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Soil moisture monitoring in amenity turfgrass ecosystems

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Summary

Riassunto

La scienza e la gestione del tappeto erboso sono state influenzate positivamente dalla tecnologia dei sensori utilizzata per misurare, monitorare e valutare le condizioni ambientali che hanno un impatto sulla salute delle piante e del suolo. I sensori e i dispositivi portatili per il suolo sono utilizzati principalmente per misurare l'umidità del suolo (contenuto volumetrico percentuale di acqua) e la salinità del suolo (conduttività elettrica). L'umidità del suolo e la capacità di determinare rapidamente e comodamente il contenuto idrico volumetrico del suolo utilizzando un sensore portatile portatile, è di particolare importanza per i professionisti del tappeto erboso per lo sviluppo e l'attuazione di pratiche di gestione sostenibile del tappeto erboso. Per i putting green dei campi da golf con zone radicali a base di sabbia, il numero minimo o ottimale di campioni casuali rappresentativi è compreso tra 3 e 4 per 93 m2 (equivalenti a 3-4 punti di campionamento per 1000 piedi2) per monitorare in modo affidabile l'umidità del suolo negli ecosistemi di tappeti erbosi gestiti in modo intensivo. Le zone radicali del tappeto erboso dei putting green sono molto variabili e non uniformi in tutto il profilo del suolo, tuttavia, la profondità ottimale o ideale per monitorare e misurare l'umidità e la salinità del suolo è lo strato superiore di 6 cm (ovvero, 0-6 cm di profondità). Una valutazione globale del monitoraggio dell'umidità del suolo sui green dei campi da golf con un sensore portatile portatile che utilizza la tecnologia di permittività dielettrica a impedenza coassiale ha rivelato un aumento polinomiale di 135 campioni nel 2014 a > 10.000.000 nel 2021, con la maggior parte del monitoraggio che si è verificato da maggio fino a settembre e con un aumento medio annuo del 29,25% nel periodo 2017-2021. Il contenuto di umidità del suolo, la velocità del green (cioè la distanza di rotolamento della pallina da golf) e la compattezza della superficie sono stati monitorati per un periodo di quattro giorni durante i tornei di golf professionistici. Sebbene le tre variabili misurate mostrassero associazioni deboli, le tendenze dei dati sui tornei erano coerenti e indicavano che una minore umidità del suolo era correlata a un aumento sia della velocità che della compattezza del green. Nel complesso, un programma di monitoraggio ambientale efficace, mirato e coerente con un'appropriata tecnologia di sensori portatili portatili può essere impiegato dai professionisti del tappeto erboso per misurare accuratamente le condizioni del suolo o delle zone radicali del tappeto erboso e tali informazioni possono essere utilizzate per sviluppare e supportare un ambiente sostenibile ed ecologico- programma basato sulla gestione del tappeto erboso. La tecnologia dei sensori portatili portatili è diventata uno strumento accettato e ampiamente utilizzato per supportare pratiche e programmi di gestione sostenibile del tappeto erboso.

Abstract

Turfgrass science and management have become positively influenced by sensor technology utilized to measure, monitor, and evaluate environmental conditions that impact plant and soil health. Portable hand-held soil sensors and devices are mostly utilized to measure soil moisture (percent volumetric water content) and soil salinity (electrical conductivity). Soil moisture, and the ability to quickly and conveniently determine the volumetric soil water content using a portable hand-held sensor, is of particular importance to turfgrass practitioners for developing and implementing sustainable turfgrass management practices. For golf course putting greens with sand-based rootzones, the minimum or optimum number of representative random samples is 3 to 4 per 93 m^2 (equivalent to 3 to 4 sampling points per 1000 ft^2) for reliably monitoring soil moisture in intensively managed turfgrass ecosystems. Turfgrass rootzones of putting greens are highly variable and not uniform throughout the soil profile, however. The optimum or ideal depth to monitoring and measure soil moisture and soil salinity is the upper 6 cm layer (i.e., 0-6 cm depth). A global assessment of monitoring of soil moisture on golf course putting greens with a portable hand-held sensor that utilizes coaxial impedance dielectric permittivity technology revealed a polynomial increase of 135 samples in 2014 to >10,000,000 in 2021, with the majority of monitoring occurring from May through September, and with a 29.25% annual average increase per year during 2017-2021. Soil moisture content, green speed (i.e., golf ball roll distance), and surface firmness were monitored over a four-day period during professional golf tournaments. Although the three variables measured exhibited weak associations, tournament data trends were consistent and indicated lower soil moisture was related to an increase in both green speed and firmness, although indications showed that ideal ball speed and firmness were associated with some level of moisture cautioning that this relationship is not linear. Overall, an effective, targeted, and consistent environmental monitoring program with appropriate portable hand-held sensor technology can be employed by turfgrass practitioners to accurately measure turfgrass soil or rootzones conditions, and that information can be utilized to develop and support a sustainable and ecology-based turfgrass management program. Portable hand-held sensor technology has become an accepted and heavily relied upon tool to support sustainable turfgrass management practices and programs.

Chapter 1

General introduction

1 Introduction

The turfgrass industry comprises approximately 35,000 18-hole golf course facilities, hundreds of thousands of sportsfield facilities, a multitude more of commercial, research and aesthetic facilities and residential land coverage that is exponentially larger than these specific facilities around the world. Golf and sports turf management alone utilizes several resources to maintain the level of turfgrass performance amenable to the desired use of that turfgrass system (i.e., the game of golf, a sports game, etc.). One primary resource that is depended upon and used regularly in day to day turfgrass management is water.

Until recent years, technology has not existed to be able to measure the moisture content in turfgrass systems most effectively and appropriately in a representative fashion, allowing users to know the true needs of the turfgrass system from a water perspective. While other needs exist including the need for nutrients, cultural practices to improve air movement and surface conditioning that improves the surface specific to the intended use, water, among all, has a dominant influence over all others. For instance, nutrients cannot be delivered to the turfgrass plant without an appropriate level of water at an acceptable quality. Further, water has a direct impact on playability of the turf, requiring adjustments in several other aspects of the turfgrass management operation.

Water use in golf course management alone can range from a few million gallons of water per year on a single property in a region with ample supply of water from rainfall to more than 300 million gallons of water in a region where natural rainfall is limited. This results in billions of gallons of water used in the golf industry alone, worldwide.

Traditionally, trained turfgrass managers rely on textbook education of soil types including sand, silt and clay soils, knowing that each accepts water in a unique way. However, the combination of these particles along with the inclusion of organic matter, humic substances, microbial activity and various chemical attributes as well as a multitude of natural and human surface influences greatly influences how a turfgrass system accepts water and utilizes it once applied. These combinations are infinite and lead to no two turfgrass systems being alike.

Further, in this regard, little is known as to what happens to water once it is applied. In 2014, Dr. Alec Kowalewski showed that what is measured in a traditional catch can irrigation distribution uniformity assessment (captured at the surface after an irrigation event on turf) did not correlate at all with the moisture level in the turf rootzone immediately following the irrigation event and in the minutes and hours after the irrigation event (Kowalewski, 2014). This clearly indicated that the dynamics in turfgrass exist and influence how water is received and utilized after irrigation, and that a need to understand this level of moisture from the turf's perspective far outweighs the value of knowing how much lands on the surface.

Over the past four decades, sensors have been introduced to the industry in an effort to attempt to understand the conditions of the turf and hopefully make better decisions on watering, fertilization and more. However, since these are electronic devices prone to influence from the physical and chemical attributes of a turfgrass-soil environment, problems have arisen when attempting to measure conditions in the turf and soil. This has prompted physicists to further understand the soil environment and create sensor technology that can be appropriate for turfgrass systems and maintain accuracy through the dynamics that turfgrass offers.

While every turfgrass system is unique, measuring this uniqueness has been limited and not understood in previous years since most sensing technologies require calibration, dependent on a stable, static soil environment. However, given the dynamics of turfgrass that occur through a day, week, month and season, from one turf plot to another and even within the same turf plot at the same time, it is not practical to expect sensors to be calibrated every time they are placed in the turf. This leads the industry to wonder what we can do with sensing technology most effectively in turfgrass. Further, since turfgrass is dynamic, placing sensors in situ for permanent installation is impractical since the number of sensors needed to capture a representative sampling of a turfgrass zone would require many sensors. This becomes difficult, if not impossible to manage from a practical standpoint, particularly since operations take place regularly on turfgrass systems that will disrupt any permanently installed apparatus in that turfgrass system.

It was established previously, for instance, that to take a representative sampling of a turfgrass plot (putting green, fairway, sports field, etc.) rootzone for a chemical and physical lab analysis would require approximately 12 sample cores, 12 mm in diameter to the depth of the targeted interest, across a typical, average sized putting green (~500 m2). For larger areas like golf course fairways and sports fields, sampling 20-25 cores per acre or 40 to 60 samples per hectare would be needed. Sampling for watering needs appears to require some minimum sampling array to understand the needs of the turf, but it is not well known what that minimum sampling array is. Another challenge with turfgrass systems is that its growth habit is very unique. Unlike other crops, turfgrass does not grow uniformly throughout its rootzone. Turfgrass forms a very unique thatch layer that exists just at and beneath the surface, followed by an abundance of adventitious roots that are primarily responsible for the bulk of salinity and water exchange activity. At deeper depths, roots extend and primarily function as carbohydrate storage tissue, being the first to decline in times of stress where the turfgrass system needs energy to survive, grow or withstand some other stress. It is not known entirely how the turfgrass system utilizes water and nutrients throughout the various regions of the turfgrass rootzone and if there is a particularly abundant supply of water and nutrients specific to various parts of the rootzone.

While great lengths have been made to create unique rootzone systems such as the USGA specification for putting green construction, it has not been well understood exactly how much water exchange occurs throughout this rootzone from top to bottom. While this rootzone typically extends approximately 30 cm, the abundance of adventitious roots and root hairs still exist close to the surface. An understanding of the positioning of water and nutrients is needed to help assess where we should monitor and measure to help make better decisions, particularly for irrigation inputs.

Similarly to golf course putting greens, sports field construction has attempted to create the ideal sports field rootzone to perform well enough to withstand the rigors of play on the surface while delivering water and nutrients efficiently to the turfgrass plants. This system too is not very understood as to how the water disperses throughout the rootzone and where the dominant activity may be for water and salinity exchange to the plant once established and managed in situ.

When considering how to measure the conditions in turfgrass systems, another factor is that sensors are continuous across the entire sensor. This means that they are uniform measurements, measuring the bulk activity of moisture (and other variables) across the whole of the sensor. There is an abundance of sensing technologies. However, a question exists due to the fact that there is no network analysis of the use of any one of these technologies, the data that is coming from them and how that data is influencing decisions.

However, turfgrass systems and rootzones are not uniform. In fact, the only time that a rootzone seems to be uniform is at the time of establishment, prior to any turf (or other crop) growing into that rootzone. Once the turfgrass germinates or is added on top of the rootzone as sod or a series of plugs and/or stolons through vegetative propagation, everything changes. The humic acid exchange alone has tremendous influence on the system's ability to absorb, exchange and utilize water in particular. This has been shown in studies by Dr. Andrea Carminati who has extensively looked at the rhizosphere and its changes through growing activities of plant tissue (Carminati, 2016) (Campbell, Dielectric Properties and Influence of Conductivity in Soils at One to Fifty Megahertz, 1990). The widespread use of sensor technology over the past fifty years has only recently become a popular topic despite key sensor technology being created in the 1980's that has significant benefit to turfgrass systems. Dr. Jeff Campbell, during his PhD studies at Dartmouth University, created a unique technology that focused primarily on the dielectric permittivity of soils and variables in them to determine precisely what moisture level and salinity level existed regardless of the changing dynamics of the soil (Campbell, Dielectric Properties and Influence of Conductivity in Soils at One to Fifty Megahertz, 1990). The unique technology is called Coaxial Impedance Dielectric Permittivity (CIDP) which measures the specific dielectric permittivity of a multitude of variables, including water and electro-conductivity which are unique to that variable. It does so using a complex algorithm measuring influences on an electromagnetic field that the sensor produces in the soil environment (Campbell, Interview with Dr. Jeff Campbell on HydraProbe and sensor technology performance, 2018).

This allows the sensor to measure precisely and accurately in an environment where dynamics are changing, such as the unique turfgrass environment since these variables do not influence the sensor's calibration to measure in the way it does. The sensor effectively needs no calibration to measure effectively. This is vastly different from traditional methods that use electronic pulses or waves or which use mineral substances influenced by the soil itself where that apparatus must be calibrated for that soil to be able to measure effectively. This invention was a breakthrough in physics and how it is measured, and it was a significant departure from the traditional means of measuring moisture (and other variables) using technologies such as gypsum blocks, capacitance sensors, time domain reflectometry (TDR), frequency domain reflectometry (FDR) and other electronic apparatuses of various electronic design which all required calibration to utilize them effectively.

In studies completed where this technology was analyzed for its precision in changing soil dynamics, the sensor technology has proven to be precise and accurate in such changing environments. This makes this sensor technology a prime candidate for use in turfgrass where dynamic changes occur every day.

While other technologies also existed that measured the soil water potential, or the potential water supply for plants, what made the Campbell invention unique was its ability to measure volumetric water content which was an indication of available water to the plant rather than what could be available to the plant from bound up sources in various soil conditions. This obviously presents an opportunity to understand the conditions and changing conditions in turfgrass which highly depends on these changing conditions day to day.

Several challenges existed in applying any sensor technology to measuring turfgrass systems. The sensor would first have to withstand the rigors of the turfgrass environment, withstanding corrosion and wear from normal, repeated use in turfgrass systems. Additionally, it would have to be able to measure the conditions of the turfgrass environment accurately and precisely to be referenceable over time. Further, the positioning of the sensor would have to be understood as well as the number of sample points needed to get a representative sampling of a turfgrass system to understand the true needs of the turfgrass system from day to day and throughout a growing season.

Prior to Dr. Campbell's invention, all sensors required a calibration procedure for each and every measurement it took, unless the system was static. Further, no clear understanding of where to position sensors or how many samples needed to be taken was established. Many measurements using these other technologies existed in farming soils which tend to be static and only manipulated by seasonal tillage, weather and an occasional broad application of fertilizer. These are quite different in physical and chemical qualities to turfgrass soils and rootzones which are highly dynamic. Despite this, these sensors slowly became utilized in turfgrass systems without an understanding of how to use them most effectively, leading to a broad use of technologies without an understanding of what it was teaching the turfgrass manager and without referenceable data to make informed decisions over time and from plot to plot.

Two major questions arise from this understanding. One, where in the profile should sensing take place to truly understand the watering (and other) needs of a turfgrass system. And two, how many samples need to be taken to understand the needs of the turfgrass system for a specific property in a specific plot of turf. Specifically, what would define a representative sampling of a turfgrass zone for understanding watering needs in particular.

Dr. Campbell's invention, now called the HydraProbe (originally called the Vitel sensor after being licensed out from Dartmouth University where Dr Campbell did his dissertation) has gone on to be adapted by the United States Department of Agriculture (USDA), NASA, United States Geological Survey (USGS), and international soil monitoring organizations. In Dr. Clint Waltz's dissertation, this sensor was used early on prior to any adaptation in turfgrass but with promising performances identified in his work (Waltz, 2001) (Kowalewski, 2014)According to the International Soil Moisture Network (ISMN), the HydraProbe is a dominant significant technology utilized around the globe in the world's ground truthing and soil moisture monitoring network (International Soil Moisture Network, 2022; Campbell, Interview with Dr. Jeff Campbell on HydraProbe and sensor technology performance, 2018). Today, it is owned and manufactured by Stevens Water Monitoring Systems, Portland Oregon USA and supplied to these organizations.

Despite this, it has been slow to adapt to the turfgrass industry until recent years. It first found its way by Advanced Sensor Technology out of Pennsylvania USA in 2005 (no longer in operation) who adapted it to a buried wireless apparatus to attempt to measure moisture, electro-conductivity and temperature in one or two sample spots per turf plot. For reasons related to the challenges outlined here, this application did not become widespread as the need for understanding turfgrass conditions across the entire zone existed, and this setup left turfgrass managers wondering what the true conditions of the turf were across the entire turfgrass plot including putting greens, fairways, sports fields and more. Much more research is needed to understand how to truly adapt this technology effectively.

In the words of one avid and ambitious turfgrass manager, Matthew Shaffer (now retired, globally known golf course tournament manager) who had hoped to use this buried technology to assist him with tournament conditioning, “While this technology was exciting, it did not give me the full view of the entire putting green to understand the needs from one end to the other. I want to see a problem coming before the problem shows up so I can make better decisions. We all want this. Clearly there are things happening we don’t understand, and an analysis of what is happening and how the things we do are impacting the turf is needed. That is what I want and what we need in the industry” (Shaffer, 2021).

In 2014, the HydraProbe was adapted to a new commercially available system called the POGO TurfPro system. This system included a portable apparatus with the sensor mounted on the end of it, an on-board GPS receiver and Bluetooth radio and an associated Android or Apple app that was used as a data collection and analysis portal for the measured variables. With a patent issued for this unique apparatus in 2017 by the United States Patent Office (Patent US D796,354 S), this set a new standard in applying science and practical use of sensors for turfgrass systems. Utilizing Amazon Web Services (AWS) cloud services to manage the data and return analysis in a unique visual non-manipulated way, interest in using this technology quickly elevated. Since 2014, this technology, despite being one of many available to turfgrass managers today, has grown significantly in use around the globe. Little is known as to the scientific benefits of measuring with this system using this unique sensor.

A unique opportunity arose to utilize this technology on golf course and sports turf properties around the globe, allowing a vast amount of data to be collected and analyzed to help understand the value of monitoring and how to do it most effectively. This sets the basis for this thesis.

An understanding of where in the profile is best to measure is needed. Understanding that turfgrass roots and the uptake of water in particular are not uniform prompts us to truly understand where is the best place to measure the conditions that impact the turfgrass system most, without diluting this measurement beyond the targeted region. For instance, while sensors measure uniformly across the entire metal sensor apparatus, extending this sensor out of a particularly more influential region of the rootzone and into a more raw rootzone medium where less water or salinity exchange occurs would have an impact on the measurement that is most important. This prompts a need to measure the rootzone profile to understand precisely where the measurement position should be.

Finally, the need for representative sampling exists for anything that is going to be measured. Similarly to how a doctor takes a representative analysis of your entire health system to make a diagnoses of your specific health condition, it is vitally important to measure a turfgrass system in a representative way that gives us the view of the entire turfgrass plot or zone specific to that turfgrass system such as a putting green or sports field. Some number of samples is needed to make this proper assessment, and the research is needed to indicate what that is.

This thesis is formulated to answer these questions, look at the use of this technology as it grows around the globe and learn from what is being measured to allow us to make better decisions for irrigating turfgrass systems and improving our overall management of turfgrass systems over time. The need to understand this is great. A fact is that for every 5% volumetric difference in water content in a turf system, this equates to approximately 106,000 liters of water per hectare (~11,000 gallons per acre) every irrigation cycle. If 100 irrigation cycles take place in a season, this equates to 2.3 million gallons of water per acre annually. And this is just a 5% volumetric change. Early indications from assessing monitored conditions shows that we have more room to improve than one may think.

For instance, through Dr. Michael Dukes' work at the University of Florida, USA, it is estimated that turfgrass is irrigated to as much as 80% more than necessary. This is not through careless or ignorant practices. It is simply due to not knowing the limitations or actual needs of the turf. Dr. Al Turgeon indicates that turfgrass is trainable and adaptable to a vast level of conditions, available water being one of them. Proper sensing and monitoring as well as the ensuing analysis will allow us to greatly improve watering practices by understanding how the turfgrass utilizes water, what the optimal levels are and how to effectively maintain them over time.

2 Objective and Outline

The objective of this thesis is to understand where in the turfgrass rootzone would be an ideal position for monitoring moisture content in particular as it influences the surface condition and the use of water overall. In addition, a need to understand the sampling pattern method needed to have a representative analysis of moisture across a turf zone is a necessity to complete a successful outcome of this thesis.

The thesis will be comprised of multiple studies focused on key monitoring technology, sampling patterns needed to assess a turfgrass plot or zone (putting green, sports turf), assessments of key turfgrass performance variables and how water influences them or not, sampling patterns of the industry and trending practices in the global turfgrass industry, and an assessment of a professional golf tournament and influences of water on the conditioning of that tournament.

At the conclusion of this thesis, a discussion will take place to determine actions needed as the research is expanded into the future and expected practice alterations as a result of what we have learned here.

3 References

Amazon. (2022). *Amazon Web Services*. Retrieved from Amazon Web Services: https://aws.amazon.com/

Balogh, J. W. (1992). *Golf Course Management & Construction.* Chelsea MI, USA: Lewis Publishers.

Beard, J. B. (2002). *Turf Management for Golf Courses.* Hoboken, New Jersey: John Wiley & Sons, Inc.

Brady, N. W. (2004). *Elements of the Nature and Properties of Soils.* Upper Saddle River, NJ, USA: Pearson Prentice Hall.

Burns T., A. J. (n.d.). Laboratory calibration of the Hydra Probe soil moisture sensor: comparison of infiltration wet-up vs. dry-down. *Vadose Zone Journal, 13*(12), 1-10.

Campbell, J. (1990). Dielectric Properties and Influence of Conductivity in Soils at One to Fifty Megahertz. *Soil Science Society of America Journal, 54*, 332-341.

Campbell, J. (2018, June 12). Interview with Dr. Jeff Campbell on HydraProbe and sensor technology performance. (C. Magro, Interviewer)

Carminati, A. Z. (2016). Engineering Rhizosphere Hydraulics: Pathways to Improve Plant Adaptation to Drought. *Vadose Zone Journal, DOI: 10.2136/vzj2016.09.0090*(https://www.researchgate.net/publication/311486187).

Fry, J. H. (2004). *Applied Turfgrass Science and Physiology.* Hoboken, N.J, USA: John Wiley & Sons, Inc.

Gelernter, W. S. (2015). Documenting trends in water use and conservation practices on. U.S. golf courses. *Crop, Forage and Turfgrass Management, 1*, 1-10.

Grabow, G. G. (2013). Water application efficiency and adequacy of ET-based and soil moisture-based irrigation controllers for turfgrass irrigation. *Journal of Irrigation and Drainage, 139*(2), https://doi.org/10.1061/(ASCE)IR.1943-4774.0000528.

Haley, M. a. (2012). Validation of landscape irrigation reduction with soil moisture sensor irrigation controllers. *Journal of Irrigation and Drainage, 138*(2), https://doi.org/10.1061/ASCE)IR.1943-4774.0000391.

Harivandi, A. B. (2012). Golf's use of water: Solutions for a more sustainable game. *USGA Turfgrass and Environmental Research Online, 11*(12), 1-70.

Havlin, J. B. (1999). *Soil Fertility and Fertilizers.* Upper Saddle River, New Jersey, USA: Prentice Hall.

International Soil Moisture Network. (2022). *ISMN*. Retrieved from International Soil Moisture Network: https://ismngeo.tuwien.ac.at/en/

Karcher, D. R. (2019). What the tech? Moisture meters for greater efficiency, healthier turf. *Golf Course. Management*, http://www.gcmonline.com/tags/moisture-meters-golf.

Kowalewski, A. M. (2014, December). Relationship between distribution uniformity and soil moisture content. *Golf Course Management, issuu.com/golfcoursemanagement/docs/dec-2014-gcm/105*, pp. 84-87.

Lawrence, P. R. (2020). Guiding soil sampling strategies using classical and spatial statistics: A review. *Agronomy Journal, 112*(4), https://doi.org/10.1001/agj2.20048.

Mead, R. C. (2003). Statistical Methods in Agriculture and Experimental Biology.

Moeller, A. (2012). Identify soil moisture status more accurately than ever before! *USGA Green Section Record, 59*(9), 1-5.

Pathan, S. B. (2007). Evaluation of a soil moisture sensor to reduce water and nutrient leaching in turfgrass (Cynodon dactylon cv. Wintergreen). *Australian Journal of Experimental Agriculture, 47*, 215-222.

POGO. (2022). *POGO TurfPro*. Retrieved from POGO TurfPro: www.pogoturfpro.com

Precisionusa.com. (2022). *Precision Putting Green Firmness Compaction Meter*. Retrieved from https://www.precisionusa.com/mStorefront/itemDetail.do?item-id=25014&order-quantity=1&customer-item=108GFM-K&order-uom=EA&warehouse-id=1&item-number=108GFM-K

Roberson, T. B. (2021). Improving soil moisture assessment of turfgrass systems utilizing field radiometry. *Agronomy, 11*(1060), https://doi.org/10.3390/agronomy11101960.

Seyfried, M. G. (2005). Dielectric Loss and Calibration of the Hydra Probe Soil Water Sensor. *Vadose Zone Journal, 4*, 1070-1079.

Shaffer, M. (2021, December 8). Retired, Director of Golf Course Operations, Merion Golf Club, Ardmore PA. (C. Magro, Interviewer)

Soilsensor.com. (2022). *Soilsensor.com*. Retrieved from https://soilsensor.com

Stevens Water Monitoring Systems. (2022). *Stevens Water Monitoring Systems*. Retrieved from https://stevenswater.com

Throssell, C. L. (2009). Golf course environmental profile measures water use, source, cost, quality, management and conservation strategies. *Applied Turfgrass Science, 6*, 1-16.

Turgeon, A. (2005). *Turfgrass Management, 7th ed.* Upper Saddle River, NJ, USA: Pearson Education.

United States Golf Association. (2022). *USGA Putting Green Construction Resources.* Retrieved from Recommendations for a Method of. PUtting Green Construction: https://www.usga.org/course-care/specialty-articles/usga-putting-green-construction.html

USGA Stimpmeter. (2022). *Stimpmeter Instruction Booklet.* Retrieved from https://www.usga.org/content/dam/usga/pdf/imported/StimpmeterBookletFINAL.pdf

Waltz, F. C. (2001). The Influence of Peat and Inorganic Amendments on Physical Propertiers of Sand-Based Rootzones. *Unpublished Doctoral Dissertation*.

Chapter 2

Considerations with determining the minimum number of volumetric water content measurements for turfgrass rootzones.

Abstract

Water is considered the most important natural resource utilized on managed amenity grasslands, and water conservation is an integral part of an overall program in environmental stewardship and best management practices. Measuring and monitoring the soil water content of turfgrass rootzones has become an important and routinely accepted practice of golf courses and sports pitches. In recent years, portable hand-held soil moisture meters or sensors have become commercially available and affordable, and therefore have become a valuable and often relied-upon tool for the turfgrass industry practitioner. To maximize or optimize the time and resources needed to measure the rootzone volumetric water content of a turf site, a field experiment was conducted to determine the minimum number of soil moisture readings needed per 93 m^2 of a sand-based rootzone. Of note, 93 m^2 is equivalent to 1,000 ft^2 which is the common form of area measurement utilized by the turfgrass industry in the USA. The standard error of the mean calculated from sampling data revealed that three to four measurements per 93 m^2 were the minimum number required. Soil moisture meters should be utilized in a structured, purposeful, and site-specific manner along with traditional soil moisture evaluation methods of diligent scouting for visual signs of turfgrass wilt and drought stress, as well as examining soil rootzone cores, to support prudent irrigation water management practices. Knowledge of the soil moisture

status will support best practices for water conservation and environmental stewardship while optimizing turfgrass quality, function, and performance.

1 Introduction

At professionally managed and maintained turfgrass sites, soil or rootzone moisture (i.e., volumetric water content; VWC), also known as water fraction volume (wfv), is measured using various commercially available hand-held devices (Moeller, 2012). The main purpose of measuring VWC is to assess the soil water status to ultimately determine irrigation needs of the turf (Throssell et al., 2009). Other reasons to monitor VWC include optimizing the timing and coordinated efforts of cultural management practices (i.e., aeration, cultivation, mowing, fertilizing, etc.), determining the potential threat of abiotic stresses (i.e., saturated rootzone conditions during high air temperature periods that favor plant pathogenic fungi activity), evaluating surface grooming and conditioning practices to improve ball roll (for putting greens) and bounce and footing (for sports fields), and maintaining the overall aesthetic quality and function of the turfgrass community.

