $P \leq 0.05$. * indicates significant dates.

Infiltration Rates

Based on ANOVA, there was a significant capping depth main effect on infiltration rate, when pooled across all other treatments and over both years of the study (Table 3.3; Figure 3.28). Mean infiltration rate for the two years ranged from 1.7 to 2.2 mm $s^{-0.70}$. The 20 cm capping depth plots had a significantly higher mean infiltration rate than the 10 cm capping depth plots.

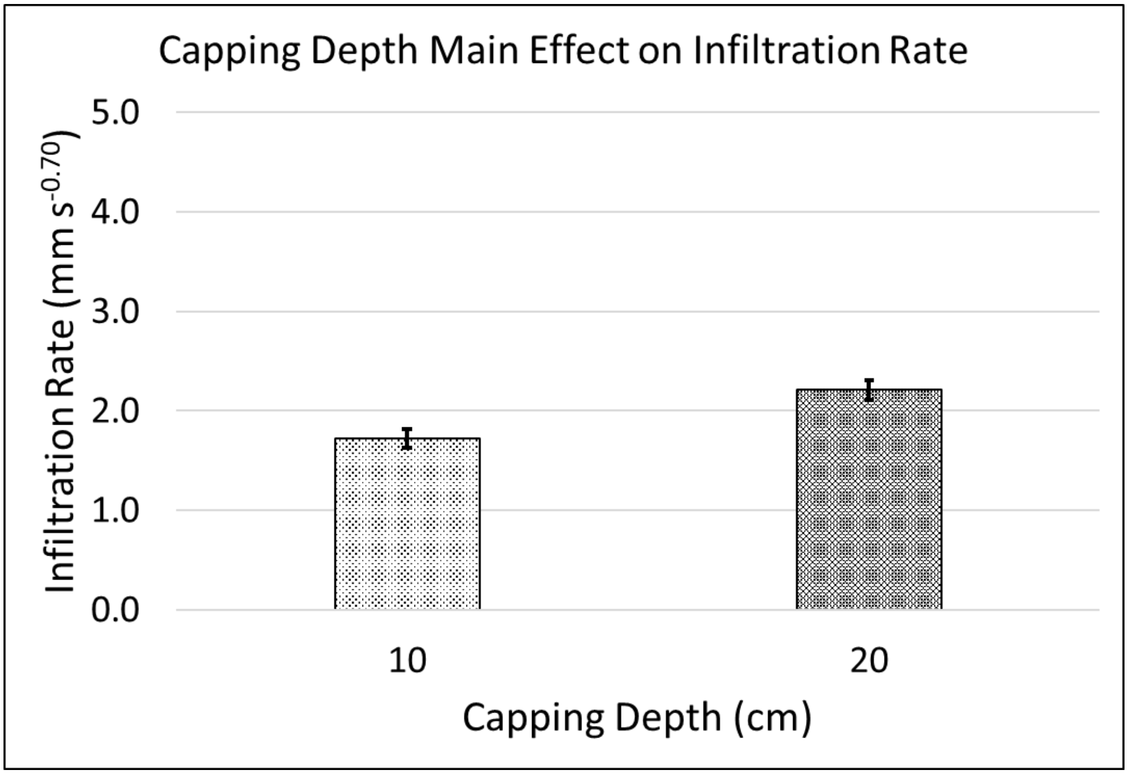


Figure 3.28. Infiltrate rate as affected by capping depth. Data are pooled over years, cultural practices, and Worm Power treatments. Error bars indicate Fisher’s LSD at $P \leq 0.05$.

Thatch Depth

The ANOVA detected a significant capping depth main effect on depth of thatch, when pooled across all other treatments and over both years of the study (Table 3.3; Figure 3.29). Thatch depth ranged from 2.17 to 2.41 cm. Thatch depth in the 20 cm capping depth plots was found to be significantly greater than that for the 10 cm capping depth plots.