The turfgrass industry typically utilizes the term “soil moisture meters” to describe devices used to measure soil rootzone “moisture” or volumetric water content. When these soil moisture meters are employed properly and effectively, they can provide insight about environmental conditions that predispose a managed turfgrass ecosystem to abiotic and biotic stresses and potential problems associated with non-optimum rootzone water content (Turgeon, 2005). A soil moisture meter offers the turfgrass practitioner a tool to identify environmental conditions that occurring before those stress symptoms are visible to the human eye (Moeller, 2012). Thus, monitoring and measuring soil moisture can provide further insight otherwise not possible from traditional methods of visual scouting for turfgrass problems such as wilt and other signs of drought stress, visual inspection of the soil for the formation of “black layer”, and visually evaluating a turf site for other signs of abiotic and biotic stresses developing due to non-optimum rootzone water content (Karcher et al., 2019).

An additional benefit of proper soil moisture monitoring is improved communication between staff managing turfgrass sites and the players or stakeholders enjoying those turf surfaces (Moeller, 2012). Objectively, turfgrass managers can present valid information that justifies the cultural practices needed and the regulations imposed upon those turf sites (Karcher et al., 2019). Water is fundamentally the most important natural resource utilized in turfgrass management operations, and it is the industry's obligation to use it most effectively and wisely (Turgeon, 2005). Representative monitoring with sensors facilitates an excellent opportunity for the improved and efficient use of water within a turfgrass management program, regardless of location in the world or demands on the turf site (Throssell et al., 2009). Sensor-based or sensor-guided irrigation practices has been shown to decrease water use, and/or utilize water more effectively and efficiently, in intensively management turfgrass ecosystems (Harivandi et al., 2005). Thus, monitoring VWC has become a heavily relied-upon and sustainable best management practice for the turfgrass industry (Gelernter et al., 2015; Grabow et al., 2013; Haley and Dukes, 2012; Pathan et al., 2007; Roberson et al., 2021).

The POGO TurfPro (Stevens Water Monitoring Systems, Inc; Portland, OR, USA) is a portable device that has become a popular monitoring platform in the turfgrass industry, and it is used to monitor and measure rootzone VWC and also soil temperature and soil electrical conductivity (Figure 1). The POGO was developed from the patented HydraProbe II sensor, which measures the water fraction volume based on coaxial impedance dielectric permittivity technology requiring no calibration in turfgrass systems (Burns et al., 2015). The unique processes of this sensor make it an ideal choice for managed amenity turfgrass sites given the many changing dynamics that occur in turf systems from soil texture and structural alterations, soil microbiology, plant species, soil electrical conductivity alterations from irrigation water, fertilization practices, and weather conditions and local climate, soil compaction from routine maintenance practices, and the influence from play or use (Turgeon, 2005). The POGO also is equipped with precision global position satellite technology to compile and analyze data spatially across a defined area (i.e., putting green, fairway, football pitch, etc.). The POGO interface utilizes a smartphone or tablet application for monitoring, measuring, and analyzing, and presenting data (Figure 2), orchestrated by a true cloud-based platform hosted by Amazon Web Services (AWS).

Figures 1 and 2 located on next two pages.

Figure 1. The POGO TurfPro (Stevens Water Monitoring Systems; Portland, OR, USA) is a portable device equipped with 5.6 cm metal rods that measures soil volumetric water content to the 5.71 cm depth. The extended metal rod at right side of device measures soil temperature.

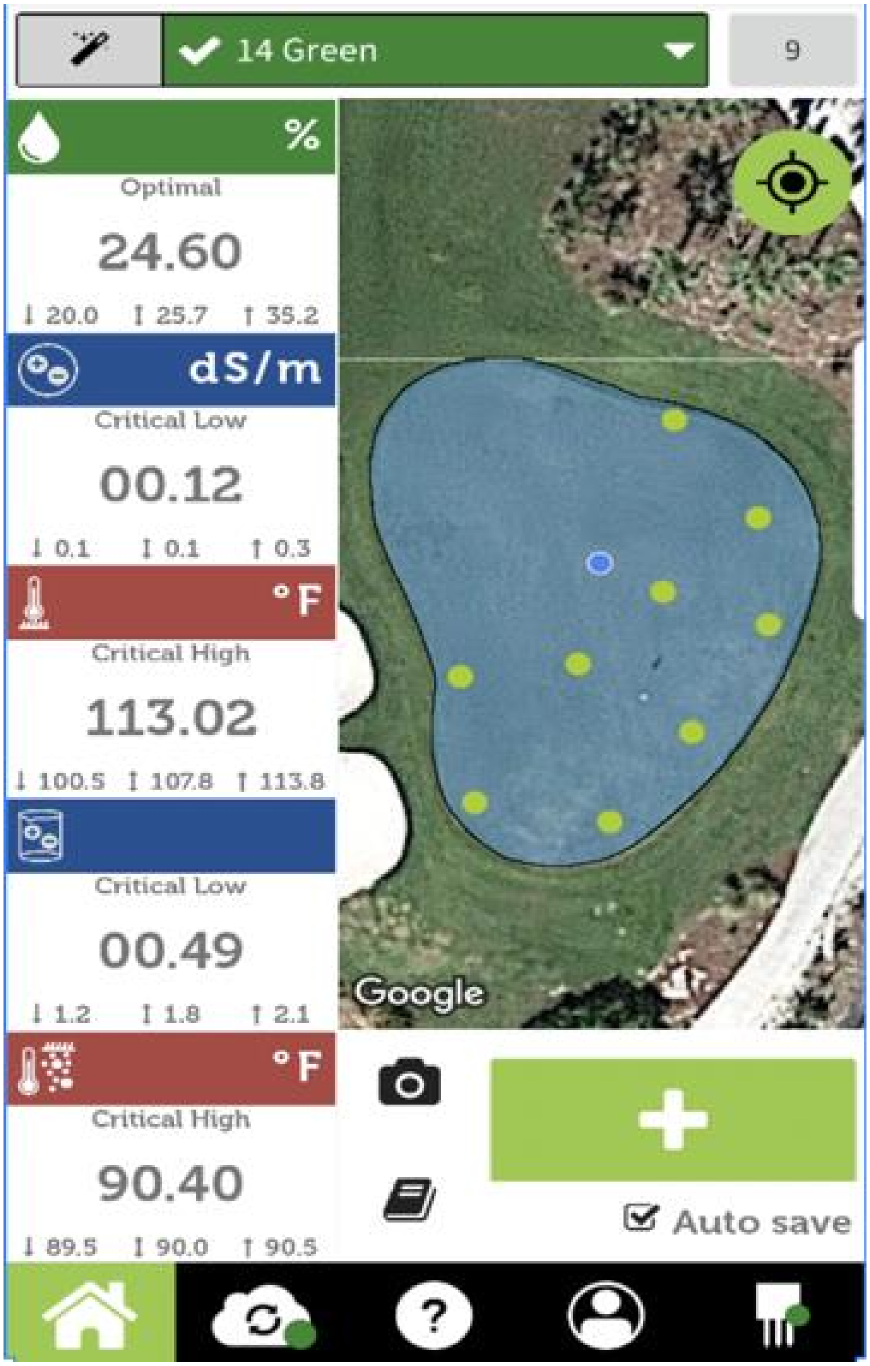


Figure 2. The POGO TurfPro (Stevens Water Monitoring Systems; Portland, OR, USA) utilizes a bluetooth-linked mobile application (TurfPro Mobile) for data collection and analysis. This is an example of a data collection and analysis output from green #14 on a golf course. The image indicates the perimeter of the site (i.e., putting green), the location of all nine sampling sites within that putting green thus far, soil moisture (percent volumetric water content), soil electrical conductivity ($dS \cdot m^{-1}$), surface temperature heat index (as ^{o}C or ^{o}F), salinity concentration index ($dS \cdot m^{-1}$), and rootzone temperature (as ^{o}C or ^{o}F).

Turfgrass management practitioners and professionals (i.e., golf course superintendents/course care managers, sports turf/pitch managers, and grounds/lawncare managers) can spend a great deal of employee time and labor resources measuring rootzone VMC at their respective sites (i.e., putting greens, fairways, pitches, lawns and landscapes). The number of VWC measurements needed for a single turf site or field, however, has not been determined. For example, how many VWC measurements are needed on a single putting green or fairway or pitch to provide an accurate assessment and determination of the VWC for the entire putting green or fairway or pitch? Therefore, the objective of this study was to determine the minimum or optimum number of POGO-based VWC measurements needed to obtain an accurate or representative rootzone VWC value of a turf site with a sand rootzone.

2 Materials and methods

2.1 Study site

This study was located at the Center for the Agricultural Sciences and a Sustainable Environment, at the Berks Campus of the Pennsylvania State University, in Reading, PA (USA). The turf was a mature stand of Creeping bentgrass (*Agrostis stolonifera* L. 'PennTrio') maintained on a 10 cm coarse sand-capped rootzone over native clay loam soil. Physical analysis of the sand layer revealed 90.3, 7.9, and 1.7% sand, silt, and clay content, respectively (Table 1). Within the sand fraction, 92.9% measured as coarse to very coarse (Table 1). The sand layer pH was 7.1, with 0.3% organic matter as determined by percent lost on ignition method. The site was maintained as a typical golf course fairway in the Mid-Atlantic USA region, and it was mowed two to three times per week as needed with a reel mower at a 12 mm height-of-cut with clippings not removed.

Table 1. Physical analysis of the sand rootzone at the study site(1).

Physical analysis										
--------Soil separate ---------				Sieve size/Sand fraction ------------------------- sand particle diameter as percent retained ----------------------						
Sand	Silt	Clay	OM[y]	No.10 Gravel 2 mm	No. 18 V. Coarse 1 mm	No. 35 Coarse 0.5 mm	No. 60 Medium 0.25 mm	No. 100 Fine 0.15 mm	No. 140 V. Fine 0.10 mm	No. 270 V. Fine 0.05 mm
--------------- % ---------------				-- % ---						
90.3	7.9	1.7	0.3	0.0	9.1	83.8	6.3	0.6	0.1	0.1

(1)Study site: creeping bentgrass (*Agrostis stolonifera* L.) maintained at 12 mm height-of cut on a 10 cm coarse sand-capped rootzone over clay loam soil.

2.2 Experimental design

Individual test plots measured 2.1 m × 2.1 m and arranged in a square grid pattern of 9 plots × 9 plots, for a total of 81 plots that occupied a total area of 368.7 m^2. Rootzone VWC at the 5.71 cm depth was measured using the POGO TurfPro that is equipped with 5.6 cm length metal rods of the HydraProbe II sensor (Figure 2).

One in-ground pop-up irrigation sprinkler is located on each outer corner of the 21.5 × 21.5 m (464.5 m^2) area which contained the study site. Each sprinkler distributes irrigation water at a 90-degree arc. Although the study site has an irrigation system calibrated to deliver a uniform distribution of water when needed, a natural precipitation event occurred on 30 October 2021 that measured 11.0 mm of rain. Therefore, the study site's rootzone was considered as uniformly wetted prior to VWC sampling. All VWC sampling was conducted on 2 November 2021, at approximately 0700 to 1100 a.m. One rootzone VWC measurement was obtained per plot, for 81 total measurements for each site (Figure 3). This was repeated five more times, for a total of six separate or replicated VWC measurements per plot. The VWC readings were recorded as a percent and entered onto a spreadsheet for data analysis.

Figure 3 located on next page.

81 measurements

901	902	903	904	905	906	907	908	909
801	802	803	804	805	806	807	808	809
701	702	703	704	705	706	707	708	709
601	602	603	604	605	606	607	608	609
501	502	503	504	505	506	507	508	509
401	402	403	404	405	406	407	408	409
301	302	303	304	305	306	307	308	309
201	202	203	204	205	206	207	208	209
101	102	103	104	105	106	107	108	109

30 measurements

901	902		904		906		908	909
701	702		704		706		708	709
501	502		504		506		508	509
301	302		304		306		308	309
101	102		104		106		108	109

12 measurements

	802			805			808	
	602			605			608	
	402			405			408	
	202			205			208	

25 measurements

901		903		905		907		909
701		703		705		707		709
501		503		505		507		509
301		303		305		307		309
101		103		105		107		109

10 measurements

	802			805			808	
	502		504		506		508	
	202			205			208	

20 measurements

	902		904		906		908	
	702		704		706		708	
	502		504		506		508	
	302		304		306		308	
	102		104		106		108	

9 measurements

	802			805			808	
	502			505			508	
	202			205			208	

16 measurements

	802		804		806		808	
	602		604		606		608	
	402		404		406		408	
	202		204		206		208	

5 measurements

	802						808	
				505				
	202						208	

15 measurements

	902			905			908	
	702			705			708	
	502			505			508	
	302			305			308	
	102			105			108	

3 measurements

	802							
				505				
							208	

Figure 3. At the study site, 81 plots were identified by individual plot numbers, with plots shown (in bold) where rootzone volumetric water content was measured. Individual plot size was 2.1 m × 2.1 m and arranged in a square grid pattern of 9 plots × 9 plots, for a total of 81 plots that measured 368.7 m^2.

2.3 Data analysis

All data were extracted to represent eleven sample sizes, consisting of 81, 30, 25, 20, 16, 15, 12, 10, 9, 5, and 3 VWC measurements for the 368.7 m^2 test site area (Figure 2). The data for each sampling size were compiled and the mean, standard deviation, standard error, and coefficient of variation were calculated as follows:

mean =

$$\sum \left[\frac{x_i}{n}\right]$$

where x_i equals the i^{th} variable, and n equals the number of variables in the data set;

standard deviation =

$$\sqrt{\frac{(x_i - \bar{x})}{n - 1}}$$

where x_i represents each individual data point, $\bar{x}$ represents the mean of the data set, and n represents the total number of data points in the data set;

standard error =

$$\frac{\sigma}{\sqrt{n}}$$

where σ equals standard deviation and n equals number of samples; and

coefficient of variation (%) =

$$\left[\frac{\sigma}{\bar{x}}\right] \times 100$$

where σ equals standard deviation and $\bar{x}$ represents the mean of the data set. All data representing each category of mean, standard deviation, standard error, and coefficient of variation were subjected to analysis of variance, and the eleven sampling size data sets compared using Fisher's protected least significance difference test at $p \leq 0.05$ (Mead et al., 2003).

3 Results and discusssion

3.1 Mean

The mean volumetric water content for all 11 sampling "categories" (i.e., 3 to 81 sampling points in the 368.7 m^2 area) reveals a range of 23.8 to 27.8% from 3 through 81 samples, respectively (Table 2). Utilizing results from the 81-sampling number (i.e., the most sampling points reflects the best accuracy and representation of volumetric water content of that site), no statistical differences ($p \leq 0.05$) were detected when comparing the mean from 81 samples (27.8%) through 9 samples (27.2%) (Table 2). The means from 3 samples (23.8%) or 5 samples (24.1%), however, were statistically lower versus the mean from 81 samples (27.8%) (Table 2).

3.2 Standard deviation

The standard deviation of the mean revealed a range of 10.01 to 7.03 from 3 through 81 samples, respectively (Table 2). No statistical differences ($p \leq 0.05$) were detected when comparing the standard deviation from 5 (9.49) through 81 samples (7.03) (Table 2). Only the standard deviation from 3 samples (10.01) was statistically higher versus 81 samples (7.03) (Table 2).

3.3 Standard error

The standard error of the mean revealed a range of 5.77 to 0.78 from 3 through 81 samples, respectively (Table 2). No statistical differences ($p \leq 0.05$) were detected when comparing the standard error from 81 samples (0.78) through 15 samples (1.82) (Table 2). The standard error from 3 samples (5.77) to 12 samples (2.18) were statistically higher versus 81 samples (0.78) (Table 2).

Table 2. Statistical analysis of VWC (volumetric water content) sampling data from the study site[(1)].

Sampling Number[(2)]	Mean ---- % VWC ----		Standard deviation		Standard error		Coefficient of variation ------- % --------	
81	27.8	ab[(3)]	7.03	bc	0.78	f	25.0	c
30	28.9	ab	7.32	bc	1.34	ef	24.8	c
25	29.6	a	6.81	c	1.36	ef	22.9	c
20	28.5	ab	7.13	bc	1.59	def	24.4	c
16	27.1	b	7.14	bc	1.79	cdef	25.8	c
15	27.9	ab	7.97	bc	1.82	cdef	27.8	bc
12	26.8	b	7.55	bc	2.18	cde	27.5	bc
10	27.8	ab	7.97	bc	2.52	cd	28.1	bc
9	27.2	b	8.41	ab	2.80	bc	30.2	bc
5	24.1	c	8.49	ab	3.80	b	35.6	ab
3	23.8	c	10.01	a	5.77	a	42.1	a

[(1)]Study site: Creeping bentgrass (*Agrostis stolonifera* L.) maintained at 12 mm height-of cut on a 10 cm coarse sand-capped rootzone over clay loam soil.
[(2)]Number of soil volumetric water content sampling events within the 368.7 m^2 study area, as measured by the POGO portable meter (Stevens Water Monitoring Systems; Portland, OR, USA) at the 5.71 cm depth.
[(3)]Data are means (n = 6) for each sampling number for the measured percent volumetric water content, standard deviation of the mean, standard error of the mean, and percent coefficient of variation of the mean; the same letter for each mean represents no significant difference ($p \leq 0.05$) according to Fisher's protected last significant different test.

3.4 Coefficient of variation

The coefficient of variation of the mean revealed a range of 42.1 to 25.0% from 3 through 81 samples, respectively (Table 2). No statistical differences ($p \leq 0.05$) were detected when comparing the coefficient of variation from 81 samples (25.0%) through 9 samples (30.2%) (Table 2). The coefficient of variation from 3 samples (42.1%) to 5 samples (35.6%) were statistically higher versus 81 samples (25.0%) (Table 2).

3.5 Further discussion

Mean percent soil VWC data revealed that a range of 9 to 30 measurements or samples provided a VWC mean that was statistically similar to 81 samples (Table 2). Data for the standard deviation of the mean, as well as percent coefficient of variation, did not provide any further separation among the sampling numbers, as no clear or distinct statistical differences were detected among nearly all sampling levels (Table 2).

In this field experiment, the standard error represents an estimate of the variability among the many VWC measurements obtained within the 368.7 m^2 turf area. The standard error was lowest from the 81 measurements or samples (Table 2). The standard error can be decreased by increasing the sample size (i.e., the maximum 81 VWC measurements with the 368.7 m^2 turf area). However, taking 81 measurements within a 368.7 m^2 turf area would be too time consuming in practice. A total of 15 measurements was the minimum number that resulted in a standard error statistically similar with 81 measurements (Table 2). Therefore, 15 would be considered the minimum or optimum number of VWC measurements required per 368.7 m^2 turf area, or, three to four measurements per 93 m^2 (i.e., 93 m^2 is equivalent to 1,000 ft^2 which is the common form of area measurement utilized by the turfgrass industry in the USA).

Further research is warranted that considers monitoring VWC within the irrigation water delivery patterns of in-ground pop-up sprinklers. In the reality of intensively maintained turfgrass sites, VWC data within a specific coverage area of an irrigation sprinkler may be more valuable than VWC data from a larger area or zone of turf (Harivandi et al., 2005; Karcher et al., 2019; Lawrence et al., 2020; Moeller, 2012). For example, for turfgrass practitioners, this could perhaps translate to 50 to 60 VWC sampling points on one hectare of a golf course fairway that corresponds with 15 to 20 irrigation sprinklers installed on that fairway. Also for turfgrass practitioners, measuring VWC may warrant a more site-specific or structured approach in which certain zones or "hot spots" (i.e., sites with a historical record or repeated expression of abiotic stress, or sites subjected to heavy traffic, or sites that are sloped or demonstrate irrigation inefficiency, etc.) are monitored more intensively (Gelernter et al., 2015; Grabow et al., 2013; Harivandi et al., 2005; Lawrence et al., 2020; Throssell et al., 2009; Turgeon, 2005).

4 Conclusion

In conclusion, based on the calculated standard error of the mean of POGO-obtained VWC data from the sand-capped rootzone within the parameters of this field study, a minimum of 15 VWC samples are required per 368.7 m^2 managed turf area, or more specifically, three to four VWC samples per 93 m^2 (~1,000 ft^2 area as utilized in the USA) to optimize VWC monitoring of turfgrass sand-based rootzones.

5 References

Burns T., Adams J., and Berg A. 2015. Laboratory calibration of the Hydra Probe soil moisture sensor: comparison of infiltration wet-up vs. dry-down. Vadose Zone Journal, 13(12):1-10.

Gelernter, W.D., Stowell, L.J., Johnson, M.E., Brown, C.D., and Beditz, J.F. 2015. Documenting trends in water use and conservation practices on U.S. golf courses. Crop, Forage and Turfgrass Management 1:1-10.

Grabow, G.L., Ghali, i.e., Huffman, R.L., Miller, G.L., Bowman, D., and Vasanth, A. 2013. Water application efficiency and adequacy of ET-based and soil moisture-based irrigation controllers for turfgrass irrigation. Journal of Irrigation and Drainage 139(2). https://doi.org/10.1061/(ASCE)IR.1943-4774.0000528

Haley, M.B. and Dukes, M.D. 2012. Validation of landscape irrigation reduction with soil moisture sensor irrigation controllers. Journal of Irrigation and Drainage 138(2). https://doi.org/10.1061/(ASCE)IR.1943-4774.0000391

Harivandi, A., Brown, P., and Kenna, M. 2012. Golf's use of water: Solutions for a more sustainable game. USGA Turfgrass and Environmental Research Online 11(12):1-70.

Karcher, D., Richardson, M., and O'Brien, D. 2019. What the tech? Moisture meters for greater efficiency, healthier turf. Golf Course Management. https://www.gcmonline.com/tags/moisture-meters-golf

Lawrence, P.G., Roper, W., Morris, T., and Guillard, K. 2020. Guiding soil sampling strategies using classical and spatial statistics: A review. Agronomy Journal 112(4). https://doi.org/10.1001/agj2.20048

Mead, R., Curnow, R.N., and Hasted, A.M. 2003. Statistical Methods in Agriculture and Experimental Biology. Chapman and Hall/CRC Press, Boca Raton, FL.

Moeller, A. 2012. Identify soil moisture status more accurately then ever before! USGA Green Section Record 59(9):1-5.

Pathan, S.M., Barton, L., and Colmer, T.D. 2007. Evaluation of a soil moisture sensor to reduce water and nutrient leaching in turfgrass (*Cynodon dactylon* cv. Wintergreen). Australian Journal of Experimental Agriculture 47:215-222.

Roberson, T.L., Badzmierowski, M.J, Stewart R.D., Ervin E.H., Askew S.D., and McCall D.S. 2021. Improving soil moisture assessment of turfgrass systems utilizing field radiometry. Agronomy 11:1960. https://doi.org/10.3390/agronomy11101960

Throssell, C.S., Lyman, G.T., Johnson, M.E., Stacey, G.A., and Brown, C.D. 2009. Golf course environmental profile measures water use, source, cost, quality, management and conservation strategies. Applied Turfgrass Science 6:1–16.

Turgeon, A.J. 2005. Turfgrass Management, 7th ed.; Pearson Education: Upper Saddle River, NJ, USA.

Chapter 3

Considerations with determining optimum turfgrass soil depth for environmental monitoring.

Abstract

Turfgrass ecosystems are dynamic and unique to each golf course, sports pitch, and lawn and landscape, and this is especially true with turfgrass soils and rootzones. Portable hand-held environmental monitoring devices and instruments are commonly employed by turfgrass practitioners. However, it is not clearly understood where in the soil profile would be the ideal region to monitor and measure water and salinity. Soil samples were collected from a total of 30 golf course sand-based putting greens during May through September in 2005 through 2020. The golf courses were located in nine countries in North America, Europe, and Asia, and the turfgrasses were either cool-season or warm-season species. At each site, 24 soil cores of 1.9 cm width × 18 cm depth were randomly extracted, resulting in 12 soil cores partitioned into 3 cm segments or layers from the 0 to 18 cm depth (i.e., 0-3, 3-6, 6-9, 9-12, 12-15, 15-18 cm), and an additional 12 soil cores separated into 6 cm layers from the 0 to 18 cm depth (i.e., 0-6, 6-12, 12-18 cm). At each site, each individual 3 or 6 cm layer was combined into one composite sample, resulting in a total of 30 samples for each of the 3 cm layers, and a total of 30 samples for each of the 6 cm layers. All soil samples were subjected to laboratory analysis to determine the soil moisture saturation index (percent saturated water loss upon drying), and salinity as measured by the electrical conductivity of the saturated soil-paste extract (ECe) and the electrical conductivity of the soil pore water (ECw). Analysis of the soil data confirmed that soil moisture and salinity

were not uniformly distributed through the rootzone profile from the 0 to 18 cm depth, and the majority of soil moisture and salinity was measured and observed within the upper layers at the 0 to 6 cm depth. Therefore, the analysis of soil samples from golf course putting green sand-based rootzones indicated an optimal position or placement for monitoring the highest concentrations of water (indicated by the soil moisture saturation index) and salinity (indicated by ECe and ECw) was 6 cm (i.e., the 0 to 6 cm depth). When using portable hand-held soil moisture and salinity meters, turfgrass practitioners should consistently monitor putting green rootzones of the upper 0 to 6 cm depth.

1 Introduction

Turfgrass water conservation is an example of a sustainable turfgrass management practice commonly accepted and utilized in the turfgrass industry (Gelernter et al., 2015; Lyman et al., 2007; Schiavon and Serena, 2023; Throssell et al., 2009; Turgeon, 2005; Waltz and Carrow, 2007). These and other best management practices can be a challenge to implement successfully with turfgrass maintained on adverse soil conditions (McCarty, 2011). Uniform and consistent soil or rootzone conditions (i.e., biological, chemical, and physical) are ideal for establishing, growing, and maintaining healthy turfgrass with consistent playing or performing surface characteristics (Waddington et al., 2002). However, turfgrasses are often maintained on non-uniform soils that were originally installed in that condition during establishment and/or developed from soil amendments, various other inputs, maintenance practices, and use (Soldat and Koch, 2023). Although only a few millimeters in thickness, the development of multiple soil layers or horizons in turfgrass rootzones has a negative impact on producing and maintaining optimum turfgrass growing conditions and playing surfaces, especially for sand-based golf course putting greens (Thoms and Lindsey, 2023).

Monitoring and measuring soil moisture in rootzone is critical to making decisions for sustainable turfgrass water conservation practices (Moeller, 2012). Thus, the variability that often exists in turfgrass soils increases the need for a more precise and reliable approach to monitoring soil moisture in the rootzone. Soil biological, chemical, and physical properties are important with turfgrass management (Turgeon, 2005). With turfgrass soil, and specifically the rootzone, water relations are important to optimize water available for plant update and prevent or manage any potential problems associated with soluble salts and salinity. (Fidanza et al., 2023; York et al., 2016).

Currently it is not clearly or completely understood, however, exactly where or within the turfgrass soil environment to monitor conditions or parameters that would provide the best insight toward understanding soil moisture status and/or how much water or nutrients may be needed (McCarty, 2011; Moeller, 2012; Whitlark, 2014; Wu, 1985). Although soil moisture sensors are calibrated to measure consistently and uniformly within their own apparatus and operating parameters (Burns et al., 2014; Campbell, 1990); Seyfried, et al., 2005), inserting or placing a properly functioning sensor into or across a non-uniform rootzone could produce misleading measurements and lead to incorrect interpretations of the measured variable(s) of interest by the turfgrass manager (Jespersen et al., 2023; Kopp and Jiang, 2013; Kostka et al., 2007; Leinauer and Devitt, 2013). For example, turfgrass rootzones – especially sand-based golf course putting greens – can become compacted and accumulate high organic matter content in the uppermost portion of the soil profile, thus resulting in poor soil moisture and salinity conditions (Kowalewski et al., 2023; Whitlark, 2014).

Soil moisture or the status of the soil water content is turfgrass rootzones is commonly expressed as percent volumetric water content (Turgeon, 2005). For sand-based soils of golf course putting greens, the United States Golf Association (USGA) recommends a soil moisture range of 15-25% volumetric water content (i.e., physical property of 15-25% capillary porosity) (Beard, 2001). Portable or hand-held soil moisture meters and devices are commonly employed to monitor and measure soil moisture and provides an in-situ assessment of percent volumetric water content (Moeller, 2012). Soil moisture monitoring could be more accurate and insightful if it was known exactly where in the turfgrass soil profile resides the dominant or most influential moisture and salinity levels (Kowalewski et al., 2014; Whitlark, 2014). Therefore, utilizing standard soil laboratory methods to measure soil properties at various depths could provide further understanding and insight as to how and where to best monitor the turfgrass soil environment. The consistent and reliable monitoring of an optimum or proper or "best" soil depth may lead to supporting better turfgrass management decisions for sustainable irrigation and fertilization inputs and practices.

With intensively managed turfgrass ecosystems (i.e., golf courses, athletic fields or sports pitches, lawns and landscapes), soil moisture and soil salinity are two important factors that impact turfgrass management practices and overall turfgrass health, quality, and performance (McCarty, 2011; Turgeon, 2005). In the laboratory, specifically a typical soil test laboratory, the measuring and determination of the soil moisture saturation index is often used as an indicator of the status or amount of soil water content often used for drought monitoring in agricultural crops (Dane and Topp, 2002). The measurement of soil salinity is a quantification of the total salts present in the liquid portion of the soil (Corwin and Yemoto, 2017). The salt concentration in the soil solution consists primarily of dissolvable salts of the cations calcium (Ca^{2+}), potassium (K^{+}), magnesium (Mg^{2+}), sodium (Na^{+}), and ammonium ($NH4^{+}$), and the anions chloride (Cl^{-}), carbonate (CO_3^{2-}), bicarbonate (HCO^{3-}), nitrate (NO^{3-}), and sulfate (SO_4^{2-}) (Weil and Brady, 2018). Some sources of soluble salts include commercial fertilizers, organic soil amendments and fertilizers, soil organic matter, poor irrigation water (i.e., irrigation water that contains high concentrations of dissolved salts), and poor soil drainage (Pathan et al., 2007; Straw et al., 2022; Waddington et al., 2002).

Soils with salinity problems (i.e., high soluble salt concentrations and/or high sodium content) produce a rootzone environment that can be very difficult to grow and maintain healthy and functional turfgrass (Beard, 2001; McCarty, 2011; Turgeon, 2005; Waddington et al., 2002). The most common laboratory technique or test for soil salinity is to measure the electrical conductivity of the soil solution or soil-water extract of the soil sample (Weil and Brady, 2018). The electrical conductivity, expressed as $dS \bullet m^{-1}$, refers to the ability of the soil to conduct an electrical current. For example, as soluble salt concentration increases in the soil, the soil solution becomes a better conductor of electrical current and the electrical conductivity also increases (Dahnke and Whitney, 1988). Therefore, electrical conductivity represents an indirect measurement of soil salinity (Waddington et al., 2002).

Therefore, the objective of this study was to measure soil moisture and soil salinity from soils of golf course putting greens and utilize the results of those measurements to determine the optimum or “best” depth for a portable sensor to monitor and measure those two important environmental parameters. Turfgrass soil samples were obtained from a variety of geographic locations and the soil was partitioned into various depths for laboratory analysis. Specifically, the laboratory analysis methods determined soil moisture as measured from the soil moisture saturation index, and soil salinity was determined by measuring the electrical conductivity of the saturated soil-paste extract, and the electrical conductivity of the soil pore water.

2 Materials and methods

Soil samples (i.e., turfgrass rootzones) were obtained from golf course putting greens from nine countries in North American, Europe, and Asia. The putting greens were composed of cool-season (n=15) or warm-season (n=15) turfgrasses. With cool-season putting greens, species were primarily Creeping bentgrass (*Agrostis stolonifera* L.) or a mixed-stand of Creeping bentgrass and Annual bluegrass (*Poa annua* L.). With the warm-season putting greens, species were primarily Hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy] or Seashore paspalum (*Paspalum vaginatum* Swartz). Of note, the specific turfgrass cultivar names were not obtained during the soil sample collection process.

The predominant soil texture for all putting greens sampled was sand (i.e., ≥ 90% sand content), and consisted of mostly medium, coarse, and very coarse sand size fractions. All putting greens were originally constructed of either a USGA-specification sand or a modified USGA-specification sand rootzone (United States Golf Association, 2004) or were ‘push up’ from native on site soil, and most putting greens incorporated sand topdressing either periodically or more frequently during the year or growing season which is a common practice in turfgrass management (Beard, 2001). Of note, the specific ages of all putting greens were not obtained during the soil sample collection process but did vary in age. Also of note, information about other soil physical properties (i.e., bulk density, infiltration, etc.) was laboratory-assessed but not analyzed for the purposes of this study.

2.1 Soil sample collection

Soil samples were obtained from a total of 30 golf courses during local season in 2005 through 2020. At each golf course, one putting green was selected that was considered to be a typical or representative putting green for that location. For the selected putting green, 24 soil samples were collected at random, as guided by the sampling recommendations by Walworth (2007). The soil sampler or soil core extraction device was a soil probe measuring 1.9 cm width × 18 cm depth (Figure 1). Therefore, each soil sample or soil core sample measured 1.9 cm width × 18 cm depth.

Figure 1. Example of a soil core extraction utilizing a soil probe of 1.9 cm width × 18 cm depth (A), and a soil core collection from a golf course putting green (B).

Of the 24 soil samples collected, 12 were segmented in 3 cm layers, and 12 were segmented into 6 cm layers. The 12 soil samples segmented into 3 cm layers (i.e., 0-3 cm, 3-6 cm, 6-9 cm, 9-12 cm, 12-15 cm, and 15-18 cm) were combined for each depth and mixed thoroughly. For example, all 12 of the 0-3 cm segments were combined and mixed thoroughly in a small bucket to represent the one composite 0-3 cm sample for that putting green. This process was repeated for each segmented layer that resulted in one soil sample for each 3 cm depth (i.e., 0-3, 3-6, 6-9, 9-12, 12-15, 15-18 cm) for that putting green. The entire process was repeated for the 12 soil samples segmented into 6 cm layers (i.e., 0-6 cm, 6-12 cm, and 12-18 cm). This process also resulted in one soil sample for each 6 cm depth (i.e., 0-6, 6-12, 12-18 cm) for that putting green. A total of 30 soil samples were collected for each 3 cm depth or segment, for a grand total of 180 soil samples. A total of 30 soil samples also were collected for each 6 cm depth or segment, for a grand total of 90 soil samples.

2.2 Soil analysis

All soil samples were analyzed using the United States Department of Agriculture's Recommended Chemical Soil Test Procedures (https://agsci.psu.edu/aasl/soil-testing/methods) at the Agricultural Analytical Services Laboratory (University Park, PA, USA; https://agsci.psu.edu/aasl/soil-testing) and Harris Ag Source Laboratories, Lincoln NE, USA; https://agsource.com/). Specifically, laboratory analysis was conducted on each soil sample to determine the soil moisture saturation index, the electrical conductivity of the soil, and the electrical conductivity of the soil pore water.

The soil moisture saturation index represents the percent of water loss after a saturated soil sampled has dried (Dane and Topp, 2002; Dobriyal et al., 2012; Hillel, 1980; Sushalekshmi et al., 2014). To determine the soil moisture saturation index, distilled or deionized water is added in mL increments to a 100 g oven-dried soil sample until saturation is achieved. The total amount of water added is recorded. Next, the soil sample is permitted to drain (i.e., gravitational water is released) as it is being air dried at room temperature, and that water is collected and measured and therefore is considered "saturated water loss upon drying". The amount of water loss is compared to the amount of water initially added to calculate the "percent of saturated water loss upon drying":

$$\frac{\text{mL water added to achieve saturation} - \text{mL water collected during drying}}{\text{mL water added to achieve saturation}} \times 100 = \text{percent of saturated water loss upon drying}$$

The electrical conductivity of the soil (ECe) refers to the measuring of the electrical conductivity of the saturated soil-paste extract (Rhoades et al., 1989). The ECe is determined as $dS \cdot m^{-1}$, and the specific analytical techniques and methods for measuring ECe are discussed in detail in Corwin and Scudiero (2016), Dane and Topp (2002), and Sparks (1996). Therefore, soil salinity is determined from measuring ECe, or the electrical conductivity of the saturated soil-paste extract solution, which is proportional to the concentration of ions in the saturated soil-paste extract solution (Corwin and Yemoto, 2017).

The electrical conductivity of the soil pore water (ECw) refers to measuring of the electrical conductivity of the water occupying the pore space within the soil sample (Hillel, 1980; Weil and

Brady, 2018). The ECw is determined as dS•m^{-1}, and the specific analytical techniques and methods for measuring ECw also are discussed in further detail in Corwin and Scudiero (2016), Dane and Topp (2002), and Sparks (1996). Therefore, the salinity of the ECw, or the electrical conductivity of the soil pore water solution also is proportional to the concentration of ions in the soil pore water solution (Corwin and Yemoto, 2017).

2.3 Data analysis

All data were subjected to analysis of variance using Agricultural Research Management software (GDM Solutions; Brookings, SD, USA). Soil segment depth means were compared using Fisher's protected least significant different test at $p \leq 0.05$ (Mead et al., 2003).

3 Results and discussion

Analysis from the 30 golf course putting greens at both 3 cm and 6 cm segments focused on data obtained from the soil moisture saturation index test (i.e., percent saturated water loss upon drying), the measured electrical conductivity of the saturated soil-paste extract (ECe), and the measured electrical conductivity of the soil pore water solution (ECw). Soil cores from the 30 golf course putting greens were obtained over a 16-year period from 2005 to 2020 from nine countries in three different continents. Future research could be more consistent with soil core sampling within a country or continent, within cool-season or warm-season turfgrass species of those putting greens, and within a specific time-frame (i.e., one typical growing season within one single year). Also, future research should consider a review and analysis of more detailed information about the putting green soil samples that could include age of the putting green, specific sand percent in the rootzone, specific percent fraction sizes of the sand, organic matter content, chemical properties (i.e., soil pH, macronutrients, micronutrients, cation exchange capacity, etc.), turfgrass maintenance practices (i.e., mowing height and frequency, fertilizer/fertility program, irrigation program, use of biostimulants and soil surfactants and other products), and weather (i.e., air temperature and precipitation). However, for the purposes of this study, a random analysis of various turfgrass systems was needed to assess a random analysis of soil water and EC content and positioning.

3.1 Turfgrass soil samples of 3 cm segments to 18 cm depth.

Data analysis for soil samples (n = 30) partitioned into 3 cm segments for the 0 to 18 cm depth are presented in Table 1. All raw data measured and determined from the soil moisture saturation index test, and raw data representing ECe and ECw, are listed in Table 2.

With percent saturated water loss upon drying (i.e., the soil moisture saturation index test), the amounts measured were not uniformly or equally distributed throughout the 0-18 cm soil depth. For the entire 0-18 cm soil depth, the saturated water loss ranged from 16.3 to 61.8%, with the highest amount of water loss measured at the 0-3 cm depth (61.8%), and the lowest amount of water loss measured at the 15-18 cm depth (16.3%). While the greatest amount of water loss was measured at the 3-6 cm depth (61.8%), the second highest amount of water loss was measured at the 0-3 cm depth (53.9%). Statistically significant differences for percent saturated water loss upon drying from highest to lowest amount of water loss per soil depth were observed as follows: 3-6 > 0-3 > 6-9 > 9-12 > 12-15 = 15-18 cm. Based on percent saturated water loss upon drying, the majority or greatest amount of water loss occurred at the combined 0-6 cm depth. Therefore, the 0-6 cm depth would represent the ideal depth to monitor and measure soil moisture with a portable hand-held soil moisture meter.

With soil salinity measured as ECe (i.e., electrical conductivity of saturated soil-paste extract), the ECe values were not uniformly or equally distributed throughout the 0-18 cm soil depth. With the entire 0-18 cm profile, the ECe ranged from 0.116 to 0.849 $dS \cdot m^{-1}$. This ECe range is acceptable for growing and maintaining turfgrass (Beard, 2001). The highest ECe of 0.849 $dS \cdot m^{-1}$ was measured at the 3-6 cm depth, and the lowest ECe of 0.116 $dS \cdot m^{-1}$ was measured at the 15-18 cm depth. While the highest ECe was measured at the 3-6 cm depth (0.849 $dS \cdot m^{-1}$), the second highest ECe was measured at the 0-3 cm depth (0.646 $dS \cdot m^{-1}$). Statistically significant differences for ECe from highest to lowest per depth were measured as follows: 3-6 > 0-3 > 6-9 = 9-12 > 12-15 = 15-18 cm. Based on ECe, the highest salinity concentration occurred at the combined 0-6 cm depth. Therefore, the 0-6 cm depth would represent the ideal depth to monitor and measure ECe with a portable hand-held soil EC meter.

With soil salinity measured as ECw (i.e., electrical conductivity of soil pore water solution), the ECw values also were not uniformly or equally distributed throughout the 0-18 cm soil depth. With the entire 0-18 cm depth, the ECw ranged from 0.072 to 0.304 $dS \cdot m^{-1}$. This ECw range also is acceptable for growing and maintaining turfgrass (Beard, 2001). The highest ECw of 0.304 $dS \cdot m^{-1}$ also was measured at the 3-6 cm depth, and the lowest ECw of 0.072 $dS \cdot m^{-1}$ was measured at the 12-15 cm depth. The highest ECw was measured at the 3-6 cm depth (0.304 $dS \cdot m^{-1}$) and the second highest ECw was measured at the 0-3 cm depth (0.199 $dS \cdot m^{-1}$). Statistically significant differences for ECe from highest to lowest per depth were measured as follows: 3-6 > 0-3 > 6-9 = 9-12 > 12-15 = 15-18 cm. Based on ECw, the highest salinity concentration occurred at the combined 0-6 cm depth. Therefore, the 0-6 cm depth would represent the ideal depth to monitor and measure ECw with a portable hand-held soil EC meter.

Tables 1 and 2 located on next two pages

Table 1. Analysis of turfgrass rootzones, 3 cm segments to 18 cm depth.

Rootzone sampling depth	Saturated water loss upon drying[1]	Salinity (ECe)[2]	Salinity (ECw)[3]
--- cm ---	--------- % ---------	-------- $dS \cdot m^{-1}$ --------	-------- $dS \cdot m^{-1}$ --------
0 – 3	53.9 b[4]	0.646 b	0.199 b
3 – 6	61.8 a	0.849 a	0.304 a
6 – 9	43.7 c	0.262 c	0.150 c
9 – 12	31.5 d	0.248 c	0.123 c
12 – 15	17.6 e	0.148 d	0.072 d
15 – 18	16.3 e	0.116 d	0.073 d
LSD value	4.71	0.0539	0.0281
Standard Deviation	9.23	0.1056	0.0551
Rep. Prob. (F)	0.0601	0.0566	0.0814
Treat. Prob. (F)	0.0001	0.0001	0.0001

[1]Saturated water loss upon drying refers to water loss from a saturated soil sample subjected to the soil moisture saturation index test (Dane and Topp, 2002).
[2]Salinity as measured from the saturated soil-paste extract solution (Corwin and Yemoto, 2017).
[3]Salinity as measured from the soil pore water solution (Corwin and Yemoto, 2017).
[4]Means (n=30) followed-by the same letter are not statistically different according to Fisher's protected least significant difference test a $p < 0.05$.

Table 2. Laboratory produced raw data[1] for turfgrass soil samples (n = 30) at 3 cm depth segments; statistical analysis of data presented in Table 1.

	0-3 cm			3-6 cm			6-9 cm			9-12 cm			12-15 cm			15-18 cm		
Sample	Saturation % (Loss on Drying)	Saturated Paste Extract (EC)	Deionized Water Extract (Ece)	Saturation % (Loss on Drying)	Saturated Paste Extract (EC)	Deionized Water Extract (Ece)	Saturation % (Loss on Drying)	Saturated Paste Extract (EC)	Deionized Water Extract (Ece)	Saturation % (Loss on Drying)	Saturated Paste Extract (EC)	Deionized Water Extract (Ece)	Saturation % (Loss on Drying)	Saturated Paste Extract (EC)	Deionized Water Extract (Ece)	Saturation % (Loss on Drying)	Saturated Paste Extract (EC)	Deionized Water Extract (Ece)
1	57	0.78	0.18	65	0.94	0.22	32	0.33	0.08	27	0.24	0.05	17	0.07	0.01	11	0.04	0.01
2	45	0.89	0.28	67	0.91	0.27	65	0.42	0.17	64	0.31	0.13	67	0.24	0.16	63	0.13	0.05
3	59	0.78	0.14	64	0.79	0.16	27	0.09	0.07	22	0.24	0.08	14	0.1	0.04	13	0.04	0.02
4	53	0.41	0.11	74	0.59	0.31	56	0.13	0.14	48	0.23	0.11	39	0.06	0.03	26	0.08	0.05
5	43	0.49	0.17	71	0.8	0.38	38	0.1	0.08	22	0.15	0.17	19	0.06	0.04	17	0.09	0.12
6	51	0.59	0.19	73	0.58	0.32	30	0.19	0.16	15	0.24	0.08	18	0.24	0.02	15	0.04	0.03
7	46	0.61	0.2	52	0.94	0.28	47	0.3	0.15	63	0.44	0.17	10	0.03	0.04	12	0.2	0.09
8	45	0.57	0.19	50	1.11	0.3	29	0.08	0.09	50	0.19	0.15	13	0.14	0.09	15	0.15	0.12
9	59	0.59	0.24	69	0.8	0.4	49	0.12	0.1	19	0.27	0.08	19	0.02	0.01	13	0.19	0.12
10	43	0.6	0.09	62	0.89	0.24	60	0.08	0.04	15	0.1	0.11	14	0.2	0.06	13	0.09	0.09
11	52	0.68	0.29	45	0.82	0.28	34	0.25	0.18	32	0.35	0.17	8	0.16	0.05	8	0.13	0.13
12	64	0.72	0.31	65	1.08	0.25	28	0.21	0.17	26	0.25	0.11	10	0.23	0.14	11	0.12	0.09
13	56	0.67	0.24	60	0.62	0.37	33	0.48	0.3	30	0.27	0.14	12	0.14	0.02	10	0.1	0.02
14	46	0.68	0.17	61	0.93	0.35	47	0.38	0.37	13	0.34	0.17	13	0.1	0.03	10	0.16	0.03
15	52	0.73	0.19	62	1.12	0.37	53	0.59	0.11	27	0.16	0.09	8	0.19	0.1	12	0.12	0.09
16	59	0.49	0.16	45	0.97	0.35	54	0.36	0.11	38	0.34	0.15	15	0.12	0.07	25	0.19	0.03
17	49	0.51	0.13	74	1.02	0.24	61	0.16	0.15	43	0.59	0.19	11	0.15	0.08	22	0.11	0.07
18	60	0.68	0.21	67	0.8	0.34	61	0.44	0.13	37	0.23	0.15	18	0.21	0.01	8	0.19	0.02
19	60	0.65	0.25	54	0.54	0.3	32	0.36	0.23	27	0.33	0.09	18	0.16	0.03	19	0.05	0.08
20	43	0.59	0.17	49	0.91	0.32	35	0.21	0.13	20	0.16	0.13	11	0.18	0.09	13	0.14	0.12
21	55	0.6	0.19	67	0.56	0.31	53	0.28	0.08	40	0.12	0.13	35	0.09	0.03	34	0.12	0.13
22	55	0.71	0.23	46	0.86	0.34	38	0.16	0.11	19	0.15	0.07	13	0.16	0.11	7	0.12	0.13
23	55	0.75	0.27	73	1.03	0.38	36	0.39	0.24	34	0.35	0.17	27	0.16	0.13	22	0.04	0.06
24	61	0.71	0.31	74	1.01	0.38	53	0.1	0.06	19	0.14	0.11	19	0.09	0.07	19	0.15	0.1
25	51	0.64	0.17	68	0.81	0.25	49	0.24	0.13	26	0.21	0.12	13	0.23	0.11	15	0.09	0.07
26	69	0.63	0.23	61	0.64	0.2	35	0.28	0.18	34	0.27	0.18	12	0.22	0.14	11	0.09	0.05
27	69	0.71	0.26	47	0.69	0.31	33	0.2	0.13	35	0.13	0.11	17	0.2	0.1	11	0.15	0.05
28	50	0.74	0.18	67	0.99	0.33	54	0.4	0.1	37	0.38	0.1	8	0.17	0.12	14	0.09	0.01
29	61	0.58	0.15	63	1.03	0.21	50	0.4	0.38	36	0.11	0.07	17	0.18	0.16	12	0.19	0.1
30	48	0.59	0.08	59	0.7	0.37	39	0.14	0.12	28	0.14	0.12	13	0.14	0.08	8	0.08	0.1

[1]"Saturated % (Loss on Drying)" = percent saturated water loss upon drying refers to water loss from a saturated soil sample subjected to the soil moisture saturation index test (Dane and Topp, 2002); "Saturated Paste Extract (EC)" = salinity as determined by electrical conductivity as measured from the saturated soil-paste extract solution (Corwin and Yemoto, 2017); "Deionized Water Extract (ECe)" = salinity as determined by electrical conductivity as measured from the soil pore water solution (Corwin and Yemoto, 2017).

3.2 Turfgrass soil samples of 6 cm segments to 18 cm depth.

Data analysis for soil samples (n = 30) partitioned into 6 cm segments for the 0 to 18 cm depth are presented in Table 3. All raw data measured and determined from the soil moisture saturation index test, and raw data representing ECe and ECw, are listed in Table 4.

With percent saturated water loss upon drying, the amounts measured were not uniformly or equally distributed throughout the 0-18 cm soil profile. For the entire 0-18 cm soil column, the saturated water loss ranged from 18.0 to 69.2%, with the highest amount of water loss measured at the 0-6 cm depth (69.2%), and the lowest amount of water loss measured at the 12-18 cm depth (18.0%). Statistically significant differences for percent saturated water loss upon drying from highest to lowest amount of water loss per soil depth were observed as follows: 0-6 > 6-12 > 12-18 cm. Based on percent saturated water loss upon drying, the majority or greatest amount of water loss occurred at the 0-6 cm depth. Therefore, the 0-6 cm depth would represent the ideal soil depth or rootzone layer to monitor and measure soil moisture with a portable hand-held soil moisture meter.

With soil salinity measured as ECe, those ECe values were not uniformly or equally distributed throughout the 0-18 cm soil profile. With the entire 0-18 cm soil column, the ECe ranged from 0.131 to 1.027 $dS \cdot m^{-1}$. This ECe range is acceptable for growing and maintaining turfgrass (Beard, 2001). The highest ECe of 1.027 $dS \cdot m^{-1}$ was measured at the 0-6 cm depth, and the lowest ECe of 0.131 $dS \cdot m^{-1}$ was measured at the 12-18 cm depth. Statistically significant differences for ECe from highest to lowest per depth were measured as follows: 0-6 > 6-12 > 12-18 cm. Based on ECe, the highest salinity concentration occurred at the 0-6 cm depth.

Therefore, the 0-6 cm depth would represent the ideal depth to monitor and measure ECe with a portable hand-held soil EC meter.

With soil salinity measured as ECw, the ECw measured values also were not uniformly or equally distributed throughout the 0-18 cm soil depth. With the entire 0-18 cm soil column, the ECw ranged from 0.081 to 0.371 $dS \bullet m^{-1}$. This ECw range also is acceptable for growing and maintaining turfgrass (Beard, 2001). The highest ECw of 0.371 $dS \bullet m^{-1}$ also was measured at the 0-6 cm depth, and the lowest ECw of 0.081 $dS \bullet m^{-1}$ was measured at the 12-18 cm depth. Statistically significant differences for ECw from highest to lowest per depth were measured as follows: 0-6 > 6-12 > 12-18 cm. Based on ECw, the highest salinity concentration was measured at the 0-6 cm depth. Therefore, the 0-6 cm depth also would represent the ideal depth to monitor and measure ECw with a portable hand-held soil EC meter.

Tables 3 and 4 located on next two pages.

Table 3. Analysis of turfgrass rootzones, 6 cm segments to 18 cm depth.

Rootzone sampling depth	Saturated water loss upon drying[1]	Salinity (ECe)[2]	Salinity (ECw)[3]
--- cm ---	--------- % ---------	-------- $dS \cdot m^{-1}$ --------	-------- $dS \cdot m^{-1}$ --------
0 – 6	69.2 a[4]	1.027 a	0.371 a
6 – 12	34.3 b	0.289 b	0.140 b
12 – 18	18.0 c	0.131 c	0.081 c
LSD value	5.48	0.0699	0.0273
Standard Deviation	10.61	0.1352	0.0529
Rep. Prob. (F)	0.1112	0.1134	0.1375
Treat. Prob. (F)	0.0001	0.0001	0.0001

[1]Saturated water loss upon drying refers to water loss from a saturated soil sample subjected to the soil moisture saturation index test (Dane and Topp, 2002).
[2]Salinity as measured from the saturated soil-paste extract solution (Corwin and Yemoto, 2017).
[3]Salinity as measured from the soil pore water solution (Corwin and Yemoto, 2017).
[4]Means (n=30) followed-by the same letter are not statistically different according to Fisher's protected least significant difference test a $p < 0.05$.

Table 4. Laboratory produced raw data for turfgrass soil samples (n = 30) at 6 cm depth segments; statistical analysis of data presented in Table 3.

	0-6 cm			6-12 cm			12-18 cm		
Sample	Saturation % (Loss on Drying)	Saturated Paste Extract (EC)	Deionized Water Extract (Ece)	Saturation % (Loss on Drying)	Saturated Paste Extract (EC)	Deionized Water Extract (Ece)	Saturation % (Loss on Drying)	Saturated Paste Extract (EC)	Deionized Water Extract (Ece)
1	75	1.10	0.33	70	0.36	0.15	70	0.15	0.06
2	56	1.34	0.37	55	0.22	0.17	17	0.17	0.13
3	73	1.31	0.31	28	0.29	0.13	12	0.14	0.10
4	67	0.75	0.45	33	0.32	0.16	11	0.11	0.02
5	82	0.70	0.39	16	0.28	0.09	17	0.05	0.03
6	69	1.36	0.45	29	0.19	0.10	13	0.14	0.10
7	75	0.68	0.38	44	0.14	0.15	38	0.14	0.14
8	83	1.22	0.46	21	0.16	0.13	21	0.17	0.11
9	50	1.17	0.43	41	0.40	0.17	28	0.21	0.03
10	53	0.83	0.38	38	0.15	0.13	12	0.17	0.06
11	82	1.25	0.46	37	0.41	0.19	24	0.05	0.07
12	73	1.14	0.27	29	0.28	0.06	12	0.05	0.01
13	75	1.20	0.40	40	0.44	0.11	16	0.10	0.01
14	83	1.23	0.29	47	0.69	0.22	24	0.12	0.08
15	68	0.77	0.24	37	0.32	0.21	12	0.10	0.06
16	77	0.97	0.49	21	0.32	0.09	14	0.21	0.13
17	60	0.65	0.37	29	0.39	0.10	21	0.06	0.09
18	52	1.04	0.41	21	0.18	0.08	8	0.14	0.14
19	58	1.14	0.34	69	0.51	0.19	13	0.23	0.10
20	76	0.98	0.31	28	0.25	0.14	17	0.10	0.08
21	55	1.10	0.39	22	0.19	0.15	14	0.16	0.13
22	50	0.99	0.34	35	0.41	0.19	9	0.15	0.14
23	66	0.85	0.45	31	0.16	0.14	9	0.09	0.11
24	72	0.96	0.20	24	0.28	0.09	14	0.05	0.02
25	71	1.25	0.26	39	0.13	0.08	13	0.21	0.11
26	75	0.97	0.41	40	0.27	0.17	9	0.21	0.02
27	83	0.71	0.38	52	0.27	0.13	29	0.09	0.06
28	80	0.97	0.46	24	0.18	0.19	19	0.10	0.13
29	69	1.08	0.29	16	0.12	0.13	14	0.10	0.10
30	68	1.13	0.43	14	0.40	0.19	11	0.18	0.03

[1]"Saturated % (Loss on Drying)" = percent saturated water loss upon drying refers to water loss from a saturated soil sample subjected to the soil moisture saturation index test (Dane and Topp, 2002); "Saturated Paste Extract (EC)" = salinity as determined by electrical conductivity as measured from the saturated soil-paste extract solution (Corwin and Yemoto, 2017); "Deionized Water Extract (ECe)" = salinity as determined by electrical conductivity as measured from the soil pore water solution (Corwin and Yemoto, 2017).