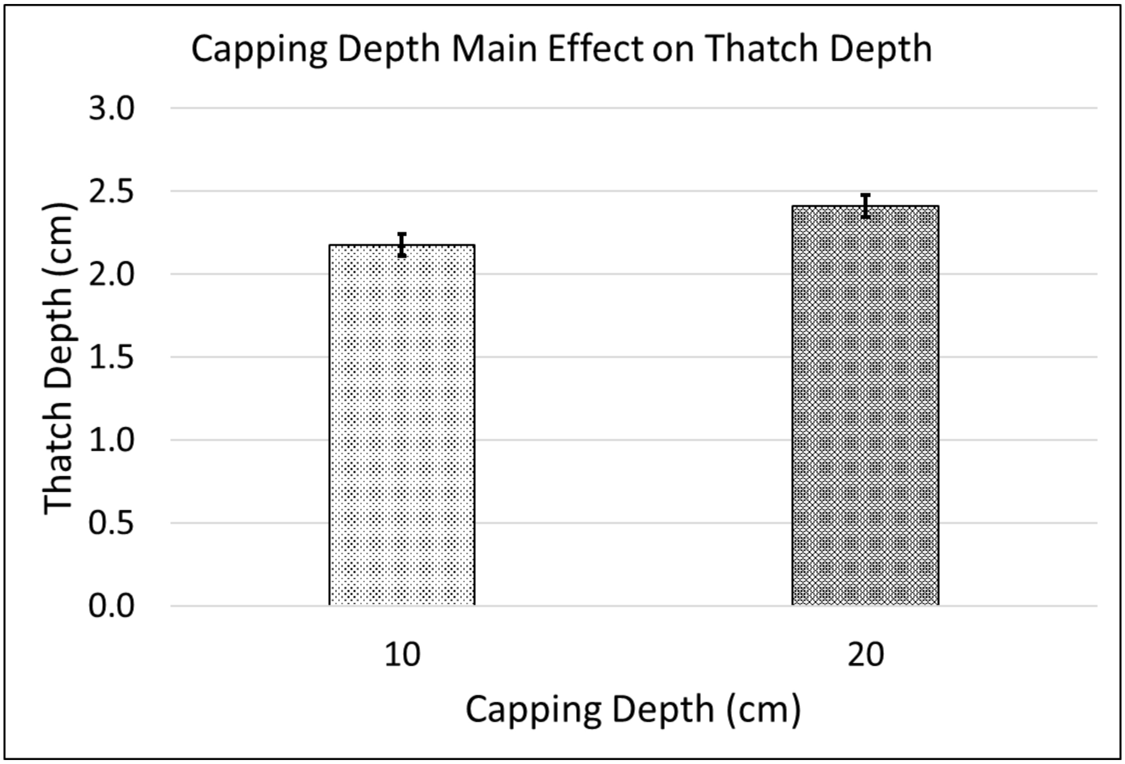


Figure 3.29. Thatch depth across both years as affected by capping depth. Data are pooled across cultural practice, Worm Power, and years. Error bars indicate Fisher's LSD at $P \leq 0.05$.

Organic Matter Content

Based on ANOVA, there was a significant capping depth main effect on organic matter content (based on loss on ignition), when pooled across all treatments and over both years of the study (Table 3.3; Figure 3.30). Mean organic matter content ranged from 64 to 71 g kg^{-1} (6.4 to 7.1%) over both years. Interestingly, although thatch depth measurements showed greater thatch depth associated with the deeper capping depth, the 10 cm capping depth plots were found to contain significantly higher organic matter content than the 20 cm capping depth plots.