3.3 Further discussion

Data from the laboratory analysis results of all soil cores provided further clarification and confirmation that soil moisture and salinity in the soil profile or rootzone of putting greens is not uniformly or equally distributed. Data from the laboratory analysis results also indicated the uppermost soil layer at the 0 to 6 cm depth had the statistically significant highest percent saturated water loss upon drying, highest ECe, and highest ECw compared to the lower soil layers at the 6-18 cm depth. Therefore, monitoring and measuring this specific soil or rootzone region in intensively managed turfgrass ecosystems would provide the turfgrass practitioner with a better understanding and more insightful information about the soil moisture and salinity status (Soldat and Koch, 2023). This information can them be used to guide the decision-making process about implementing turfgrass cultural practices, such as irrigation inputs or other turfgrass management programs (McCarty, 2011).

Essentially, a turfgrass soil measurement that exceeds 6 cm would possibly dilute or misrepresent the soil moisture and salinity status in that rootzone. Given the apparent influence the uppermost region or layer (i.e., 0-6 cm depth) has on putting green surface conditions, turfgrass cultural maintenance practices that impact variables such as ball roll on putting greens, measuring this uppermost region of turf has multiple benefits. Further, as turfgrass soil systems and rootzones depend on capillary movement of water resulting in a desired upward movement of water at various times of the day and year, this soil-water flux will have an impact and influence on that uppermost soil region (Kopp and Jiang, 2013; Weil and Brady, 2014), especially during the various wetting and drying cycles that occur over time (Fidanza et al., 2023; Kostka et al., 2007; Moeller, 2012). In addition, soil texture significantly influences soil water content (i.e., soil moisture), and in particular coarse sand has the lowest water retention and therefore a faster soil moisture depletion rate (Weil and Brady, 2014; Whitlark, 2018).m, although variances from a multitude of physical and chemical attributes will cause even a coarse sand to function like something other than a sand (Turgeon, 2005). Monitoring soil moisture in the upper rootzone at the 0-6 cm depth for turfgrasses, especially sand-based rootzones of putting greens, should be useful to identify optimum soil moisture status needed to guide irrigation inputs and programs (Kostka et al., 2007; Schiavon and Serena, 2023; Straw et al., 2022). By specifically monitoring and measuring that upper 0-6 cm region effectively and consistently over time, various "data trends" can be observed and identified over time and therefore serve as a guide to the turfgrass practitioner when preparing and maintaining the best putting green playing surfaces (Kowalewski et al., 2014).

Also of importance with that 0-6 cm turfgrass soil layer is the presence of roots and the dynamic influence of the rhizosphere (Carminati et al., 2010; Carminati et al., 2011; Carminati et al., 2013; Carminati et al, 2016; Fidanza et al., 2023; Hallett et al., 2003; Hallett et al., 2022). The presence and biological, chemical, and physical activity of those abundant adventitious roots, root hairs, and rhizosheaths has an influence and impact on soil and turfgrass health and function and therefore also has an impact and influence on putting green surface playing conditions (Whitlark, 2018; York et al., 2016). This does not mean, however, that deeper soil depths > 6 cm are not influential on turfgrass surface conditions, but it does warrant consideration that a sensor designed to measure the bulk soil conditions (i.e., water and salinity) would dilute the measuring of this dominant region of the turfgrass rootzone if that sensor passed through multiple layers of that turfgrass soil or rootzone. And deeper characteristics will undoubtedly impact shallower conditions, measured by targeted focus as outlined here.

4 Conclusion

Analysis of the laboratory data indicated the uppermost 6 cm of the putting green soil (i.e., 0 to 6 cm rootzone depth) is an important indicator of influential soil water status (i.e., soil moisture), ECe, and ECw, compared to lower soil depths of 6 to 18 cm. Analysis of the soil moisture, ECe, and ECw for all soil depths from those putting greens indicated that those three properties are not uniform or equally distributed with the turfgrass rootzone. A further understanding of how portable hand-held sensors work and function, and how best to employ them and utilize them to monitor and measure the turfgrass soil environment, could lead to more useful and impactful knowledge toward developing better or improved sustainable practices to manage and maintain golf course putting greens and other turfgrass ecosystems.

5 References

Beard, J.B. 2001. Turf management for golf courses, 2nd ed. John Wiley and Sons, Inc., Hoboken, NJ.

Burns T.T., Adams, J.R. and Berg, A. 2014. Laboratory calibration of the hydra probe soil moisture sensor: Infiltration wet-up vs. dry-down. Vadose Zone Journal 13(12): doi:10.2136/vzj2014.07.0081.

Campbell, J. 1990. Dielectric properties and influence of conductivity in soils at one to fifty megahertz. Soil Science Society of America Journal 54:332-341.

Carminati, A. and Vetterlein, D. 2013. Plasticity of rhizosphere hydraulic properties as a key for efficient utilization of scarce resources. Annals of Botany 112:277-290.

Carminati A., Moradi, A., Vetterlein, D., Vontobel, P., Lehmann, E., Weller, U., Vogel, H-J., and Oswald, S.E. 2010. Dynamics of soil water content in the rhizosphere. Plant and Soil 332:163–176.

Carminati, A., Schneider, C.L., Moradi, A.B, Zarebanadkouki, M., Vetterlein, D., Vogel, H-J., Hildebrandt, A., and Weller, U. 2011. How the rhizosphere may favor water availability to roots. Vadose Zone Journal. 10:988–998.

Carminati, A., Zarebanadkouki, M., Kroener, N., Ahmed, M.A., and Holz, M. 2016. Biophysical rhizosphere processes affecting root water uptake. Annuals of Botany 118:561-571.

Corwin, D.L. and Scudiero, E. 2016. Field-scale apparent soil electrical conductivity. Methods of Soil Analysis, Volume 1; Soil Science Society of America, Madison, WI.

Corwin, D.L. and Yemoto, K. 2017. Salinity: Electrical conductivity and total dissolved solids. Methods of Soil Analysis, Volume 2; Soil Science Society of America, Madison, WI.

Dane, J.H. and Topp, G.C. 2002. Methods of soil analysis, Part 4 - Physical methods. Soil Science Society of America, Madison, WI.

Dahnke, W.C and Whitney, D.A. 1988. Measurement of soil salinity. In: W.C. Dahnke (Ed.), Recommended chemical soil test procedures for the North Central Region; North Dakota Agricultural Experiment Station Bulletin 499.

Dobriyal, P., A. Qureshi, A., Badola, R. and Hussain, S.A. 2012. A review of the methods available for estimating soil moisture and its implications for water resource management. Journal of Hydrology 458-459:110–117.

Fidanza, M., Bigelow, C., Kostka, S., Ervin, E., Gaussoin, R., Rossi, F., Cisar, J., Dinelli, F.D., Pope, J., and Steffel, J. 2023. Advances in biostimulants in turfgrass. In: Fidanza, M. (Ed.), Achieving sustainable turfgrass management; Burleigh Dodds Science Publishing, Cambridge, UK.

Gelernter, W.D., Stowell, L.J., Johnson, M.E., Brown, C.D., and Beditz, J.F. 2015. Documenting trends in water use and conservation practices on U.S. golf courses. Crop, Forage and Turfgrass Managament 1:1-10.

Hallett, P.D., Gordon, D.C., and Bengouh, A.G. 2003. Plant influence on rhizosphere hydraulic properties: Direct measurements using a miniaturized infiltrometer. The New Phytologist 157:597-603.

Hallett, P.D., Marin, M., Bending, G.D., George, T.S., Collins, C.D., and Otten, W. 2022. Building soil sustainability from root-soil interface traits. Trends in Plant Science 27:688-698.

Harivandi, A.B. 2012. Irrigation puzzle: Sourcing water for golf courses. USGA Turfgrass and Environmental Research Online 11(12):29-31.

Hillel, D. 1980. Fundamentals of soil physics. Academic Press, New York, NY.

Jespersen, D., Wherley, B., and DaCosta, M. 2023. Advances in understanding turfgrass physiology. In: Fidanza, M. (Ed.), Achieving sustainable turfgrass management; Burleigh Dodds Science Publishing, Cambridge, UK.

Kopp, K.L and Jiang, Y. 2013. Turfgrass water use and physiology. In: Stier, J., Horgan, B.P., and Bonos, S.A. (Eds.), Turfgrass biology, use and management; Agronomy Monograph no. 56; ASA-CSSA-SSSA, Madison, WI.

Kostka, S.J., Cisar, J.L., Mitra, S., Park, D.M., Ritsema, C.J., Dekker, L.W., and Franklin, M.A. 2007. Irrigation efficiency: Surfactants can save water and help maintain turfgrass quality. Golf Course Industry 19(4):91-95.

Kowalewski, A., Mattox, C., McDonald, B., Daviscourt, B., and Magro, C. 2014. Relationship between distribution uniformity and soil moisture content. Golf Course Management 82(12):84-87.

Kowalewski, A., Schmid, C., Wang, R., and Braithwaite, E. 2023. Advances in managing organic matter in turfgrass ecosystems. In: Fidanza, M. (Ed.), Achieving sustainable turfgrass management; Burleigh Dodds Science Publishing, Cambridge, UK.

Leinauer, B. and Devitt, D.A. 2013. Irrigation science and technology. In: Stier, J., Horgan, B.P., and Bonos, S.A. (Eds.), Turfgrass biology, use and management; Agronomy Monograph no. 56; ASA-CSSA-SSSA, Madison, WI.

Lyman, G.T., Throssell, C.S., Johnson, M.E., Stacey, G.A., and Brown, C.D. 2007. Golf course profile describes turfgrass, landscape and environmental stewardship features. Applied Turfgrass Science 4:1-25.

McCarty, L.B. 2011. Best golf course management practices, 3rd Ed. Prentice Hall, New York, NY, USA.

Mead, R., Curnow, R.N., and Hasted, A.M. 2003. Statistical Methods in Agriculture and Experimental Biology. Chapman and Hall/CRC Press, Boca Raton, FL.

Moeller, A. 2012. Identify soil moisture status more accurately than ever before. USGA Green Section Record 50:1-5.

Pathan, S., Barton, L., and Colmer, T. 2007. Evaluation of a soil moisture sensor to reduce water and nutrient leaching in turfgrass (Cynodon dactylon cv. Wintergreen). Australian Journal of Experimental Agriculture 47:215-222.

Rhoades, J.D., Manteghi, N.A., Shouse, P.J., and Alves, W.J. 1989. Estimating soil salinity from saturated soil-paste electrical conductivity. Soil Science Society of America Journal 53:428-433.

Seyfried, M.G., Grant, L.E., Du, E., and Humes, K. 2005. Dielectric loss and calibration of the hydra probe soil water sensor. Vadose Zone Journal 4:1070-1079.

Schiavon, M. and Serena, M. 2023. Advances in irrigation and water management. In: Fidanza, M. (Ed.), Achieving sustainable turfgrass management; Burleigh Dodds Science Publishing, Cambridge, UK.

Soldat, D.J. and Koch, P.L. 2023. Advances in soil management for successful establishment and maintenance of turfgrass. In: Fidanza, M. (Ed.), Achieving sustainable turfgrass management; Burleigh Dodds Science Publishing, Cambridge, UK.

Sparks, D.L. 1996. Methods of soil analysis, Part 3 - Chemical methods. Soil Science Society of America; Madison, WI.

Straw, C., Bolton, C., Young, J., Hejl, R., Friell, J., and Watkins, E. 2022. Soil moisture variability on golf course fairways across the United States: An opportunity for water conservation with precision irrigation. Agrosystems, Geosciences and Environment 5(4):e20323.

Sushalekshmi, S.U., Singh, D.N., and Baghini, M.S. 2014. A critical review of soil moisture measurement. Measurement 54:92-105.

Throssell, C.S., Lyman, G.T., Johnson, M.E., Stacey, G.A., and Brown, C.D. 2009. Golf course environmental profile measures water use, source, cost, quality, and management and conservation strategies. Applied Turfgrass Science 6:1-20.

Thoms, A.W. and Lindsey, A.J. 2023. Advances in maintenance practices of turfgrass. In: Fidanza, M. (Ed.), Achieving sustainable turfgrass management; Burleigh Dodds Science Publishing, Cambridge, UK.

Turgeon, A. 2005. Turfgrass management, 7th ed. Pearson Education, Upper Saddle River, NJ.

United States Golf Association. 2004. USGA recommendations for a method of putting green construction. USGA Green Section; Far Hills, NJ.

Waddington, D.V., Rieke, P.E., and Carrow, R.N. 2002. Turfgrass soil fertility and chemical problems: Assessment and management. John Wiley and Sons, Inc., Hoboken, NJ.

Walworth, J. 2007. Soil sampling and analysis. Golf Course Industry. Source: https://www.golfcourseindustry.com/article/soil-sampling-and-analysis--research-/

Waltz, F.C., and Carrow, R.N. 2007. Applied turfgrass water use efficiency/conservation: Agronomic practices and building cooperation between industry trade associations and regulatory authorities. Acta Horticulturae 783:239-245.

Weil, R. and N. Brady. 2018. Elements of the nature and properties of soils, 4th ed. Pearson Education, New York, NY.

Whitlark, B. 2014. Winning strategies to overcome adverse soil conditions. USGA Green Section Record 52(15):1-9.

Wu, L. 1985. Matching irrigation to turfgrass root depth. California Turfgrass Culture 35(1):1-2.

York, L., Carminati, A., Mooney, S., Ritz, K., and Bennett, M.J. 2016. The holistic rhizosphere: integrating zones, processes, and semantics in the soil influenced by roots. Journal of Experimental Botany 67(12):3629-3643.

Chapter 4

Considerations with global use characteristics for monitoring volumetric water content of turfgrass rootzones.

Abstract

Since 2014, use of important or impactful environmental monitoring technology designed to measure soil volumetric water content (VWC) and other variables effectively in turfgrass ecosystems has been captured digitally by Amazon Web Services on the POGO TurfPro platform, thus resulting in the ability to evaluate sampling habits and usage trends by the turfgrass practitioner. The POGO TurfPro sensor utilizes coaxial impedance dielectric permittivity technology to measure VWC. The worldwide use of the POGO TurfPro system among turfgrass practitioners and turfgrass industry professionals was evaluated from 2014-2021. The total number of global VWC sampling events were only 135 in 2014, but increased to >10,000,000 in 2021. From 2014 to 2017, there was an exponential increase in soil sampling from 135 to nearly 4,000,000, and reaching >10,000,000 in 2021, thus representing a 29.25% annual average increase during 2017-2021. From 2016-2021, soil sampling occurred consistently from January through December, with > 50% of global sampling during May through September on a majority of the sites. This analysis of turfgrass practitioner use characteristics confirmed that portable hand-held sensor technology has become an accepted and heavily relied upon tool for supporting water conservation and other sustainable turfgrass management practices.

1 Introduction

Brosnan et al. (2020) provided a detailed review of the various ecosystem services provided by greenspaces containing turfgrass (i.e., golf courses, sports fields or pitches, parks and recreation areas, and lawns and landscapes). To establish and maintain these valuable turfgrass greenspaces to the desired level of quality and purpose, various cultural practices are employed (i.e., mowing, irrigation, fertilization, cultivation, and pest management) (Beard, 2001; Brosnan et al., 2020; Turgeon, 2005). In addition, monitoring the environment and utilizing environment-based information to make agronomic decisions also has become an important component of turfgrass management (Carlson et al., 2022; Carrow et al., 2010; Gelernter et al., 2015; Steinke and Ervin, 2013). With turfgrass science and management, the concepts of integrated pest management, best management practices, and sustainable management practices can be represented as "data are the basis of knowledge, and knowledge is power" (Danneberger, 2007). Of note, maintaining and managing turfgrass health through improved water management has become a commonly accepted practice among golf course superintendents, greenkeepers, course care managers, and sports pitch and grounds managers (Fidanza, 2023; McCarty, 2011).

Monitoring soil moisture has become an important and commonly acceptable sustainable turfgrass management practice among golf course superintendents, greenkeepers, course care managers, sports pitch and grounds managers, and other turfgrass industry professionals (Gelernter et al., 2015; Moeller, 2012; Schiavon and Serena, 2023; Soldat and Koch, 2023). For example, a recent survey indicated that total irrigation water applied to USA golf courses has declined since 2005, and this water conservation factor is attributed to an increased awareness and implementation of sustainable turfgrass management practices which include soil moisture monitoring (Shaddox et al., 2022). Specifically, the use of portable hand-held soil moisture sensors among USA golf courses was report as < 1% in 2005, 33% in 2013, and 49% in 2020 (Gelernter et al., 2015; Shaddox et al., 2022; Throssell et al., 2009). Thus, soil moisture monitoring has become a commonly utilized practice now fully integrated into turfgrass management (Jones, 2021).

A recently developed and manufactured soil moisture sensor that utilizes coaxial impedance dielectric permittivity technology has gained acceptance globally in the golf course and sports pitch industries (Burns et al., 2014; Campbell, 1988; Campbell, 1990; Magro, 2020). This technology has been commercialized as the HydroProbe™ sensor and is available as a portable hand-held device marketed as the POGO TurfPro system (Stevens Water Monitoring Systems; Portland, OR, USA).

Since 2014, the POGO TurfPro environmental monitoring platform has been commercially available for measuring soil or rootzone volumetric water content (VWC) and other variables (Magro, 2020). The POGO TurfPro system utilizes a portable, hand-held, wireless device that measures rootzone VWC, soil surface temperature heat index via infrared, soil electrical conductivity, and soil temperature (Figure 1). The environmental monitoring platform refers to the capability for the end-user to capture and store their monitored data into a digital system or "cloud", and visually review and evaluate their data at any time (Magro, 2020). All environmental data collected from POGO TurfPro is processed through Amazon Web Services (Amazon.com, Inc.; Seattle, WA, USA), which is a cloud-based technology platform that facilitates the assessment of use patterns and trends with POGO TurfPro's monitoring or sampling activity around the globe.

A B C D

Figure 1. The POGO TurfPro (Stevens Water Monitoring Systems; Portland, OR, USA) system utilizes a POGO Pro+ turfgrass insight sampling tool, and a bluetooth-linked mobile application (TurfPro Mobile) for data collection and analysis. A: Example of data collection and analysis output from putting green #14 on a golf course; the image indicates the perimeter of the site (i.e., putting green, left image), the location of the current nine sampling sites taken so far within that putting green, soil moisture (percent volumetric water content), soil electrical conductivity (dS•m^{-1}), surface heat index (as °C or °F), salinity concentration index (dS•m^{-1}), and root zone temperature (as °C or °F); the spatial analysis is completed on an Amazon Web Services hosted platform in sync with the mobile application that turfgrass managers utilize. B: POGO TurfPro hand-held wireless device or meter commercially called POGO Pro+. C: POGO TurfPro soil moisture measuring components (5.6 cm [2.2 inch] length metal rods on an integrated sensor apparatus) on left-side of image; single metal rod on right-side of image measures soil temperature. D: An example of the spatial analysis of moisture content across a football pitch.

A consistently observed trend of increased usage with soil moisture meters among end-users is attributed to an improved understanding and value of those measured environmental variables, and more so as a result of learning about the technology and learning how to fully utilize the technology into an overall turfgrass management program (Magro, 2020; Shaddox et al., 2022; Schiavon and Serena, 2023).

The POGO TurfPro cloud-based data capture, storage, and retrieval platform was first introduced in 2014 (Magro, 2020). This platform allows the end-user to visualize and utilize digitally illustrated information to assess current environmentally monitored conditions to support their turfgrass management decisions, practices, and programs. It is unclear, however, as to the extent of adaptability and widespread use of this technology among turfgrass industry practitioners (i.e., golf course superintendents, greenkeepers, course care managers, sports pitch and grounds managers, and other turfgrass industry professionals. Therefore, the objective of this study was to evaluate the worldwide use of POGO TurfPro during 2014-2021 for monitoring soil volumetric water content (VWC) among turfgrass practitioners and turfgrass industry professionals.

2 Materials and methods

Global end-user POGO TurfPro data was housed in the Amazon Web Services platform and was obtained for the years 2014 through 2021 (Amazon, 2022). Of note, global end-user data was only available for those end-users that utilize the POGO TurfPro data capture, storage, and analysis platform. The actual number of POGO TurfPro units sold and utilized during 2014-2021 was not available due to the propriety of sales and market information from the manufacturer. For this study, global data focused on VWC, and specifically, sampling events (i.e., samples obtain or sampling events = indication of use), and all data was compiled onto a digital spreadsheet for analysis by month and year and geographic location from 2014-2021. Data trend analysis was evaluated by linear regression (Mead et al., 2003).

3 Results and discussion

Overall, the POGO TurfPro end-user data indicates that since it was introduced into the global turfgrass industry in 2014, the utilization of this technology has dramatically increased over the following several years up-to-and-including 2021 (Figures 2, 3, 4a-4h, 5a-5h, 6a-6h).

3.1 Global sampling usage

Global soil moisture monitoring and sampling for 2014-2021 is illustrated in Figures 2, 3, 4a-4h, and 5a-5h. In 2014, the very first year of introduction into the turfgrass industry market, only 134 global soil VWC samples or sampling points were recorded. In 2015, the sampling exponentially increased to 265,913. This exponential increase continued in 2016 with 1,515,537 samples, and in 2017 with nearly 4,000,000 samples. Over 5,000,000 samples were recorded in 2018, and over 6,000,000 samples were recorded in 2019. In 2020, the total number of global soil VWC samples reached over 8,000,000. In 2021, the total number of global soil VWC samples reached over 10,000,000. From 2017 (nearly 4,000,000 samples) to 2021 (over 10,000,000 samples), there has been a 29.25% average annual increase in global soil VWC monitoring utilizing the POGO TurfPro platform. The global soil VWC monitoring activity from 2014 through 2021 is represented by an increasing polynomial trend (model $R^2 = 0.9915$). Thus, monitoring soil VWC has very quickly and rapidly gained acceptance and use, and also repeated use, among turfgrass practitioners.

In 2014, the majority of global soil VWC samples occurred in July. In 2015, sampling occurred from April through December, with over 50,000 during August. In 2015, monitoring during July, August, and September represented nearly 45% of all samples. In 2016, sampling occurred in all 12 months, from January through December, and this also was observed consistently in 2017-2021. In 2016, nearly 200,000 samples occurred in June and again in July. Also in 2016, the summer months of June, July, and August in the northern hemisphere represented the top three months for monitoring soil VWC. In 2017, over 400,000 samples were recorded each month for June, July, and August. Also in 2017, again the summer months of June, July, and August in the northern hemisphere represented the top three months for monitoring soil VWC. In 2018, over 500,000 samples were recorded each month for May, June, July, and August. Also in 2018, again the summer months of June, July, and August represented the top three months for monitoring soil VWC, although monitoring activity during the month of May was very similar to the month of June. In 2019, over 750,000 samples were recorded each month for July and August, with over 600,000 samples recorded each month for June and September, and nearly 600,000 for the month of May. In 2019, the months of June, July, and August represented the top three months for monitoring soil VWC, although the months of May and September were very close in sampling activity. In 2020, over 900,000 samples were recorded each month for June, July, and August. Also in 2019, the months of June, July, and August represented the top three months for monitoring soil VWC. In 2020, over 1,000,000 samples were recorded each month for June, July, and August, and over 900,000 samples each month for April, May, and September, and over 600,000 samples each month for all other months (i.e., January, February, March, October, November, and December). In 2021, again the months of June, July, and August represented the top three months for monitoring soil VWC. Also in 2021, the actual percent of global soil VWC monitoring per month ranged from a low of about 6% to a high of over 10%, thus indicating the turfgrass practitioner's global usage pattern of consistent sampling throughout the calendar year and an indication of sampling across northern and southern hemispheres.

Figures 2, 3, 4a-4h, and 5a-5h are located on the following pages.

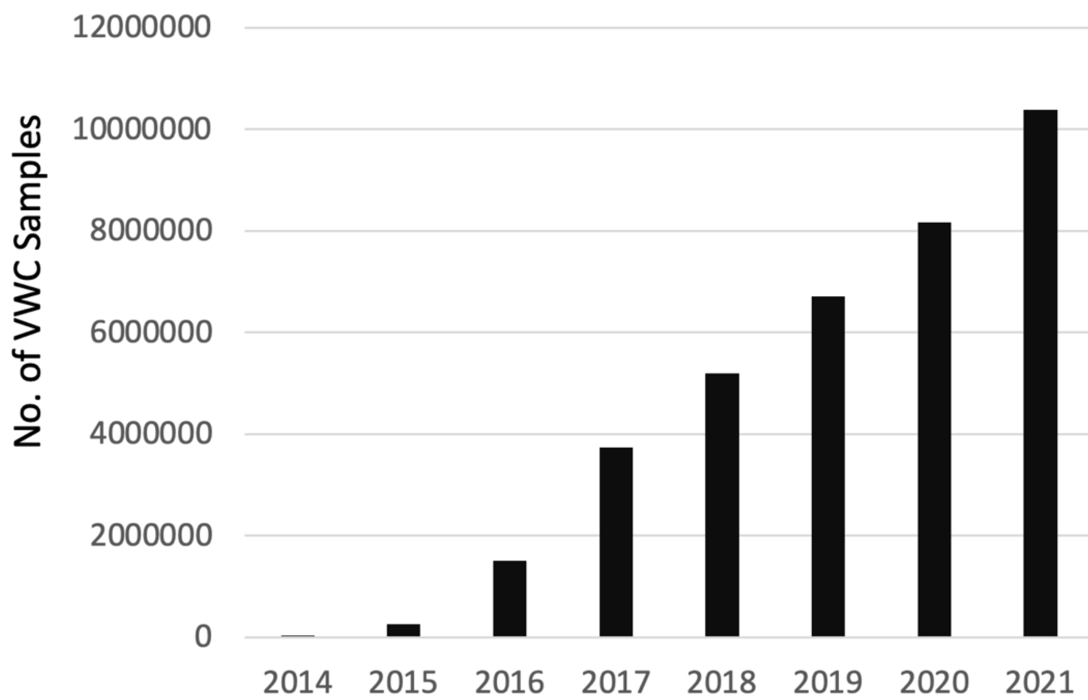


Figure 2. Total number of global soil volumetric water content (VWC) samples per year for 2014 to 2021. Note, 2014 to 2016 were < 2,000,000 (2014 = 135; 2015 = 265,913; 2016 = 1,515,537).

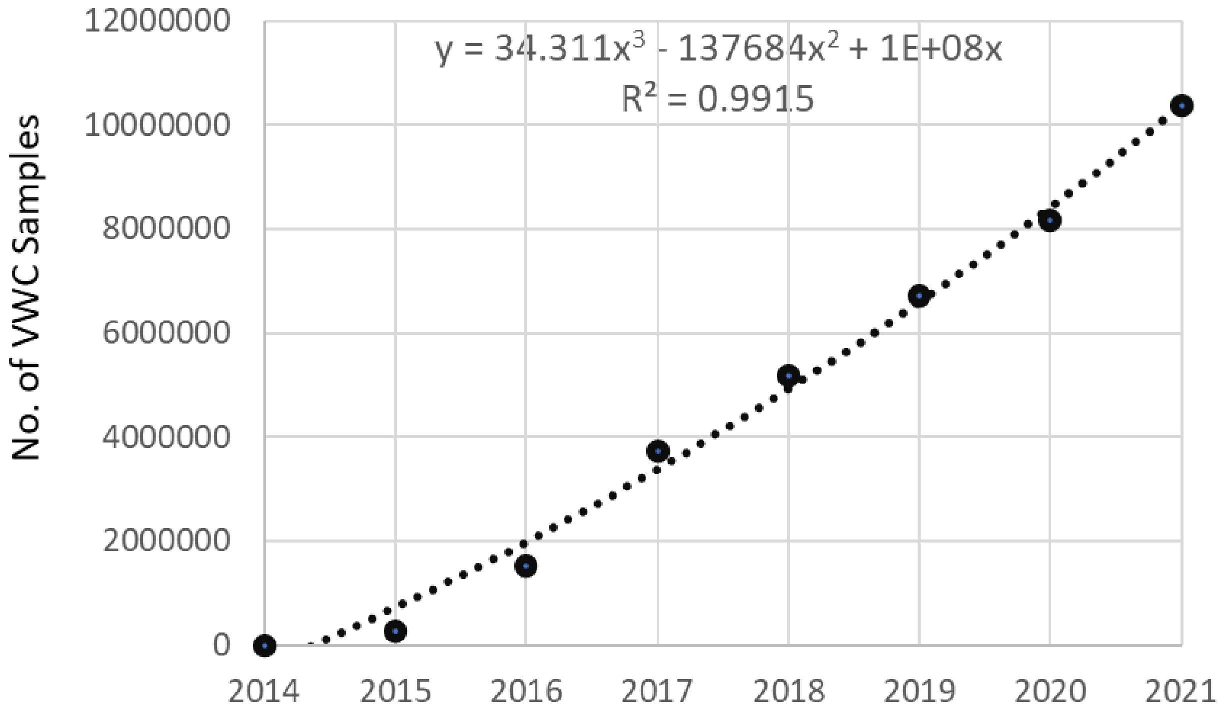


Figure 3. Polynomial increase over time for total number of global soil volumetric water content (VWC) samples per year for 2014 to 2021. Note, 2014 to 2016 were < 2,000,000 (2014 = 135; 2015 = 265,913; 2016 = 1,515,537).

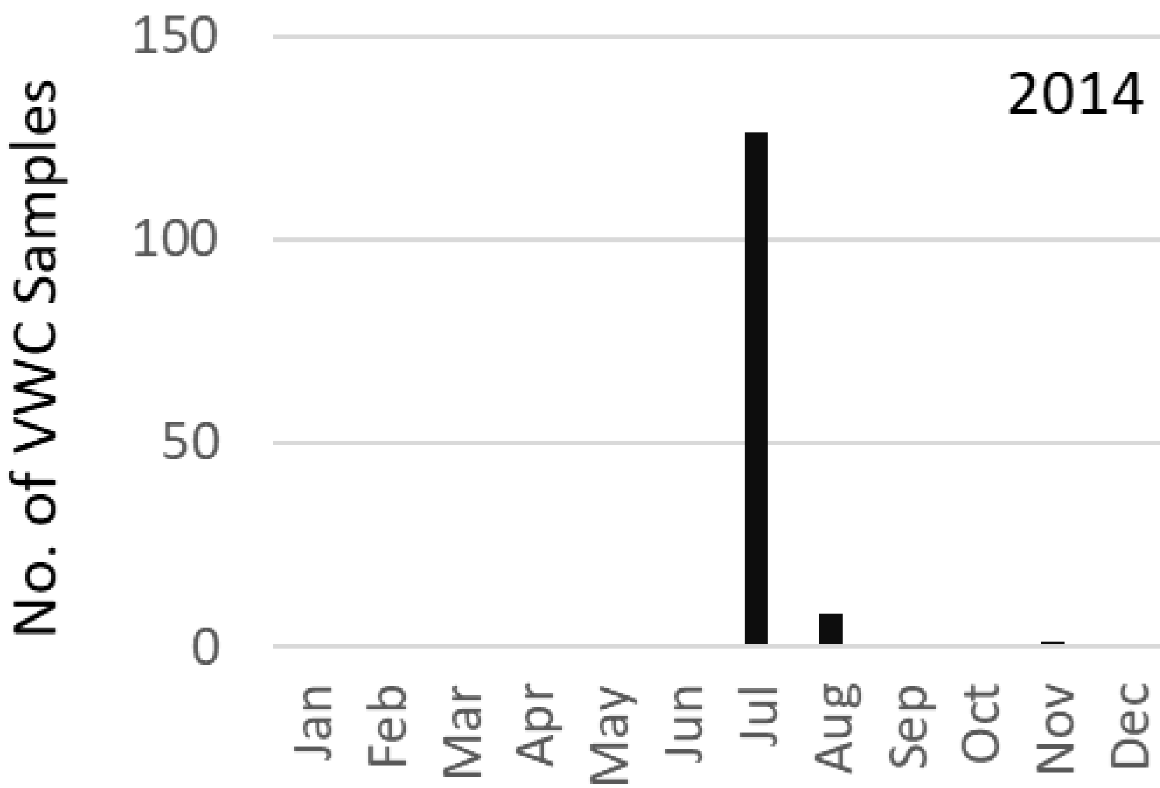


Figure 4a. Total number of global soil volumetric water content (VWC) samples per month in 2014.

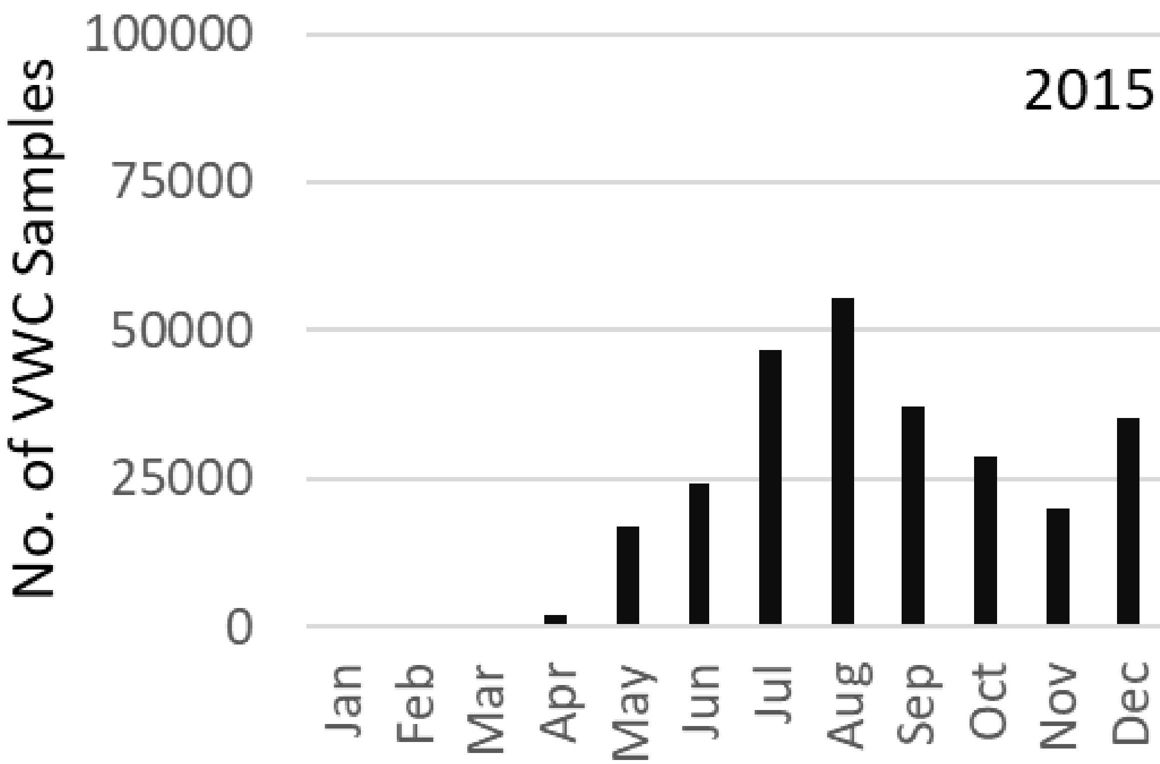


Figure 4b. Total number of global soil volumetric water content (VWC) samples per month in 2015.

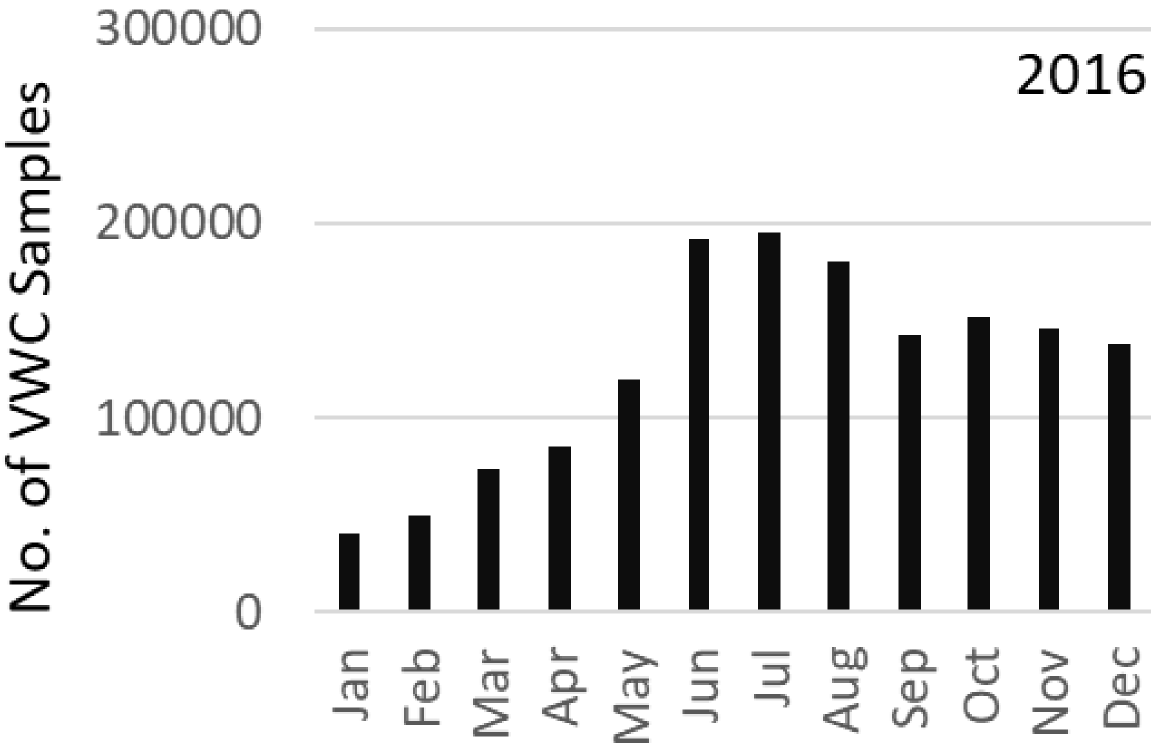


Figure 4c. Total number of global soil volumetric water content (VWC) samples per month in 2016.

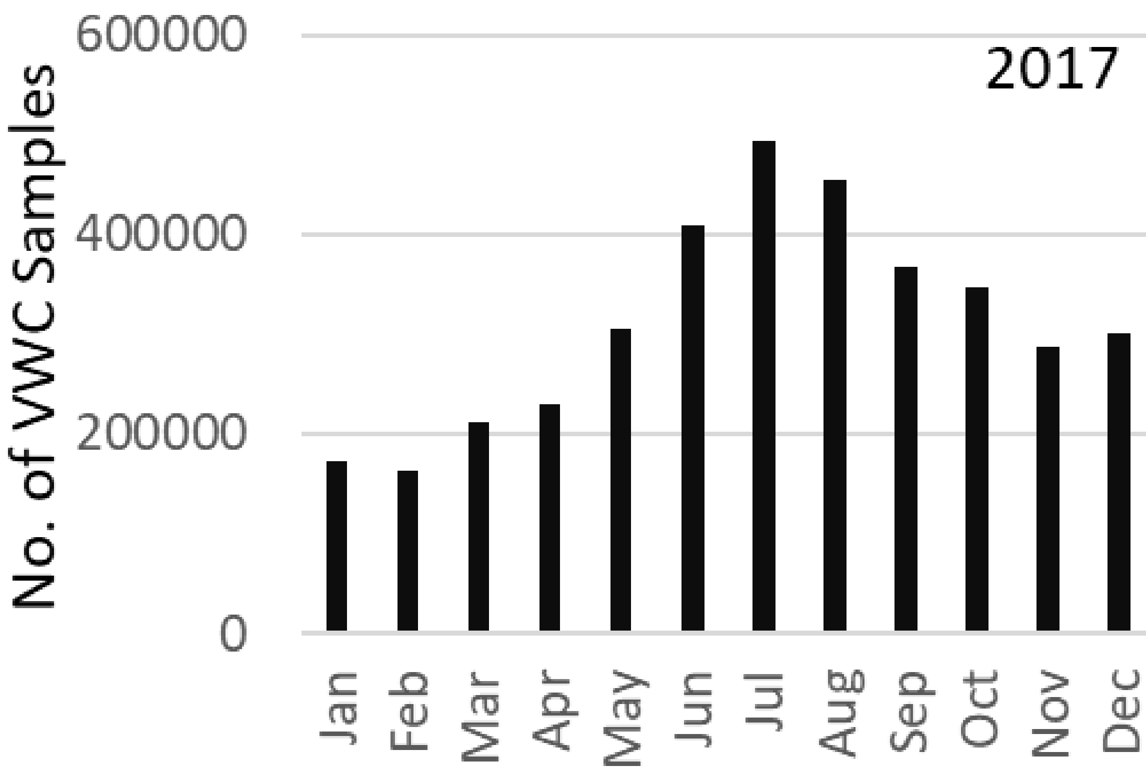


Figure 4d. Total number of global soil volumetric water content (VWC) samples per month in 2017.

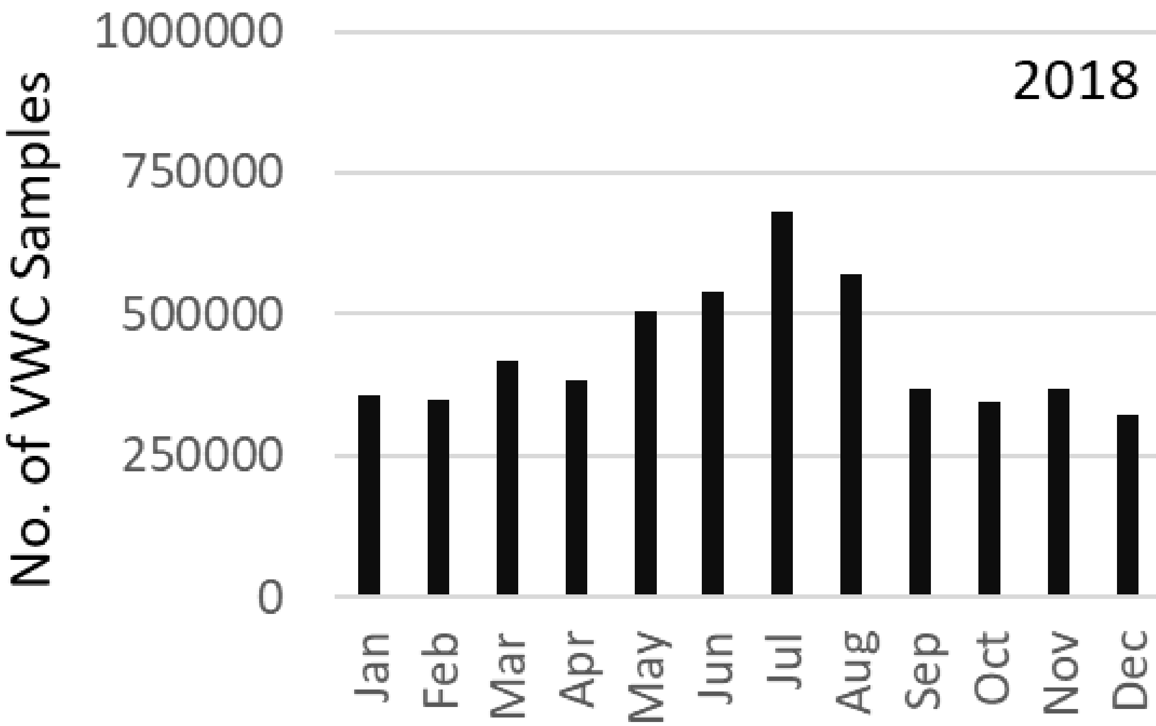


Figure 4e. Total number of global soil volumetric water content (VWC) samples per month in 2018.

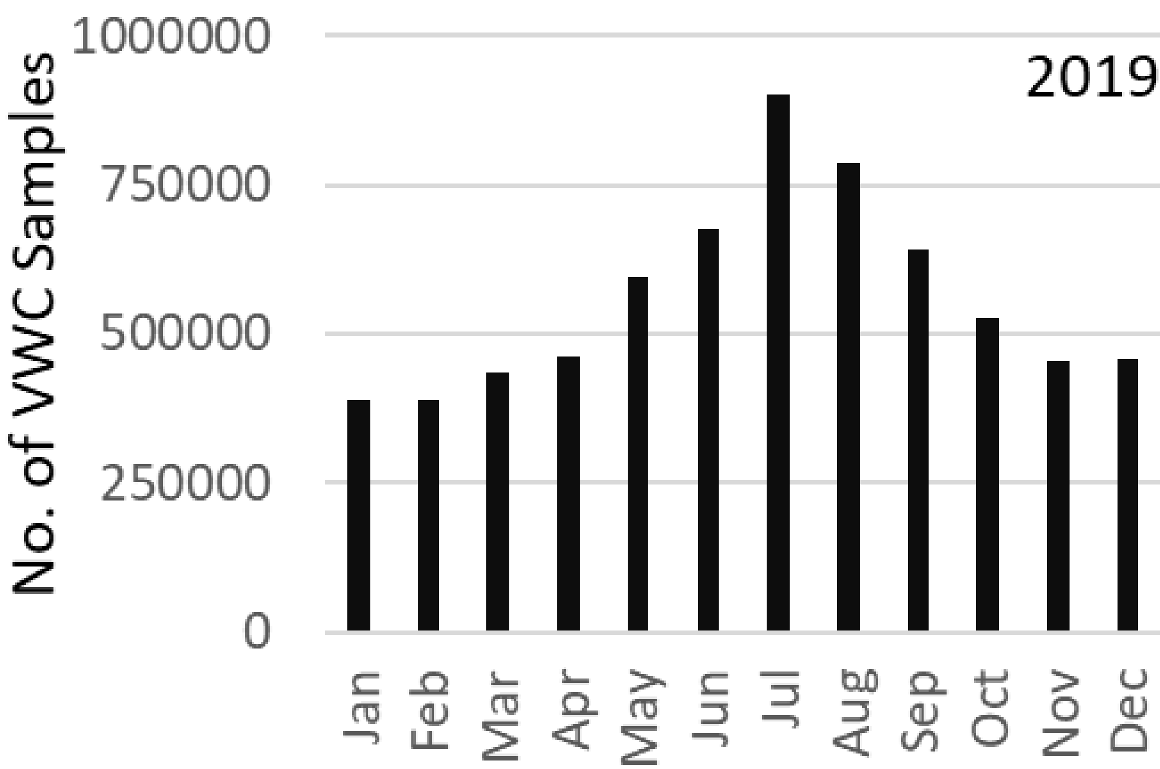


Figure 4f. Total number of global soil volumetric water content (VWC) samples per month in 2019.

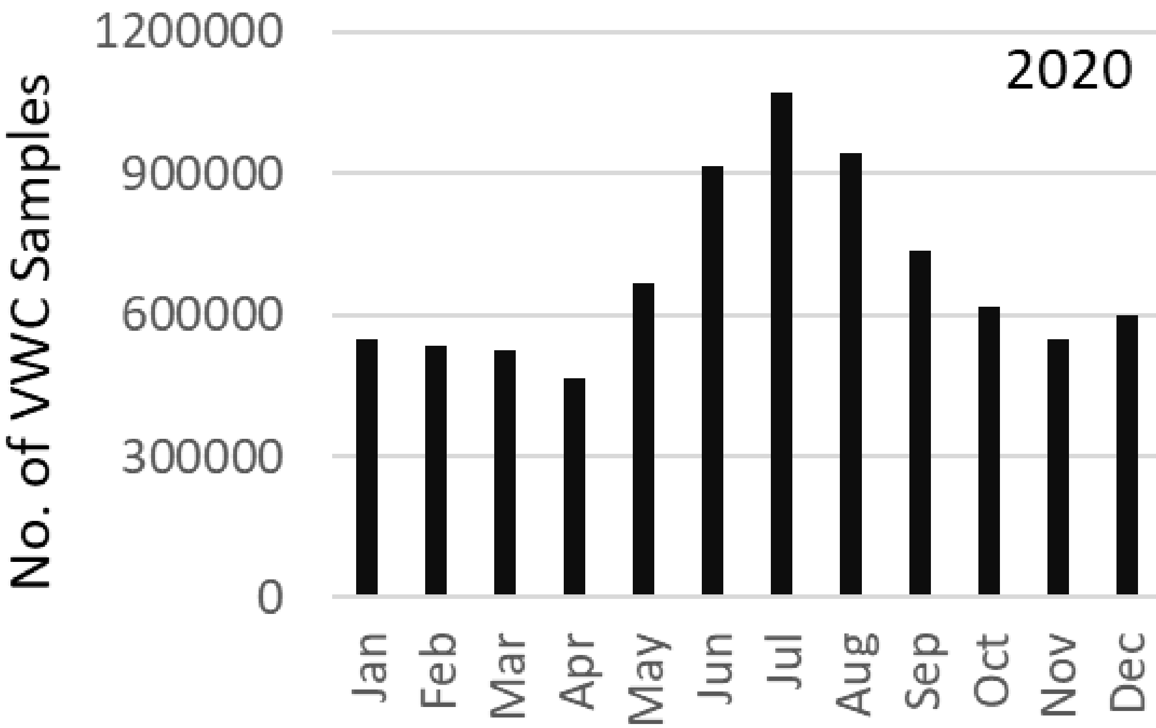


Figure 4g. Total number of global soil volumetric water content (VWC) samples per month in 2020.

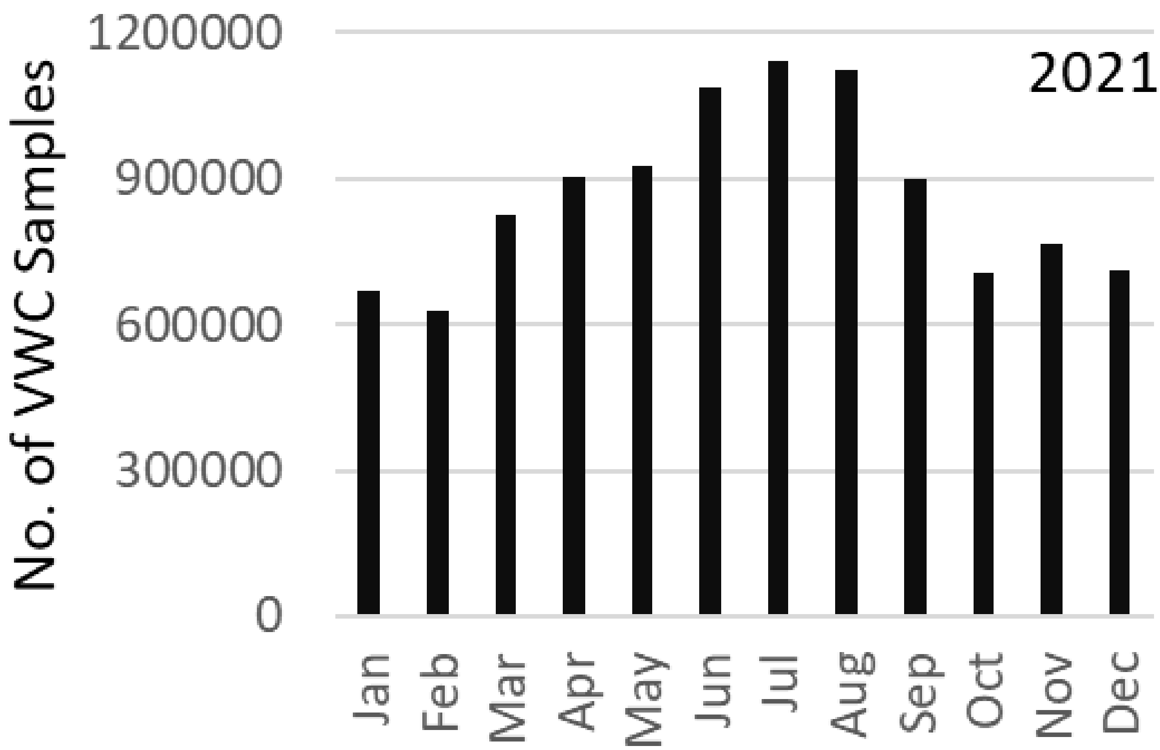


Figure 4h. Total number of global soil volumetric water content (VWC) samples per month in 2021.

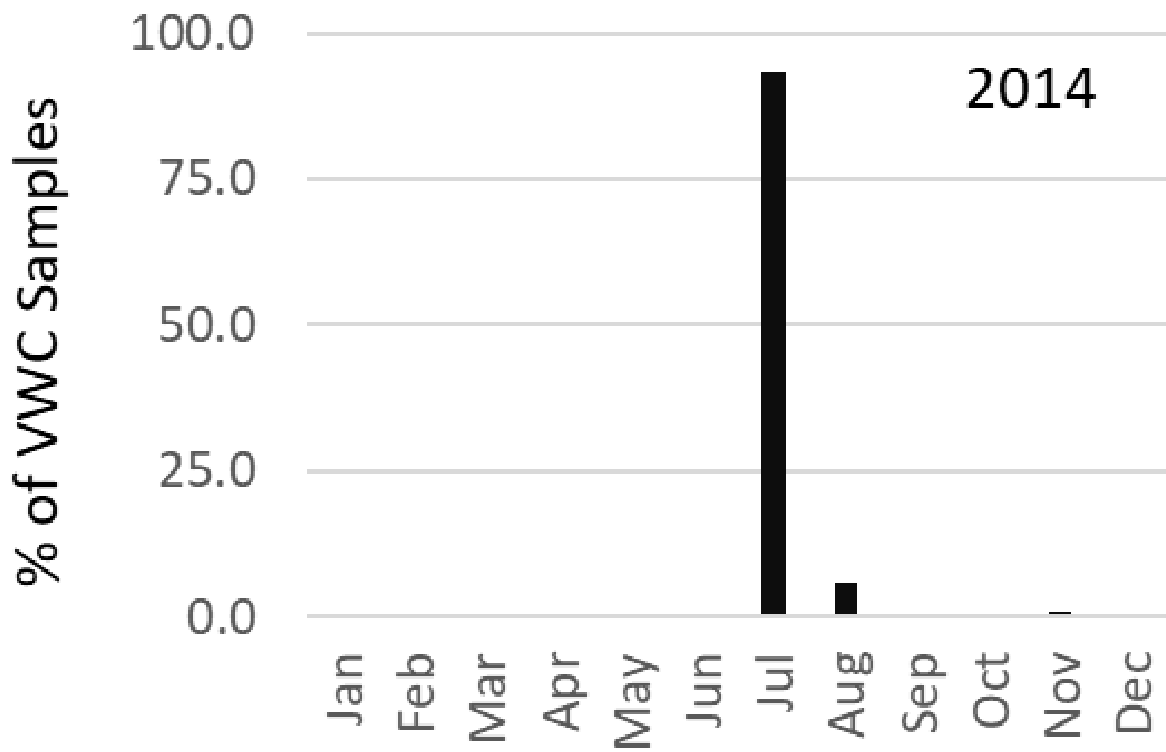


Figure 5a. Percent of total number of global soil volumetric water content (VWC) samples per month in 2014.