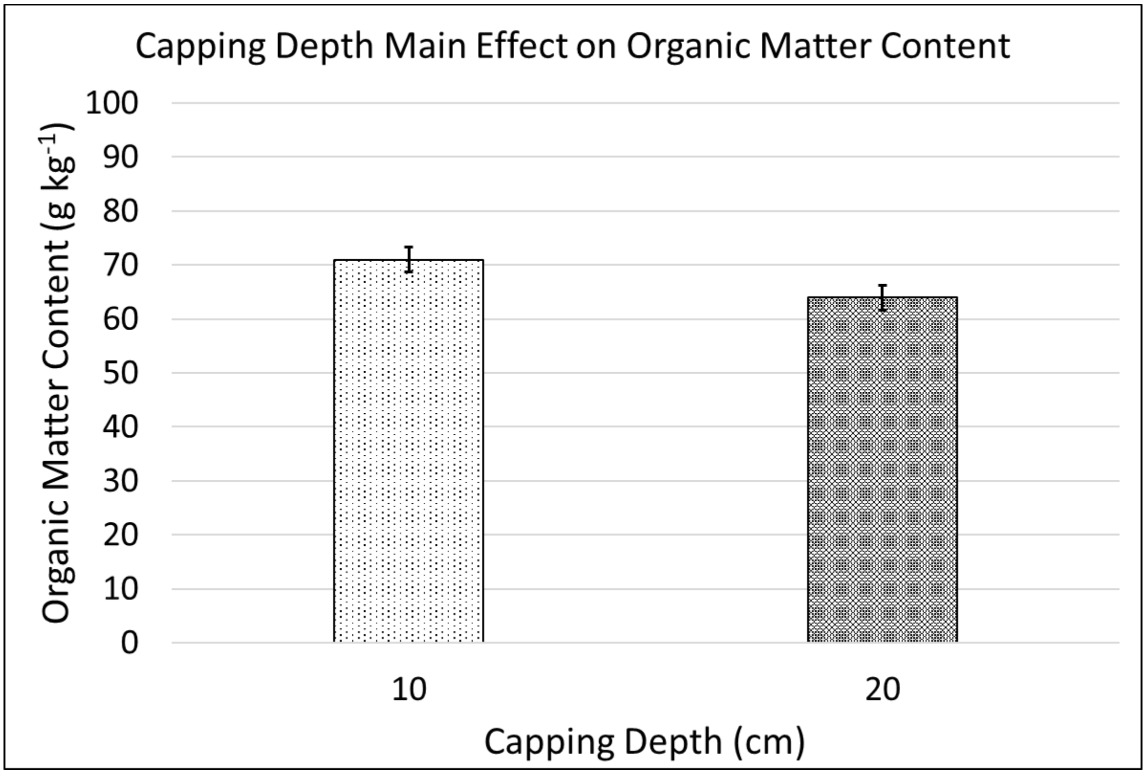


Figure 3.30. Organic matter content as affected by capping depth. Data are pooled across cultural practice, Worm Power, and year. Error bars indicate Fisher's LSD at $P \leq 0.05$.

Seasonal Dynamics of Organic Matter

The ANOVA detected a significant date main effect on monthly organic matter content in 2019 (Table 3.4; Figure 3.33). Organic matter content increased from May to July, peaking at approximately 83g kg^{-1} (8.3%) before starting its decline in August. On

October 30th, organic matter content was significantly lower than for all other dates reaching a low of 56 g kg^{-1} (5.6%).