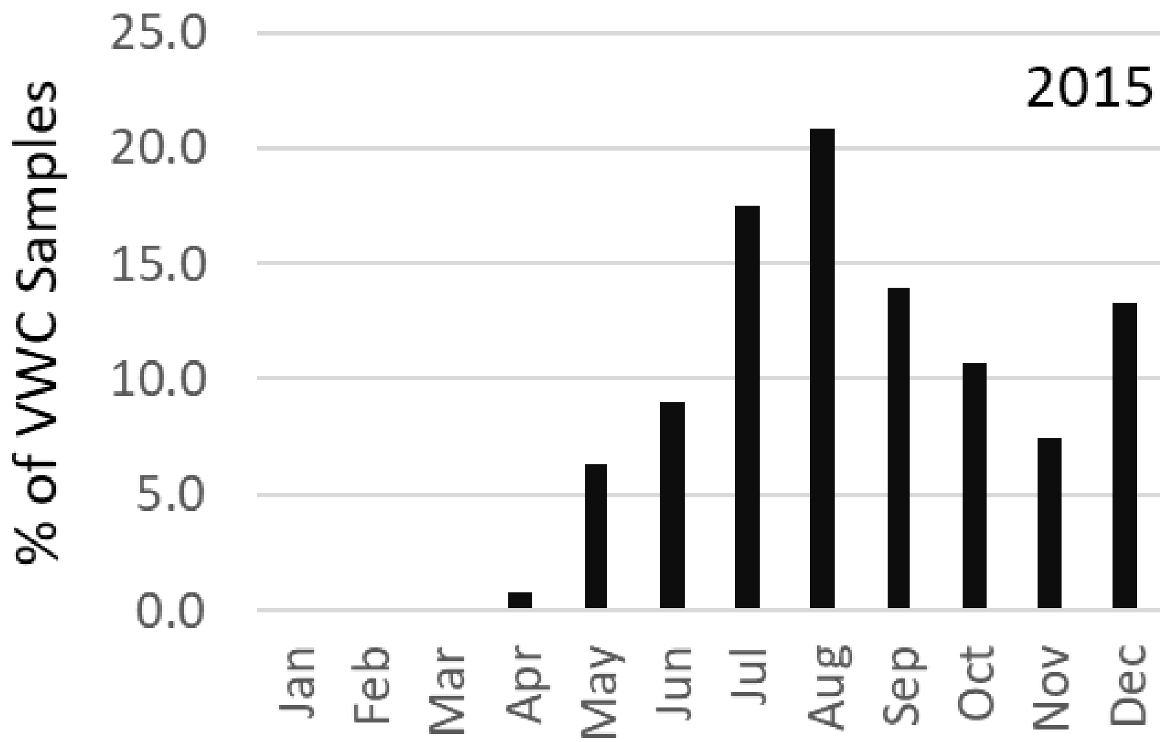


Figure 5b. Percent of total number of global soil volumetric water content (VWC) samples per month in 2015.

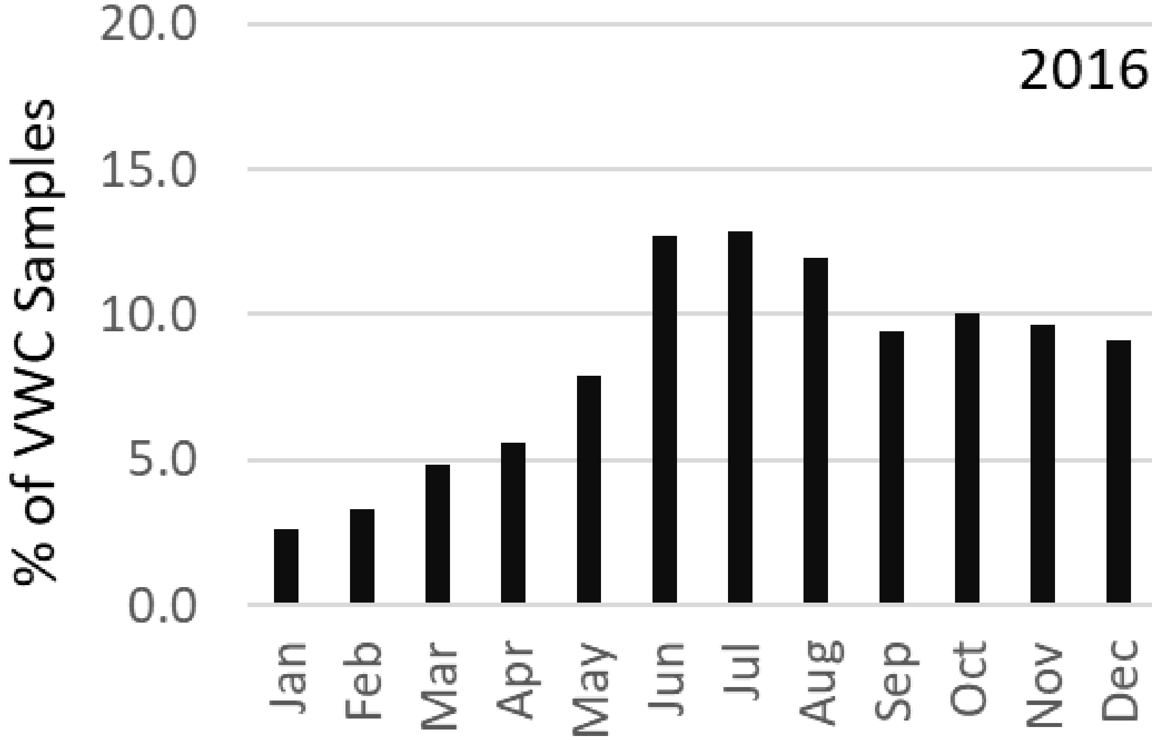


Figure 5c. Percent of total number of global soil volumetric water content (VWC) samples per month in 2016.

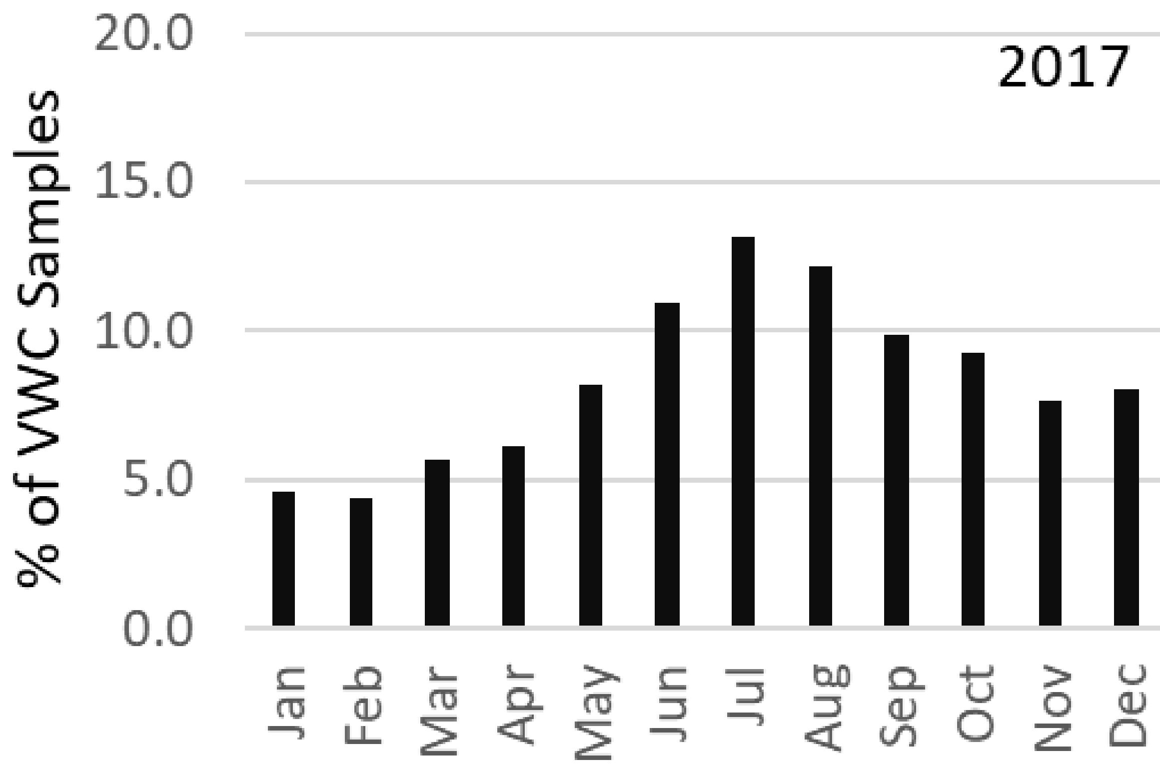


Figure 5d. Percent of total number of global soil volumetric water content (VWC) samples per month in 2017.

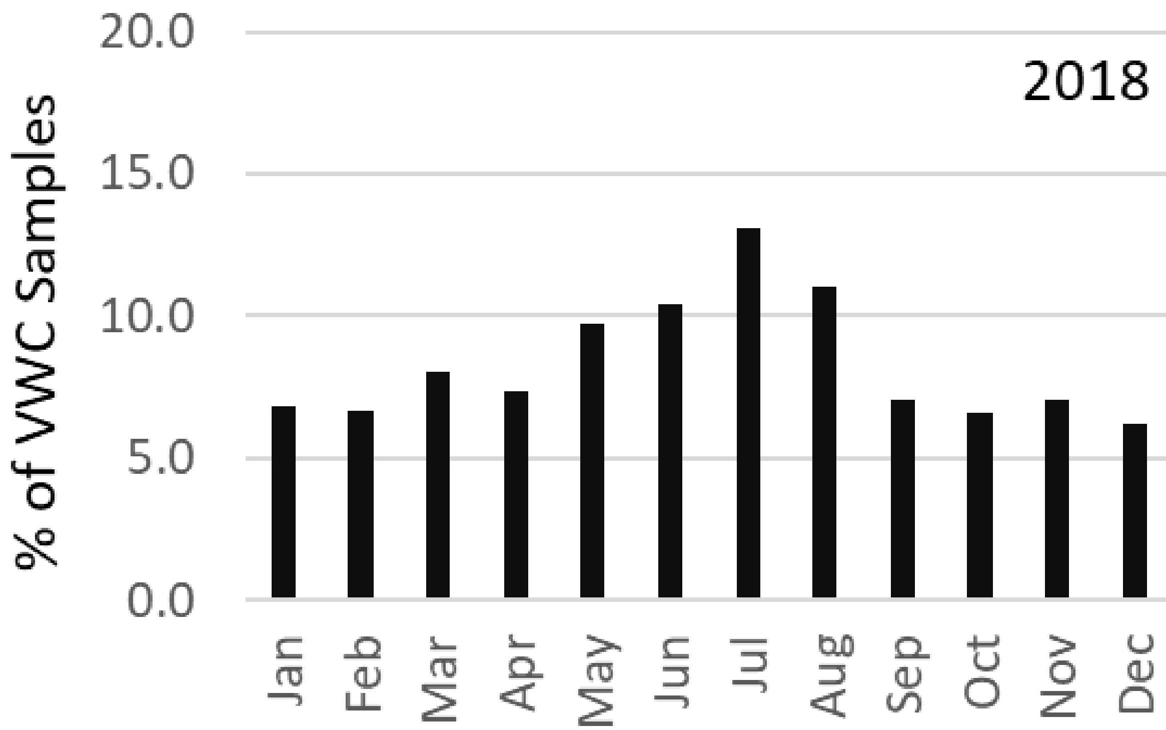


Figure 5e. Percent of total number of global soil volumetric water content (VWC) samples per month in 2018.

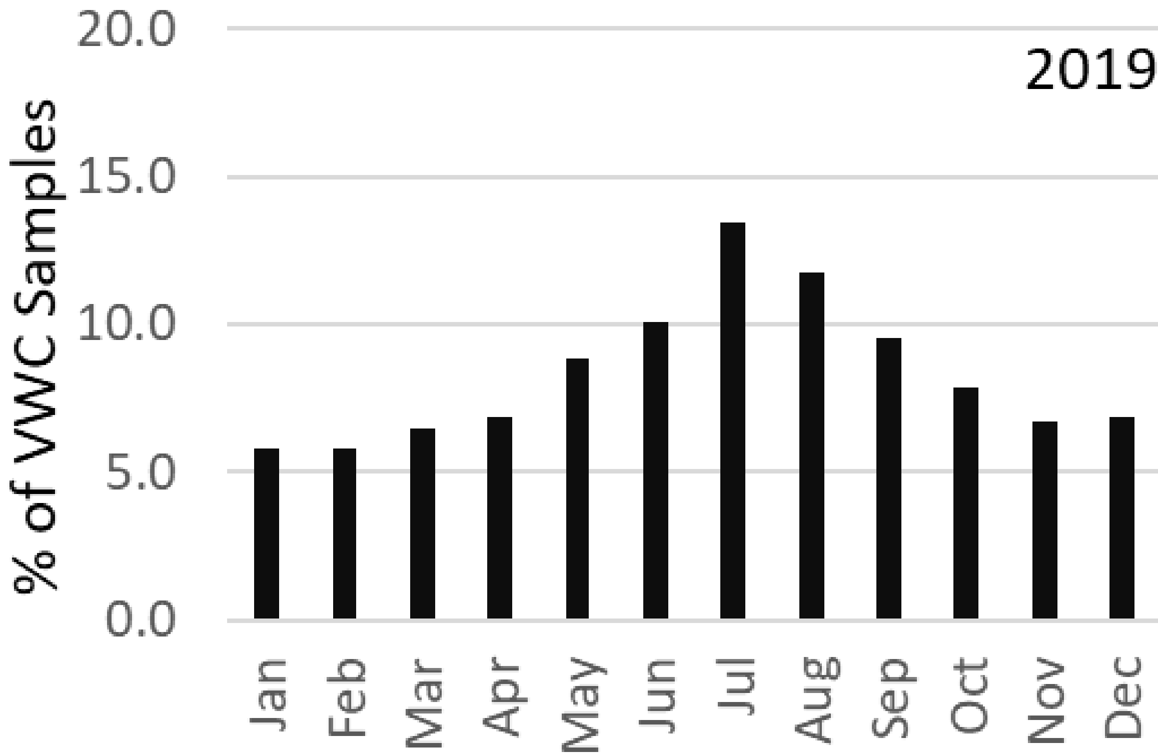


Figure 5f. Percent of total number of global soil volumetric water content (VWC) samples per month in 2019.

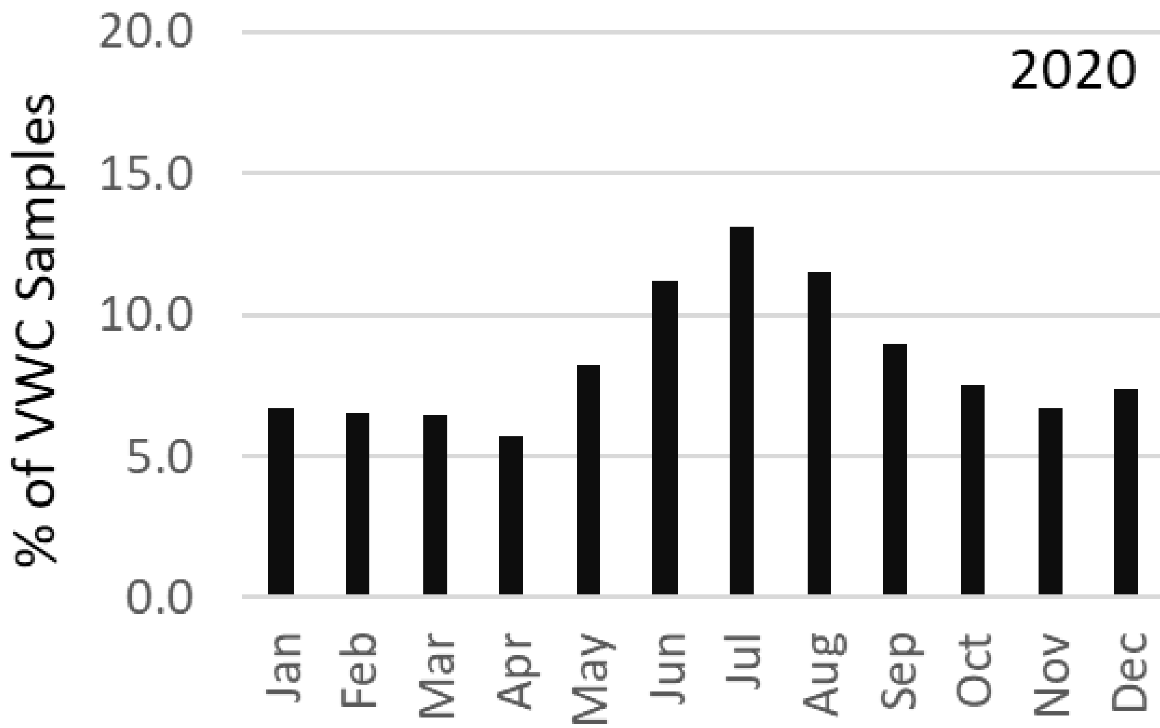


Figure 5g. Percent of total number of global soil volumetric water content (VWC) samples per month in 2020.

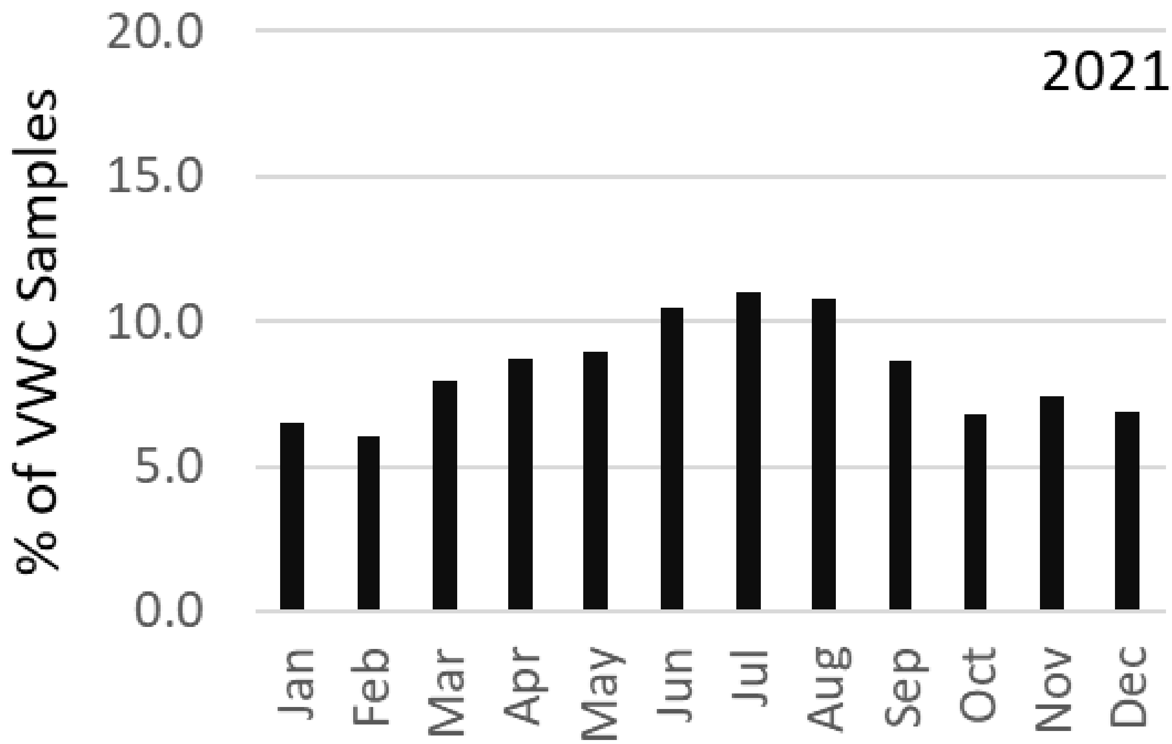


Figure 5h. Percent of total number of global soil volumetric water content (VWC) samples per month in 2021.

3.2 Global sampling locations

The geographic locations of soil moisture monitoring and sampling for 2014-2021 is illustrated in Figures 6a-6h. In 2014, the first geographical use of the POGO TurfPro and the data acquisition/collection technology platform was in the African continent and the Pacific Northwest of the USA. In 2015, sampling was recorded in North America, Central America, South America, Europe, Africa and the Middle East, Asia, and Australia. This geographic or global location trend continued through 2021, as soil VWC monitoring was observed in all continents except Antarctica. Overall, the majority of soil VWC monitoring was observed in North America (USA predominantly), the Caribbean, Europe, Southeast Asia, Australia, and also emerging sampling and soil moisture monitoring observed in South Africa and the Middle East.

Figures 6a-6h are located on the following pages.

Figure 6a. Visual representation of global number of soil volumetric water content samples in 2014.

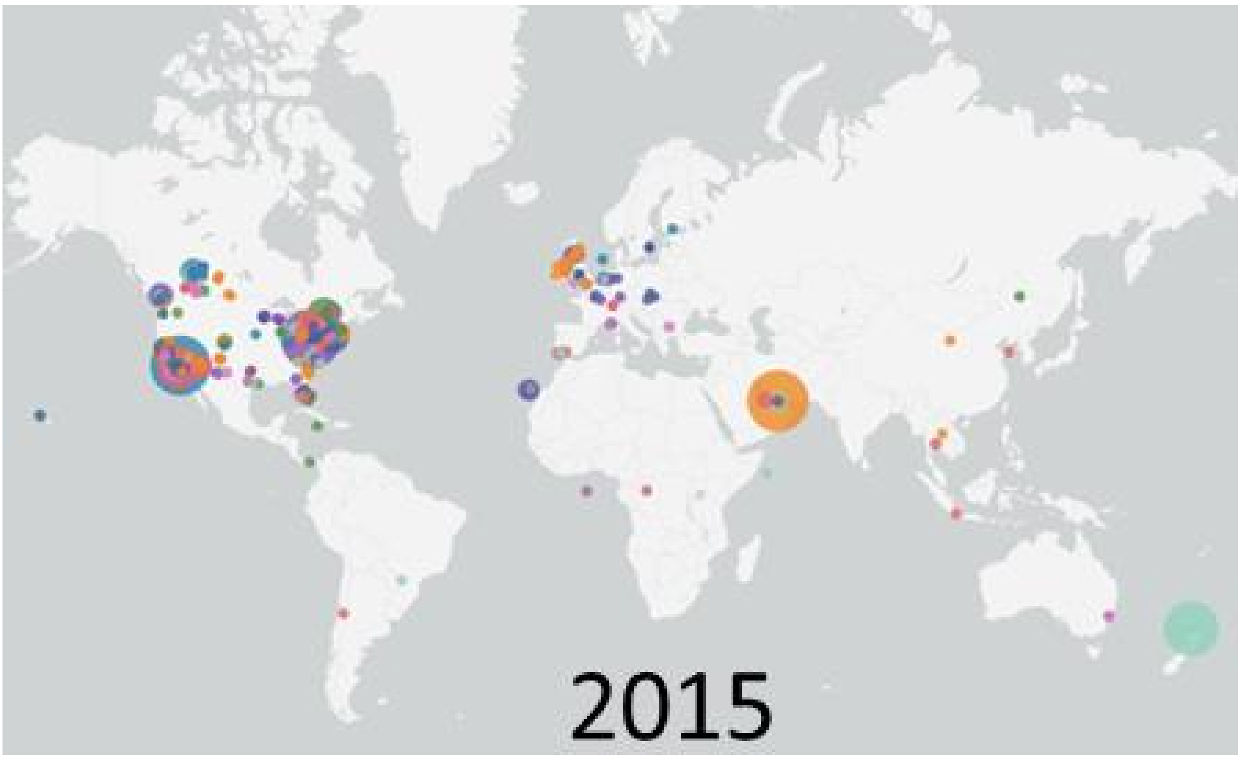


Figure 6b. Visual representation of global number of soil volumetric water content samples in 2015.

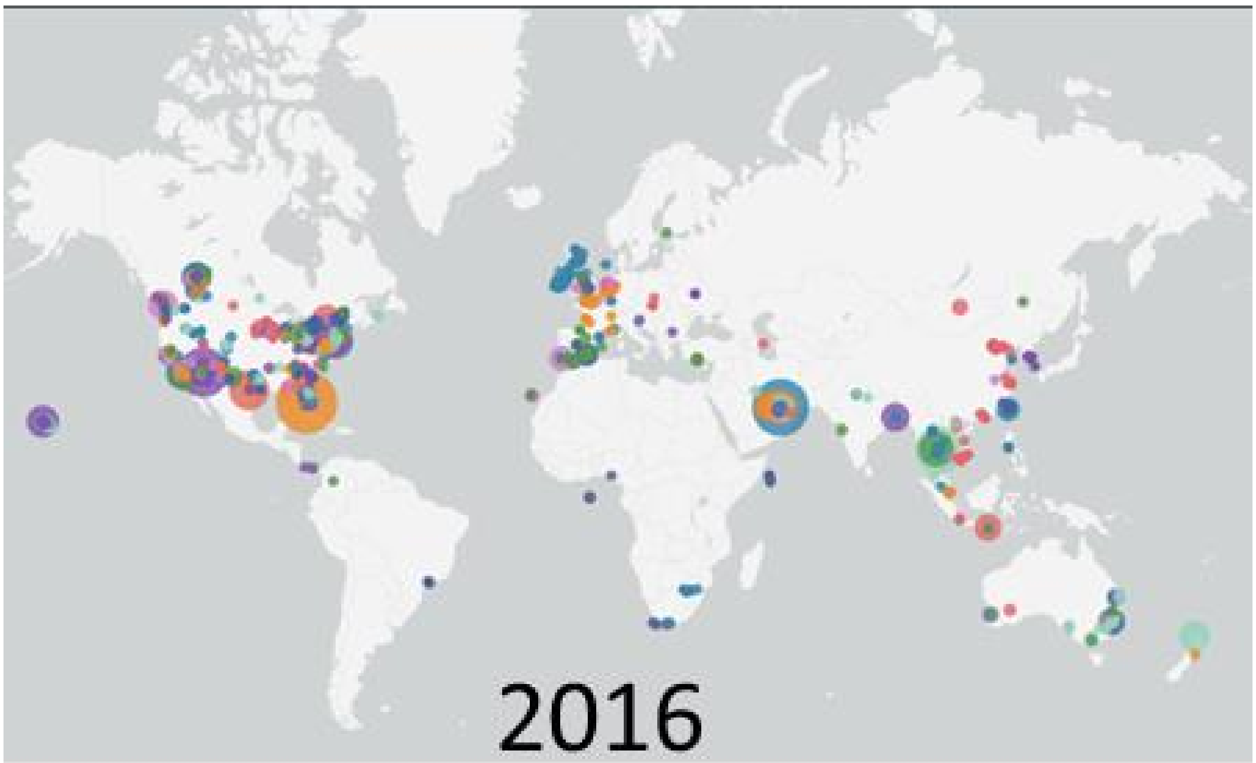


Figure 6c. Visual representation of global number of soil volumetric water content samples in 2016.

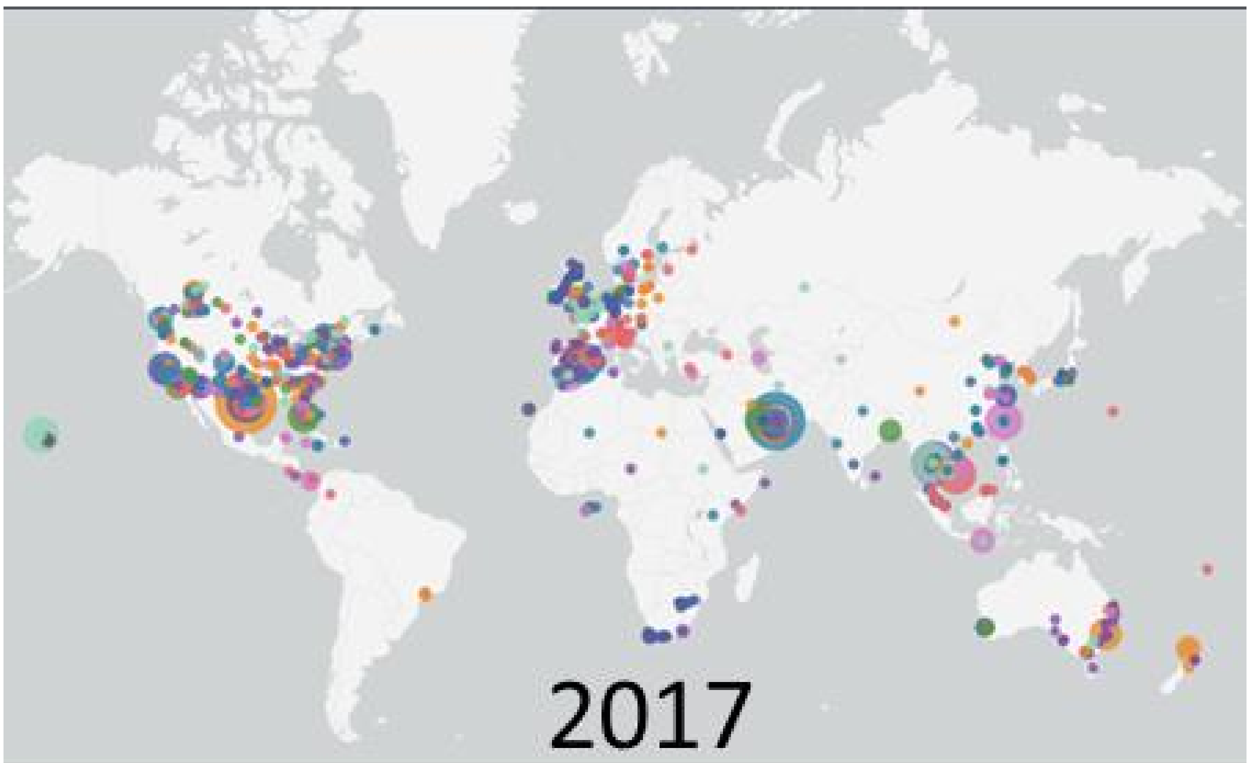


Figure 6d. Visual representation of global number of soil volumetric water content samples in 2017.

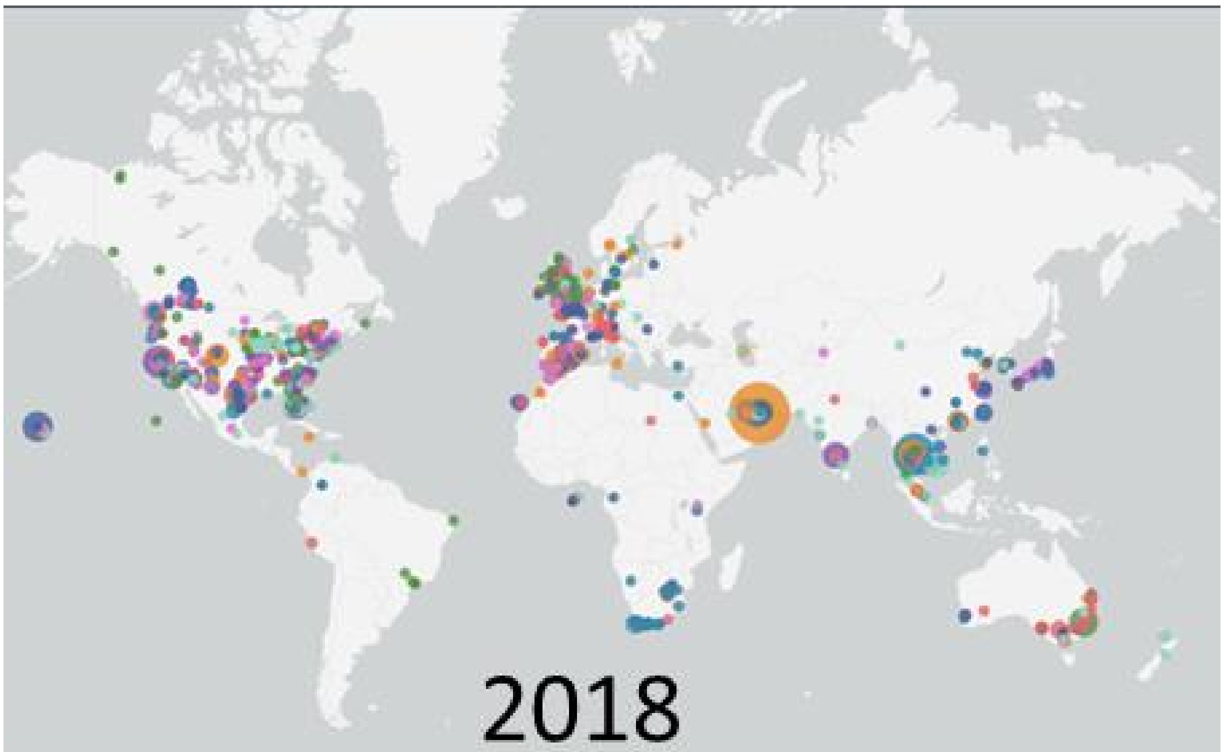


Figure 6e. Visual representation of global number of soil volumetric water content samples in 2018.

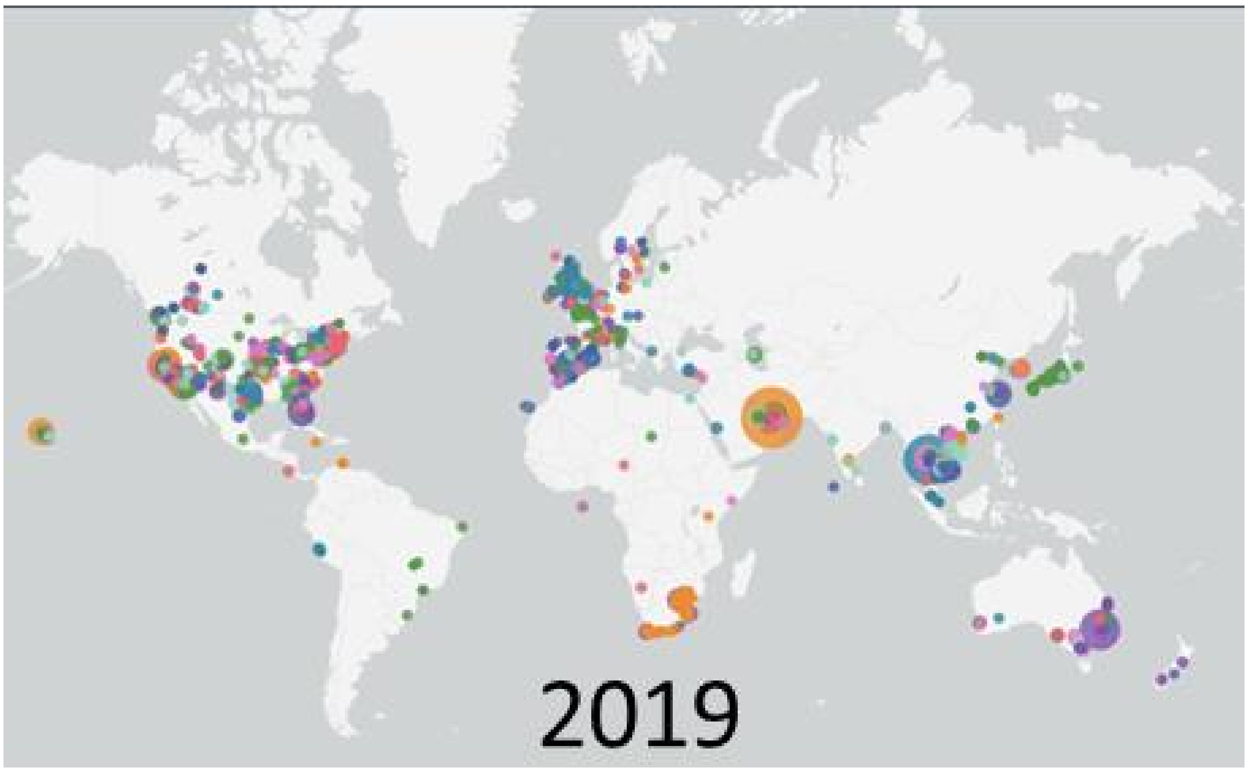


Figure 6f. Visual representation of global number of soil volumetric water content samples in 2019.

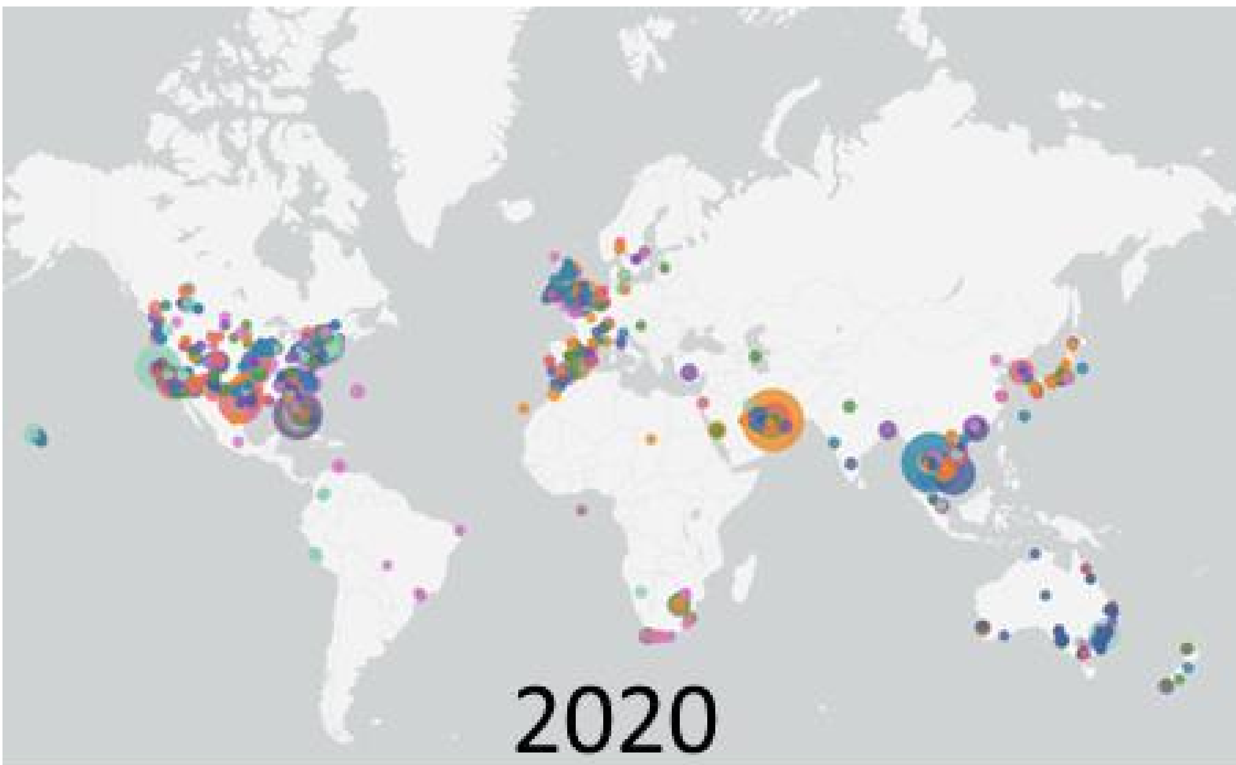


Figure 6g. Visual representation of global number of soil volumetric water content samples in 2020.

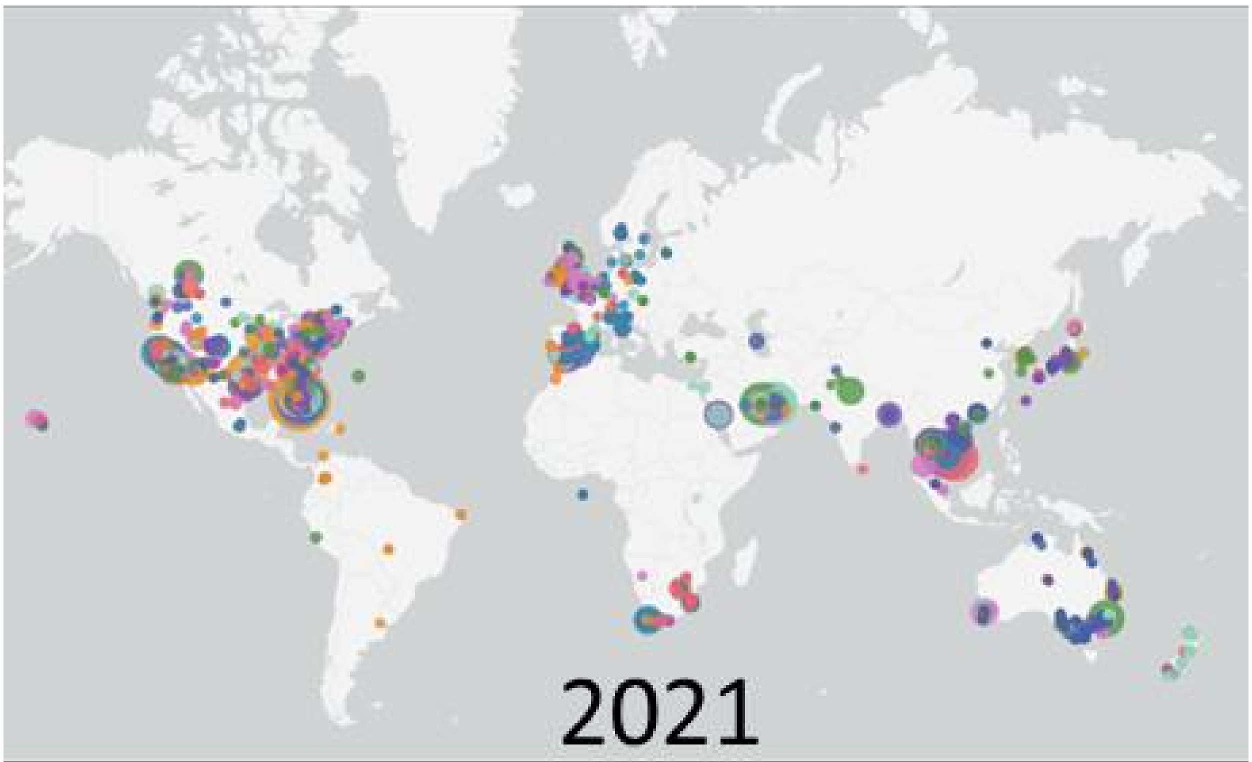


Figure 6h. Visual representation of global number of soil volumetric water content samples in 2021.

3.3 Further discussion

For the turfgrass manager, the actual practice of monitoring or sampling soil VWC alone should not be a deterrent to utilize this environmental monitoring technology. Since turfgrass managers are often under great scrutiny to manage their budget and time and resources most efficiently, a concern would be that turfgrass managers simply do not have the time to monitor and measure and sample VWC using portable hand-held sensor technology. The global use data from 2014-2021 indicated that turfgrass managers are committing the time and resources necessary to advance their soil VWC monitoring habits and programs, and therefore acquire the best environmental information to make the best turfgrass management decisions.

A particular noticeable increase in monitoring was observed during the COVID-19 pandemic from 2020 through 2021, and it is interesting to note how the use of this technology has not been favored by any one region in the world or by one type of turf manager. The increase in activity during the pandemic was interesting to observe in that end-users perhaps had more time to spend on managing their turfgrass properties due to a possible reduction in other job-related responsibilities, or even more likely, had the time to learn what the monitored information was telling them. This further indicates that if provided with useful and impactful information, turfgrass managers can utilize that information to ultimately optimize and improve their turfgrass management practices and programs (i.e., manage water more effectively, etc.).

4 Conclusion

It is this author's belief that if given useful and meaningful technology or tools that assist the turfgrass practitioner to make important ecological or environmentally-based decisions with greater confidence, they may venture in skeptically but as their confidence increases, they will embrace such tools or technology with higher confidence to eventually rely on that technology to help with their day-to-day turfgrass management responsibilities. Further, by studying trends of use and learning from end users around the globe, many ventured into a soil monitoring practice to essentially justify what they felt they already knew, particularly with regard to water management. However, as monitoring information was assessed visually, these same practitioners did in fact change the way they manage, altering practices they may have been used to for a significant period of time. As turfgrass practitioners become more educated and experienced about the information collected from those environmental variables they are measuring and monitoring, and they learn how that information can be utilized to make better or sound turfgrass management decisions, they are increasingly embracing the technology in an effort to further understand how those environmental variables impact their turfgrass management practices and programs.

If compared to the evolution of the medical world, that industry too went through a similar stage where technology allowed insight to conditions previously not measured or understood, only best-guessed from the education we had on hand at the time. The health industry has benefited greatly not only from advances in technology but in the understanding of human health overall and how systems interact with each other. Better decisions are made as a result. It is this author’s belief that we are at the threshold of crossing into territory where turfgrass managers have the ability to gain insight they otherwise will not have, by using monitoring technology properly and efficiently.

Future research should investigate the reasons as well as barriers for adopting soil moisture monitoring practices. Future research should also evaluate how soil moisture monitoring data, as well as other environmental monitoring data (i.e., soil salinity, soil temperature, heat indexes and more) is utilized in different countries for different intended use (golf course putting greens, golf course fairways, sports pitches, sod farms, lawns and landscapes, etc.). A likely evolution for understanding environmental impacts on turfgrass, both macro and micro, will include the combination of ambient conditions with turfgrass conditions, allowing better timing of not only irrigation but plant protectant products, cultural practices and nutritional management practices.

5 References

Amazon. 2022. Amazon Web Services. Retrieved from Amazon Web Services: https://aws.amazon.com/

Beard, J.B. 2001. Turf management for golf courses, 2nd ed. John Wiley and Sons, Inc., Hoboken, NJ.

Brosnan, J.T., Chandra, A., Gaussoin, R.E., Kowalewski, A., Leinauer, B., Rossi, F.S., Soldat, D.J., Stier, J.C., and Unruh, J.B. 2020. A justification for continued management of turfgrass during economic contraction. Agricultural and Environmental Letters 5(1):e20033.

Burns, T.T., Adams, J.R., and Berg, A. 2014. Laboratory calibration procedures of the Hydra Probe soil moisture sensor: Infiltration wet-up and dry-down. Vadose Zone Journal 13(12): https://*doi*.org*/10.2136/vzj2014.07.0081*

Campbell, J. 1990. Dielectric properties and influence of conductivity in soils at one to fifty megahertz. Soil Science Society of America Journal 54:332-341.

Campbell, J.E. 1988. Dielectric properties of moist soils at RF and microwave frequencies. Ph.D. Dissertation; Dartmouth College, Hanover, NH, USA. https://doi.org/10.1349/ddlp.1563

Carlson, M.G., Gaussoin, R.E., and Puntel, L.A. 2022. A review of precision management for golf course turfgrass. Crop, Forage and Turfgrass Management 8(2):e20183.

Carrow, R. N., Krum, J. M., Flitcroft, I., & Cline, V. (2010). Precision turfgrass management: Challenges and field applications for mapping turfgrass soil and stress. Precision Agriculture 11:115-134.

Danneberger, K. 2007. Routine data from the ABCs of IPM. Golfdom: https://archive.lib.msu.edu/tic/golfd/article/2007oct74.pdf

Fidanza, M. 2023. Achieving sustainable turfgrass management. Buleigh Dodds Science Publishing, Cambridge, UK.

Gelernter, W.D., Stowell, L.J., Johnson, M.E., Brown, C.D., and Beditz, J.F. 2015. Documenting trends in water use and conservation practices on U.S. golf courses. Crop, Forage and Turfgrass Managament 1:1-10.

Jones, S. 2021. USGA's Brian Whitlark on the growth of soil moisture meters in golf. Golfdom: https://www.golfdom.com/usgas-brian-whitlark-on-the-growth-of-soil-moisture-meters-in-golf/

Magro, C. 2020. How POGO's technology can help sports turf managers. Athletic Turf News: https://athleticturf.net/how-pogos-technology-can-help-sports-turf-managers/

Mead, R., Curnow, R.N., and Hasted, A.M. 2003. Statistical Methods in Agriculture and Experimental Biology. Chapman and Hall/CRC Press, Boca Raton, FL.

McCarty, L.B. 2011. Best golf course management practices, 3rd Ed. Prentice Hall, New York, NY, USA.

Moeller, A. 2012. Identify soil moisture status more accurately than ever before. USGA Green Section Record 50:1-5.

Schiavon, M. and Serena, M. 2023. Advances in irrigation and water management. In: Fidanza, M. (Ed.), Achieving sustainable turfgrass management; Burleigh Dodds Science Publishing, Cambridge, UK.

Shaddox, T.W., Unruh, B., Johnson, M.E., Brown, C.D., and Stacy, G. 2022. Water use and management practices of U.S. golf courses. Crop, Forage and Turfgrass Management 8(2):e20182.

Soldat, D.J. and Koch, P.L. 2023. Advances in soil management for successful establishment and maintenance of turfgrass. In: Fidanza, M. (Ed.), Achieving sustainable turfgrass management; Burleigh Dodds Science Publishing, Cambridge, UK.

Steinke, K., Ervin, E.H. 2013. Turfgrass ecology. In J. C. Stier, B. P. Horgan, and S. A. Bonos (Eds.), Turfgrass: Biology, use, and management. ASA, CSSA, and SSSA, Madison, WI.

Throssell, C.S., Lyman, G.T., Johnson, M.E., Stacey, G.A., and Brown, C.D. 2009. Golf course environmental profile measures water use, source, cost, quality, and management and conservation strategies. Applied Turfgrass Science 6:1-20.

Turgeon, A. 2005. Turfgrass Management, 7th ed. Pearson Eduction, Upper Saddle River, NJ.

Chapter 5

Considerations with turfgrass rootzone monitoring during a professional golf tournament.

Abstract

Among turfgrass management practitioners, there is a poorly understood and misperception about the relationship between soil or rootzone moisture and golf course putting green surface characteristics of firmness and green speed. Soil volumetric water content (VWC), surface firmness, and green speed as determined from golf ball roll distance are commonly measured and monitored during professional golf course tournaments. However, that detailed information typically is not made available to the public. This study evaluated the relationship between soil moisture, surface firmness, and green speed during the four consecutive days of professional golf tournaments. Although weak associations were observed among the three variables measured and monitored, data trends indicated the following: (1) lower soil moisture was associated with faster green speed, and green speed was slower as soil moisture increased. However, a slight increase in green speed was observed with the highest soil moisture indicating a non-linear relationship but rather an optimal moisture level for optimal ball speed; (2) lower soil moisture was also associated with firmer playing surfaces, and as soil moisture increased, surfaces were not as firm. However, more firmness also was observed with the highest soil moisture; (3) firmer surfaces typically were associated with faster green speed. However, the lowest firmness measurements also were associated with faster green speed. These results do not completely agree with the traditional or contemporary view within the turfgrass industry, particularly that an increase in soil moisture will contribute to slower green speed, and that an increase in firmness

will equate to faster green speed. This is likely due to the fact that turfgrass, unlike other species of plants, has a unique thatch layer between the soil and the surface. A properly wetted layer will result in the best acceptance of rolling, compaction and mowing while a condition that is too wet may compact excessively and/or cause a soft, weak surface while a condition that is too dry will allow the thatch to create more friction from the brittleness of the dry spongey layer. The measurement, data collection, and data analysis of these variables prompted the golf course superintendents and tournament agronomist teams to make changes to their maintenance practices for mowing, rolling, and irrigation to achieve what they determined as the optimum putting green playing conditions for the tournaments.

1 Introduction

For golf course superintendents and greenkeepers, managing turfgrass during golf tournament conditions is the culmination of months and often years of preparation to produce the best playing surfaces that meet or exceed the rigors and expectations of professional golfers (Fidanza, 2023; Radko and Bengeyfield, 1975; United States Golf Association, 2021). Agronomic and performance variables that influence the game of golf include soil volumetric water content (VWC; i.e., rootzone moisture), green speed (i.e., ball roll distance), and surface firmness (i.e., the firmness of the playing surface of a putting green) (Moeller, 2012; Waters, 2020; Zontek, 2010). These aforementioned variables and their related attributes to managing amenity and sport turfgrasses are often misunderstood, and their relationship to each other also is poorly understood or misinterpreted (Hartwiger, 2014). Oftentimes, turfgrass managers feel that drier turf surface conditions and/or drier (i.e., lower VWC) rootzones will result in faster green speed (i.e., faster ball roll across the putting surface) (Hartwiger, 2014). After witnessing many professional golf tournaments around the world and measuring the VWC of putting greens, it is interesting to observe that turfgrass has a unique thatch "cap" or "layer" at or near the soil surface (Beard, 2002), and this thatch becomes brittle as it dries which can potentially impact the actual playing surface thus contributing to slower golf ball roll due to friction and irregularity in smoothness (i.e., slower green speed).

Further, the surface firmness or the resistance of golf ball impact on the surface, as measured in either gravities of resistance against a force from a weight or by measuring the depression a weight makes into the surface as a fraction of an inch, would appear to be influenced by rootzone moisture as well (Hartwiger, 2014; Waters, 2020; Zontek, 2010). However, turfgrass managers perform several tasks (i.e., mowing, fertilization, irrigation, rolling, core cultivation, etc.) that combined with soil moisture can influence the overall turfgrass plant and soil system (Beard, 2002). Therefore, research is needed to measure, analyze, and interpret the relationship among and between rootzone moisture, green speed, and firmness.

Golf course tournament officials, consultants, and advisors are constantly looking to replicate very similar and precise playing conditions from tournament to tournament and from year to year so that they can create expectations for turfgrass performance or turfgrass quality characteristics that are reliable and repeatable for the golf professional (Radko and Bengyfield, 1975). It is generally surmised that by measuring the three key variables of soil moisture, firmness, and green speed, the turfgrass surface performance and quality conditions will become consistent and repeatable, particularly during professional golf tournaments (Shaffer, 2021). Further, in line with findings in these current studies, not only will consistency from tournament to tournament be improved, but from surface to surface at the same facility or event will as well, leading to better management of tournament events and every day turfgrass conditioning.

Agronomic decisions made during professional golf tournaments include irrigation (i.e., when to apply water and how much water to apply), rolling (i.e., whether or not to roll the putting green surfaces, and when during the tournament), and mowing (i.e., whether or not to mow in one, two, three, or more directions), or other additional agronomic procedures and techniques all designed to produce the finest playing surface conditions possible (Beard, 2002). Among all agronomic variables and properties, the rootzone moisture repeatedly is the primary topic of discussion among the golf course stakeholders and officials attempting to collaborate to produce the finest playing surface conditions during a typical four-day golf tournament or event (Moeller, 2012). These same officials realize that the focused alterations in practices at any one event will lead to more closely managed conditions in line with desires, but longer term use of such insight will reap even great rewards for each and every facility.