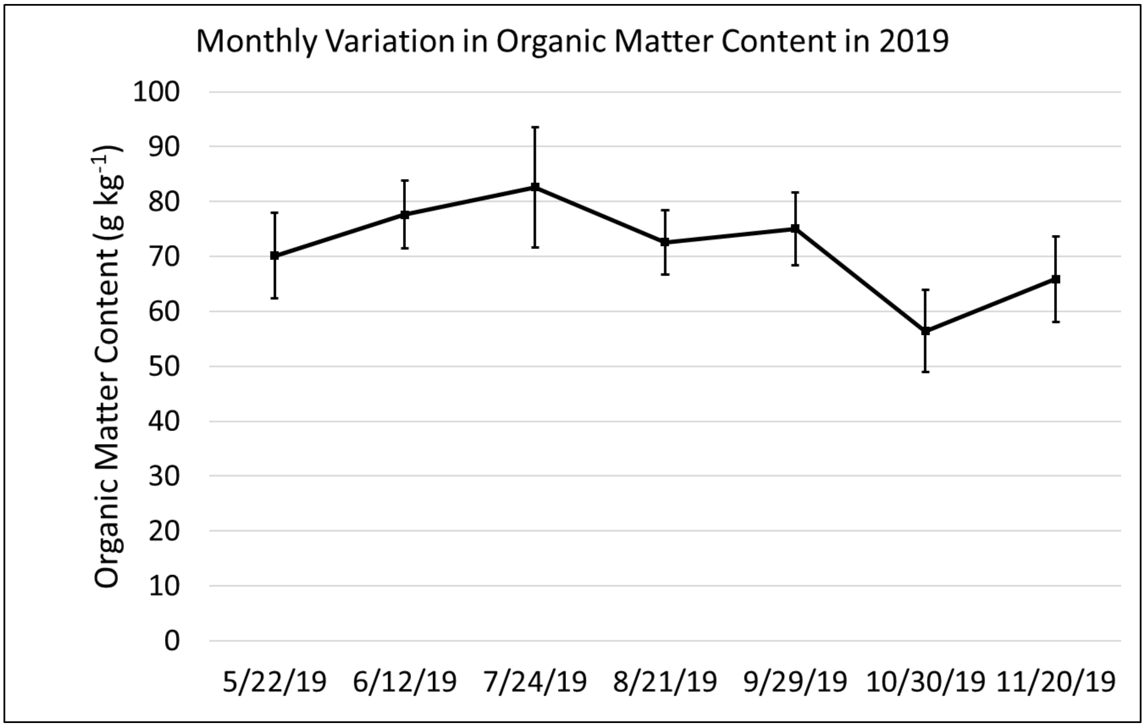


Figure 3.31. Organic matter content as affected by date for the control plots on a monthly basis. Data are pooled across capping depth and Worm Power. Error bars indicate Fisher's LSD at $P \leq 0.05$.

Discussion

Capping Depth

Capping depth played a critical role in overall turfgrass health and performance. The shallower capping depths outperformed the deepest capping depth for both TQ and %GC. Similar results regarding TQ and %GC were found in a previous study on sand-capped golf course fairways (Dyer, 2017). Capping depth played a role in surface firmness but produced different results depending on the year, probably due to different environmental conditions such as rainfall, making it hard to determine a true trend. In 2018 (Table 3.1), there was 1,278 mm of rainfall compared to only 857 mm in 2019 (Table 3.2). The 20 cm capping depth outperformed the 10 cm capping depth regarding infiltration rate suggesting a deeper capping depth may be more appropriate in areas of high rainfall. Thatch depth was significantly greater in the 20 cm caps than the 10 cm caps suggesting thatch may not break down as quickly due to dry hydrophobic conditions that arise at the deeper capping depth (Dyer, 2017). Percent organic matter was significantly greater in the 10 cm caps than the 20 cm caps. This is the opposite trend from what was observed in a previous study that utilized the same plots (Dyer, 2017). This makes sense with the results observed on thatch depth and suggest that potentially the 10 cm capping depth environmental conditions (moisture, temperature etc.) are more favorable to the breakdown of thatch leading to a higher organic matter content. In conclusion, capping depth seems to be an important factor to consider when constructing/renovating your sand-capped turfgrass systems.

Worm Power

Worm Power applications had little effect on overall turfgrass quality. This is the opposite of what was found in a previous study (Aqua-Aid Solutions and NC State, 2016) where Worm Power enhanced NDVI readings, which is another measurement for turfgrass quality. However, Worm Power had an effect on turfgrass quality depending on the cultural practices. Worm Power seemed to enhance turfgrass quality when combined with core aerification suggesting that maybe the removal of plugs allowed the product to make its way into the soil better leading to more efficacy. Previous studies have shown that core aerification leads to better infiltration of water by reducing runoff (Mitra et al., 2006). It is believed that core aeration may have a similar effect on the movement of Worm Power. However, the opposite trend was observed in the verticutting + core aeration treatment making it hard to claim its effects in combination with core aerification. Worm Power had little to no effect on turfgrass percent green cover. At the 10 cm capping depth, plots that received Worm Power in combination with verticutting were significantly firmer than plots that did not receive a Worm Power. However, this was the only capping depth and only cultural practice treatment that showed significant results making it difficult to establish a clear trend. Previous studies have shown that Worm Power has a similar level of microbial material as would be found in natural turfgrass systems and therefore could play a significant role in the breakdown or organic matter (Aqua-Aid Solutions and NC State, 2016). However, Worm Power had little to no effect on organic matter content in this study.

Cultural Practices

Cultural practices played a role in turfgrass quality with the most aggressive cultural practice leading to a short-term reduction in turfgrass quality but overall an enhanced turfgrass quality late into the season. While cultural practices at the shallower capping depths did not produce a significant differences in turfgrass quality, at the deepest capping depth there were significant differences. At the 20 cm capping depth, the most aggressive cultural practice led to the lowest turfgrass quality suggesting that this capping depth may not be as receptive to disruptive cultural practices as they are already stressed out mostly from dry hydrophobic conditions that persist (Dyer, 2017). Similar studies have shown that significant turfgrass injury could arise when using aggressive cultivation practices under dry conditions (Murphy and Rieke, 1990). Therefore, the 20 cm caps may not recover as quickly leading to the reduced overall turfgrass quality. Cultural practice seemed to play a role in percent green cover. In 2018, the untreated plots had the greatest percent green cover but in 2019 the core aerated and the verticut + core aerated plots had the greatest percent cover. This suggest that aggressive cultural practices may reduce percent green cover in the short term but enhance percent green cover long term. Core aeration and verticutting are considered to be common management practices that aid in the removal of organic matter (Moeller and Lowe, 2016). It is believed that in turn, surface firmness will increase in response to the reduction of organic matter accumulation in the thatch layer. However, cultural practices had little to no effect on surface firmness in this study.

Longer Study Time Needed

While some trends are apparent, further research is needed to better understand how sand-capped systems perform long-term. While capping depth seems to play a critical role in how sand-capped systems perform, there is still limited research on the topic. Continued research is necessary to understand how different capping depths perform in combination with various cultural practices to manage thatch and organic matter accumulation over time. Two years is not a sufficient amount of time to truly understand how organic matter accumulates in sand-capped systems and how to best manage that organic matter. Perhaps, over time, clearer trends will arise that aid in the management of sand-capped turfgrass systems.

Summary and Conclusion

Capping of degraded golf course fairways with a layer of sand to promote improved turfgrass health, performance, and playability is becoming a common practice where irrigation water is of poor quality and/or high in sodium. Benefits of sand-capping include improved drainage and increased infiltration rates, greater rooting depth, improved traffic tolerance and playing conditions, alleviated compaction, enhanced ability to flush salts, and improved soil structure (White, 2013). However, over time, unique management challenges may arise, including organic matter accumulation, surface hydrophobicity, and subsoil permeability issues. Agronomic issues resulting from surface organic matter accumulation may include, among other things, reduced water infiltration, which could lead to overly dry conditions and poor turfgrass quality. Increased accumulation of organic matter may also lead to reduced surface firmness, resulting in spongy, soft playing conditions that reduce ball bounce and roll resulting in overall poor playability. Therefore, it is important to understand how to manage organic matter accumulation in sand-capped systems through various cultural management practices. Our results indicate that capping depth is a driving factor behind overall performance across all parameters measured. Our results indicate that the shallower capping depths outperform the deepest capping depth regarding overall turfgrass quality and percent green cover. Similar results regarding turfgrass quality and percent green cover in sand-capped systems were found by Dyer, (2017). Our results indicate that the most aggressive cultural practices lead to reduced turfgrass quality initially but potentially lead to greater turfgrass quality late in the season. Our results indicate that deeper capping depths have a slightly higher infiltration rate, greater thatch depth, and a lower organic matter content than shallower capping depths. Our results indicate that the most aggressive cultural practices remove the greatest amount of organic matter from the system. Sand-capping provides many agronomic benefits to turfgrass systems but is not yet fully understood. Further research is needed to understand how organic matter accumulates in sand-capped systems long term and how this organic matter affects overall turfgrass health and playability.

CHAPTER IV

CONCLUSIONS ON THE MANAGEMENT OF SAND-CAPPED FAIRWAYS

Subsoil Sodicity and Hydrophobicity

As golf course irrigation water quality continues to decline, sand-capping of golf course fairways is increasing. Sand-capping has many agronomic benefits including improved drainage and increased infiltration, greater rooting depth, improved traffic tolerance and playing conditions, alleviated compaction, enhanced ability to flush salts, and improved soil structure (White, 2013). However, over time, unique management challenges may arise, including organic matter accumulation, surface hydrophobicity, and subsoil permeability issues, especially where irrigation water contains elevated levels of sodium. Therefore, it is important to understand how various sand-capping depths in combination with various treatments can remedy these issues and provide a high quality healthy turfgrass stand. Our results indicate that capping depth plays a critical role in TQ, VWC, %GC, and WDPT as the shallower capping depths outperformed the deepest capping depth for all parameters. The 20 cm capping depth was dryer and of poorer quality due to hydrophobic conditions that developed. While wetting agent applications helped increased VWC, our results show that they may only be necessary in deeper rather than shallower capping depths to combat hydrophobicity that is more prevalent in deeper sand-capped systems. Our results indicate that a heavy annual gypsum rate is most effective at reducing SAR compared to the untreated plots. This was a key finding as a monthly gypsum rate is what is currently recommended. While sand-capping originated to combat high annual rainfalls, it is being proven that there are many other benefits it provides to improve turfgrass health and playability. Further research is needed to see how sand-capped systems perform over longer periods of time to truly understand their longevity and the management necessary to reap the agronomic benefits they provide.

Thatch and Organic Matter Accumulation

Capping of degraded golf course fairways with a layer of sand to promote improved turfgrass health, performance, and playability is becoming a common practice where irrigation water is of poor quality and/or high in sodium. Benefits of sand-capping include improved drainage and increased infiltration rates, greater rooting depth, improved traffic tolerance and playing conditions, alleviated compaction, enhanced ability to flush salts, and improved soil structure (White, 2013). However, over time, unique management challenges may arise, including organic matter accumulation, surface hydrophobicity, and subsoil permeability issues. Agronomic issues resulting from surface organic matter accumulation may include, among other things, reduced water infiltration, which could lead to overly dry conditions and poor turfgrass quality. Increased accumulation of organic matter may also lead to reduced surface firmness, resulting in spongy, soft playing conditions that reduce ball bounce and roll resulting in overall poor playability. Therefore, it is important to understand how to manage organic matter accumulation in sand-capped systems through various cultural management practices. Our results indicate that capping depth is a driving factor behind overall performance across all parameters measured. Our results indicate that the shallower capping depths outperform the deepest capping depth regarding overall turfgrass quality and percent green cover. Similar results regarding turfgrass quality and percent green cover in sand-capped systems were found by Dyer, (2017). Our results indicate that the most aggressive cultural practices lead to reduced turfgrass quality initially but potentially lead to greater turfgrass quality late in the season. Our results indicate that deeper capping depths have a slightly higher infiltration rate, greater thatch depth, and a lower organic matter content than shallower capping depths. Our results indicate that the most aggressive cultural practices remove the greatest amount of organic matter from the system. Sand-capping provides many agronomic benefits to turfgrass systems but is not yet fully understood. Further research is needed to understand how organic matter accumulates in sand-capped systems long term and how this organic matter affects overall turfgrass health and playability.

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