Therefore, the purpose of this study was to monitor rootzone VWC, green speed, and surface firmness for all 18 putting greens during a professional golf tournament, to evaluate the relationships or associations among and between those three parameters, and to gain further insight into how those three parameters influence agronomic decision-making towards sustainable turfgrass management practices that carry beyond tournament management and into day to day turfgrass management decisions.

2 Materials and Methods

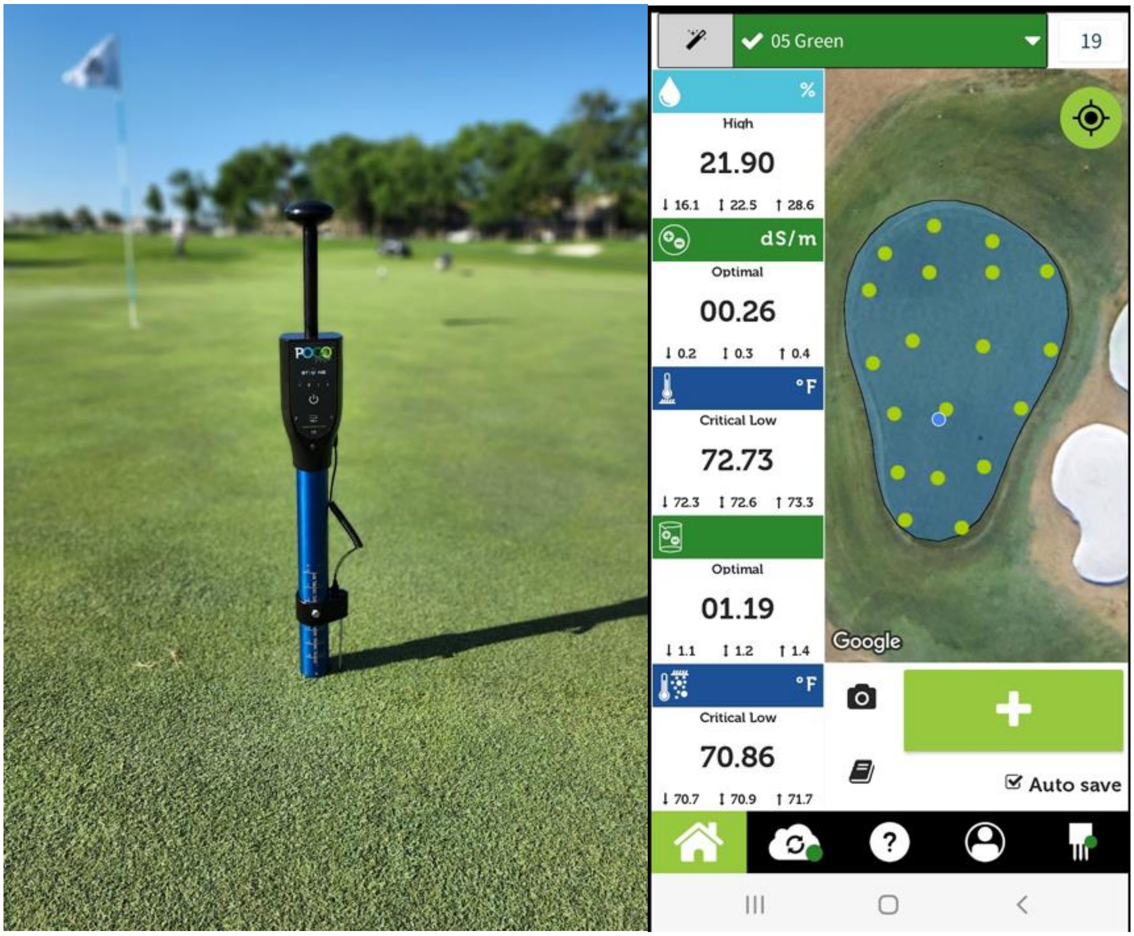
The study sites were: (1) undisclosed championship golf course, located in McKinney, Texas, USA, with putting greens consisting of a mixed-stand of several Creeping bentgrass (*Agrostis stoloniferous* L.) cultivars; and (2) undisclosed championship golf course, located in Fife, Scotland, UK, with putting greens consisting of a mixed-stand of creeping bentgrass (*Agrostis stoloniferous* L.; unknown cultivars) and *Festuca* sp. (unknown cultivars).

At the Texas site, all putting greens were mowed at 2.92 mm (0.115 inch bench setting) height-of-cut (HOC) with clippings removed. The rootzones were composed of sand and constructed according to USGA-specifications (United States Golf Association, 2022). Two-direction mowing per putting green occurred in the early morning (AM) and late afternoon/early evening (PM) hours during each of the tournament days except the last day where only morning mowing occurred. The AM operations occurred between 4:30 - 7:30 AM, and the late afternoon/early evening operations occurred between 5:30 - 9:00 PM. All putting greens were rolled immediately after both AM and PM mowing events throughout the tournament. The tournament was held over a period of four consecutive days during May of 2022. During tournament week, the weather was considered hot and dry with typical air temperatures in the early morning (i.e. 4:30 AM) at 13 C (56 F) and rising to 32 C (90 F) in the early afternoon.

At the Scotland site, all putting greens were typically mowed at 3.00 mm (0.118 inch bench setting) height-of-cut with clippings removed. The rootzones were composed of sand and amended with sand top-dressing that has historically been applied over time. One or two-direction mowing per putting green typically occurred in the early morning (AM) and late afternoon/early evening (PM) hours during each of the tournament days except the last day where only morning mowing occurred. The AM operations occurred between 4:00 - 7:00 AM, and the late afternoon/early evening operations occurred between 5:00 - 9:00 PM. All putting greens were typically rolled immediately after both AM and PM mowing events throughout the tournament. The tournament was held over a period of four consecutive days during June of 2022. During tournament week, the weather was considered hot and dry with typical air temperatures in the early morning (i.e. 4:30 AM) at 18 C (64 F) and rising to 23 C (74 F) in the early afternoon.

2.1 Rootzone volumetric water content

At both golf tournament sites, soil or rootzone VWC measurements were obtained with the POGO TurfPro system (Stevens Water Monitoring Systems; Portland, OR, USA) (Figure 1). The POGO TurfPro Pro+ multi-parameter insight tool is equipped with a HydraProbe II sensor that measures VWC at the 5.71 cm (2.25 inch) depth from four, 5.6 cm (2. 2 inch) metal rods (Seyfried et al., 2005). At the Texas site, for each putting green, VWC was measured and recorded twice daily during the AM and PM turf maintenance times. At each AM and PM times, approximately 15 to 22 random sampling sites per putting green were selected to measure and record VWC. The number of VWC measurements were dependent on the size of the putting green. The same VWC sampling procedure was utilized at the Scotland site, however, only AM monitoring was conducted.



A B

Figure 1. A: Example of the POGO TurfPro Pro+ unit (Stevens Water Monitoring Systems, Portland, OR, USA). B: Example of mobile phone image of a random sampling pattern indicating monitoring measurement locations of soil volumetric water content for this putting green.

2.2 Green speed

At both golf tournament sites, green speed (i.e., golf ball speed or golf ball roll distance) was measured in feet and inches, which is the worldwide standard for USGA's report of green speed, using the USGA Stimpmeter (United States Golf Association, 2021) (Figure 2). The USGA has developed a standard protocol and procedure with using this device which selects one consistent representative location or area on each putting green (United States Golf Association, 2021).

Green speed data as average speed (i.e. distance traveled by the golf ball) were logged into the POGO TurfPro system along with position of measurement location on each putting green.

A B

Figure 2. Example of measuring ball roll distance using the USGA Stimpmeter to determine ball speed or green speed. The Stimpmeter is employed by rolling three golf balls in each of two directions, and then calculating average distance in feet and inches which is referred to as 'green speed' by turfgrass practitioners and the professional golf industry. A: Example of a golf ball roll. B: Close-up of Creeping bentgrass putting green surface.

2.3 Firmness

At the Texas site, firmness was measured using the Precision Putting Green Firmness Compaction Meter (Precision USA; Pompano Beach, FL, USA) at various locations on each putting green to create an average firmness measurement for the entire green. With this device, a weighted steel ball is dropped from a predetermined and standardized height (limited by a fixed length chain), and next the penetration depth into the turf surface is measured with a precise gauge. Firmness data as measured in inches were logged into the POGO TurfPro system along with sampling location on each putting green.

A B

Figure 3. Example of measuring putting green surface firmness using the Precision Putting Green Firmness Compaction Meter (Precision USA; Pompano Beach, FL, USA). A: Dropping a weighted ball from an exact 1.8 m (6 feet) height to the surface. B: Measuring the depression formed in the turf surface.

At the Scotland site, firmness was measured using the 0.5 kg Clegg Impact Soil Tester (Lafayette Instrument; Lafayette, IN, USA) at various locations on each putting green to create an average firmness measurement for the entire green. Firmness data as measured in gravities were logged into the POGO TurfPro system along with sampling location on each putting green.

2.4 Data Analysis

All rootzone VWC, green speed (i.e., ball roll distance), and firmness data were assembled onto a spreadsheet for statistical analysis. The associations, relationships, and trends among all three measured parameters (i.e., VWC vs. green speed; VWC vs. firmness; green speed vs. firmness) were evaluated by linear regression (Mead et al., 2003). Rootzone VWC, green speed, and firmness parameters measured are interpreted in Figures 4, 5, and 6; respectively.

Figures 4, 5, and 6 are located on the next page.

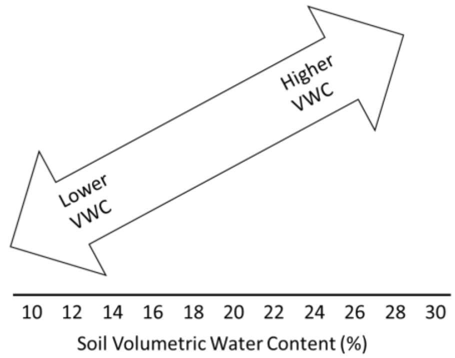


Figure 4. Turfgrass practitioner interpretation of soil or rootzone volumetric water content, as measured by the POGO TurfPro system (Stevens Water Monitoring Systems, Portland, OR, USA).

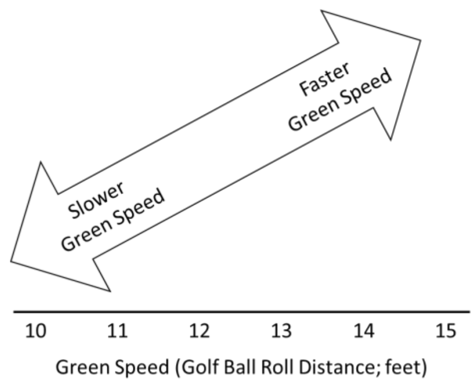


Figure 5. Turfgrass practitioner interpretation of green speed (golf ball roll distance), as measured by the Stimpmeter.

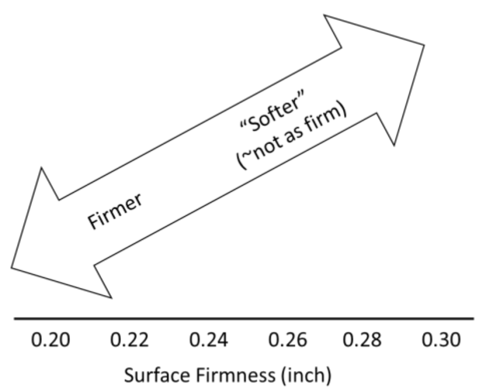


Figure 6. Turfgrass practitioner interpretation of putting green surface firmness, as measured by the Precision Putting Green Firmness Compaction Meter (Precision USA; Pompano Beach, FL, USA).

3 Results and Discussion

All measured and monitored environmental data were assembled into tables as shown in Tables 1, 2, 3, 4, 5, and 6. Statistical trend analysis to examine the relationships among soil moisture, green speed, and firmness are illustrated in Figures 7, 8, 9, 10, 11, and 12.

3.1 Green speed vs. Volumetric water content

At the Texas (USA) location, as soil moisture increased, there was a slight downward trend of ball speed. The downward trend was lessened in the PM measurements which was interesting as the overall moisture in the afternoon was significantly drier than the morning, indicating that the impact of moisture on ball speed was increased in higher moisture levels than lower ones. One consideration could be due to the morning hours having more of the turf's moisture residing on the surface due to humidity in the air and increased presence of dew, thus increasing friction with the ball and slowing its roll down. Regardless, increased moisture appears to be related to a slower ball speed on the same turf where drier conditions would otherwise exist. What is not known from this data set is where the other side of the equation exists. In other words, if the turf achieved much drier conditions, it cannot be said from this data that the ball speed would increase, only that as moisture increased, a slower ball speed was witnessed. The indications are that there is an optimal moisture for optimal ball speed, but it is not definitive that any linear relationship exists in either direction.

At the Scotland location, a similar slight downward trend appeared in the data as moisture increased and ball speed decreased. Interestingly, the overall moisture conditions at the Scotland site were approximately half of those found in Texas throughout the tournament (i.e. approximately 50% less volumetric moisture content was present throughout the tournament compared to the Texas site). This supports interpretation of this author that variances appear throughout the industry and each turf plot is unique compared to any other at a particular facility or elsewhere, further supporting benefits of monitoring for key variables routinely. Despite these variances, similar results can be achieved as one understands the unique turf and its response to inputs. While more research is needed to further clarify relationships of variables, this initial data shows no direct relationship or linear relationship between moisture and green speed, with all other factors consistent including mowing height and cut quality which can have a great impact on turfgrass performance (Turgeon, 2005). Of interest and prompting further research, the Scotland turf system is exceptionally older compared to the Texas site. Not only is the turf of different maturity but so is the rootzone. Perhaps, the most interesting insight from these compared events was what the data did not tell us rather than what it did.

3.2 Surface Firmness vs. Volumetric water content

At the Texas location, as soil moisture content increased, firmness also increased. Interestingly, in the PM when moisture content was significantly lower than the morning hours, as this moisture content increased, there is a significant trend toward increasing firmness. This is generally contradictive to regular thinking by turfgrass professionals who often talk about drier conditions being firmer. Also, with this more significant trend toward increased firmness when the average moisture starts lower and as that moisture rises, this indicates that there is an optimal moisture point where the optimal firmness occurs. This information is vitally important to turfgrass managers as, once they find this level, they will do what they can to maintain it and repeat it for consistent playing conditions over time. One consideration as to why firmness will increase with rising moisture conditions could be related to the rolling practice that was employed which would result in a more compacted surface from the weight of the roller on a wetter surface than a drier one, leading to overall firmer conditions. The maturity of the turf system may have an impact here as a more developed thatch region, under proper moisture, can be managed more effectively through consistent moisture conditioning. In other words, the conditions present would vary in a system that was rolled with water added as opposed to rolling with no water added.

At the Scotland site, as moisture increased, firmness appeared to decrease. Despite rolling after mowing events, this occurred. The overall moisture content of the rootzone was significantly drier than the Texas site. In perspective, about one fifth of pore space was filled with water in Scotland compared to more than two fifths in Texas. This could be a significant factor as to how the turf accepted water and influenced other conditions such as firmness. Both sites had water applied by hand rather than overhead sprinklers. This hand applied practice was similar at both sites where water was lightly applied throughout the surface. The percentage increase of moisture at Scotland, rising from approximately 9% to more than 10% is a significant increase of >10% overall. However, this same increase of ~1% moisture in a system that is at ~20% volumetric water content is less than 5% overall increase in moisture. These are different conditions leading to different effects, further adding to the need to monitor and use insightful information to make informed decisions that make the most sense for each turf plot.

3.3 Green Speed vs. Surface firmness

At the Texas location, there did not seem to be a significant trend relationship between ball speed and surface firmness. This too contradicts general thinking in the industry that a firmer surface relates to a faster ball roll. While significant variance existed in firmness measurements in both AM and PM data sets, the relationship with ball speed did not indicate a significant trend in either way other than a slight downward trend meaning a slight slowing down of ball speed as the surface got firmer. Remembering that turfgrass has a unique thatch layer near the top of the system and its surface leaves are what come directly in contact with the ball, underlying firmness may not impact ball roll as much as assumed, according to this data, but it may influence how the turfgrass stand performs with regard to an upright or not upright turf condition, thus impacting ball speed.

At the Scotland location, again, there did not seem to be a significant relationship between firmness and ball speed, contradicting traditional industry thinking. However, some things are important to point out. The target ball speed in Texas was ten feet nine inches (10’9”) to eleven feet three inches (11’3”) while the targeted ball speed in Scotland was ten feet zero inches (10’0”) to ten feet six inches (10’6”). A variance of nine inches is significant with regard to ball roll and tournament conditions. Specific actions are taken as data is recorded to alter the mowing and rolling patterns during tournaments, as noted earlier. Interestingly, the data in Scotland shows a tighter proximity to the targeted ball speed, indicating that efforts were likely made to micro-manipulate the conditions and drive ball speed as close to the target as possible. The variances in rolling and watering as well as single versus double versus triple or quadruple direction mowing were not considered in this study as focus was specifically given to volumetric water content, ball speed and firmness. Indications are suggesting that influences from these daily changes led to the various results at the surface, further supporting the value and insight learned from key variable monitoring employed at both events.

3.4 Further Discussion

The data indicates that there is a relationship between altered conditions, whether from moisture variances or other inputs not specifically recorded in this study, and the surface characteristics for tournament play. In other words, the actions taken by the tournament agronomists and course managers had influence on the performance of the putting surface for the tournament players. Exactly what decisions should be made and when starts long before the tournament took place as the course managers prepare the turf, soil and operation for presenting the best predictable conditions they can for the tournament when it arrives. Further research is needed to truly look at all factors impacting the final condition of the turf and the impacts that maintenance and operational practices as well as micro and macro environmental influences have on the conditions for play. This would hold true for all turf applications, especially golf and sports turf management as well as municipal or general lawn care which is highly influenced by the control of traffic and the inputs of water and fertilizers. Cut quality, height of cut, dew point, relative humidity, cloud cover, nutritional inputs and many more add to the dynamics of the turf system that impact its playability throughout the day, week and season. At the writing of this thesis, changes were implemented into the POGO TurfPro platform to allow actions to be recorded and analyzed easily so that users can learn quickly how the actions they take impact the conditions they witness. Further, the implementation of an advanced on site environmental monitoring station allows for customizable degree days and stress indicators to be set up specific to each property, combining measurements from the turf tools identified in this study with the ambient conditions above the ground. Research that capitalizes on this technology will surely advance our knowledge of the turfgrass system and conditioning to most understand the best practices we can employ.

4 Conclusion

While only two professional golf tournament events where three major factors (moisture content, green speed and surface firmness) were measured, interesting observations were made as indicated in the individual discussions. During this particular event, this information was used by the turfgrass management staff and tournament agronomists to decide on whether or not to mow in more than one direction, whether or not to roll or double roll and whether or not to add any water, typically by spot treating with a hose. The visual analysis of the data as indicated in Figure 13 using the POGO TurfPro monitoring platform was utilized to find the spot treated areas in need of water, if any existed. This visual insight color analysis was also used for ball speed and firmness using different views of the data in the system. The color indicators were decided prior to the event by the course managers and consulting tournament agronomists by setting critical high, high, low and critical low values for the putting greens. All greens on both properties were set to the same values, or warnings, throughout their respective courses. For moisture content, dark blue represented a volumetric water content above the critical high setting while red represented lower than critical low, tan represented a condition between optimal and critical low, light blue represented a condition between optimal and critical high and green represented a condition between the low and high values, or optimal targeted condition. Similar warning settings were made for firmness and ball speed with reverse coloring (i.e. red indicated critical high firmness and critical high, or too fast, ball speed.

By collecting and using this data on a regular basis, optimal levels of moisture can be determined as optimal levels of firmness and ball speed are identified and associated factors are realized which influence the combination of the three. Other factors such as mowing quality (how clean the cut is), mowing height, rigor of the turf plant from available nutrition and more can all impact these variables as well and should be noted in future analysis of these conditions. However, clearly, there seems to be an optimum level of moisture to present the optimum level of turf performance as it impacts tournament conditions.

It is this author's opinion, learning from these applications, that the visual insight of information assessed in the POGO TurfPro platform represents an interesting change in management practices related to making informed decisions. For two very different operations in very different parts of the world, new decisions were made solely based on the visual insight indicated by the POGO platform, leading to a decision that altered from traditional methods where such insight was not ascertained. While this study remained focused on these three variables, it is important to note that all other factors including weather variables, product applications, cultural practices, clipping yield and more are variables that can be inputted and assessed visually and similarly to the three variables discussed here. For instance, understanding clipping yield with nutritional inputs can greatly impact the way one fertilizes or manages nutrition, and this can be monitored for further influence on the end product, or ball speed for instance, using very similar visual analysis that we found in the POGO TurfPro platform. Like medicine experienced three decades ago and through the present, the insightful information we are learning from this POGO TurfPro platform is leading to changes in practices around the globe.

Table 1. Soil volumetric water content (VWC) of each putting green during early morning and late afternoon monitoring during each day of the professional golf tournament; McKinney, TX, USA.

Putting Green	a.m.^{z} Day 1	a.m.^{z} Day 2	a.m.^{z} Day 3	a.m.^{z} Day 4	p.m.^{z} Day 1	p.m.^{z} Day 2	p.m.^{z} Day 3	p.m.^{z} Day 4
	%^{y}				%^{y}			
1	20.7	23.4	19.9	18.9	15.9	14.7	17.2	15.8
2	20.0	20.8	18.1	17.9	15.6	14.3	16.3	15.7
3	21.2	23.5	18.2	17.2	15.7	13.9	16.6	14.7
4	22.8	18.5	19.1	17.9	16.1	14.6	14.5	14.9
5	22.4	18.6	19.4	17.0	12.8	14.9	15.0	13.9
6	21.3	22.4	19.4	17.8	14.8	14.3	16.9	16.4
7	21.1	20.0	18.5	16.3	15.1	14.3	14.4	14.7
8	20.6	22.6	18.8	18.7	13.8	14.5	13.4	13.6
9	21.9	23.7	19.9	15.5	13.8	14.5	14.5	14.1
10	22.7	18.3	16.4	17.3	13.2	14.3	11.8	11.4
11	22.0	18.8	16.2	15.8	14.7	14.1	12.8	13.5
12	23.4	18.8	17.4	16.0	14.5	15.2	12.1	11.7
13	21.7	18.5	15.9	17.9	13.7	15.1	12.7	11.5
14	20.4	19.0	16.1	16.3	14.1	14.1	13.2	12.3
15	21.9	18.2	16.0	17.3	13.3	16.0	11.5	12.6
16	20.8	19.4	15.7	17.6	12.4	13.3	12.0	12.4
17	22.3	18.2	15.2	18.5	10.4	14.4	11.2	11.7
18	22.8	18.3	18.5	17.5	14.2	15.7	11.4	12.4

^{z}Data represents mean of nine soil VWC sampling points per green, in the early morning (0600 a.m.) and late afternoon (1900 p.m.) during each day of the golf tournament; Day 1 = 11 May, Day 2 = 12 May, Day 3 = 13 May, Day 4 = 14 May 2022.
^{y}VWC measured at 5.71 cm root zone depth with a POGO TurfPro (Stevens Water Monitoring Systems, Portland, OR, USA); percent (%) volumetric water content.

Table 2. Green speed (i.e., golf ball roll) of each putting green during early morning and late afternoon monitoring during each day of the professional golf tournament; McKinney, TX, USA.

Putting Green	a.m.[z] Day 1	Day 2	Day 3	Day 4	p.m.[z] Day 1	Day 2	Day 3	Day 4
	ft[y]				ft[y]			
1	12.1	11.2	11.7	12.0	10.5	11.0	12.0	10.8
2	12.2	12.1	12.3	12.1	10.8	10.8	11.0	11.2
3	12.3	12.4	12.6	12.9	11.3	10.9	11.0	11.8
4	12.5	12.8	12.7	11.5	10.8	11.0	11.4	10.9
5	12.3	13.3	13.3	12.7	11.4	10.9	10.8	12.0
6	12.4	12.3	12.3	12.7	11.5	10.8	11.2	11.8
7	12.4	12.1	13.0	12.5	10.8	11.3	10.8	11.4
8	11.9	12.0	13.1	12.1	10.7	11.2	10.8	11.7
9	11.8	12.2	12.7	12.4	10.7	10.9	11.0	11.6
10	11.7	12.4	12.2	12.2	10.5	11.3	11.3	10.9
11	12.2	12.7	12.6	12.4	10.5	11.1	10.7	11.3
12	12.2	12.2	12.5	12.6	10.4	10.3	10.4	11.8
13	10.8	12.1	12.7	13.5	11.2	11.3	11.2	11.7
14	12.0	12.3	12.1	12.5	10.7	10.2	10.9	11.2
15	12.2	11.9	12.7	12.7	10.8	10.5	11.1	11.2
16	12.4	12.2	12.9	12.9	11.0	11.0	11.0	12.1
17	11.9	12.4	12.8	12.3	10.8	11.4	11.3	12.3
18	11.4	12.6	12.2	11.5	10.5	10.9	10.8	11.1

[z]Data represents mean of three ball roll distance measurements per green, in the early morning (0600 a.m.) and late afternoon (1900 p.m.) during each day of the golf tournament; Day 1 = 11 May, Day 2 = 12 May, Day 3 = 13 May, Day 4 = 14 May 2022.
[y]Ball roll distance measured with a StimpMeter (United States Golf Association, Far Hills, NJ, USA); 1 ft = 0.305 m.

Table 3. Surface firmness of each putting green during early morning and late afternoon monitoring during each day of the professional golf tournament; McKinney, TX, USA.

Putting Green	a.m.[z] inch[y]				p.m.[z] inch[y]			
	Day 1	Day 2	Day 3	Day 4	Day 1	Day 2	Day 3	Day 4
1	0.272	0.259	0.271	0.274	0.245	0.247	0.268	0.263
2	0.258	0.243	0.248	0.243	0.249	0.243	0.241	0.262
3	0.260	0.252	0.248	0.258	0.252	0.242	0.268	0.246
4	0.267	0.277	0.282	0.247	0.261	0.261	0.274	0.264
5	0.248	0.25	0.257	0.247	0.243	0.239	0.257	0.247
6	0.265	0.254	0.264	0.247	0.254	0.242	0.254	0.247
7	0.231	0.242	0.251	0.237	0.257	0.255	0.240	0.258
8	0.244	0.240	0.251	0.235	0.239	0.227	0.243	0.232
9	0.246	0.249	0.246	0.249	0.231	0.245	0.232	0.227
10	0.246	0.244	0.224	0.231	0.221	0.246	0.262	0.262
11	0.269	0.246	0.239	0.258	0.266	0.26	0.213	0.231
12	0.262	0.248	0.241	0.233	0.245	0.252	0.222	0.226
13	0.247	0.241	0.243	0.245	0.217	0.241	0.228	0.238
14	0.261	0.233	0.256	0.251	0.261	0.271	0.227	0.223
15	0.253	0.235	0.242	0.238	0.240	0.241	0.207	0.235
16	0.242	0.255	0.251	0.229	0.244	0.246	0.232	0.228
17	0.247	0.242	0.249	0.231	0.205	0.251	0.202	0.214
18	0.256	0.257	0.256	0.252	0.255	0.264	0.221	0.215

[z]Data represents mean of three surface firmness measurements per green, in the early morning (0600 a.m.) and late afternoon (1900 p.m.) during each day of the golf tournament; Day 1 = 11 May, Day 2 = 12 May, Day 3 = 13 May, Day 4 = 14 May 2022.
[y]Surface firmness measured with a Putting Green Digital Firmness Meter (Precision USA, Pompano Beach, FL, USA); 1 inch = 25.4 mm.

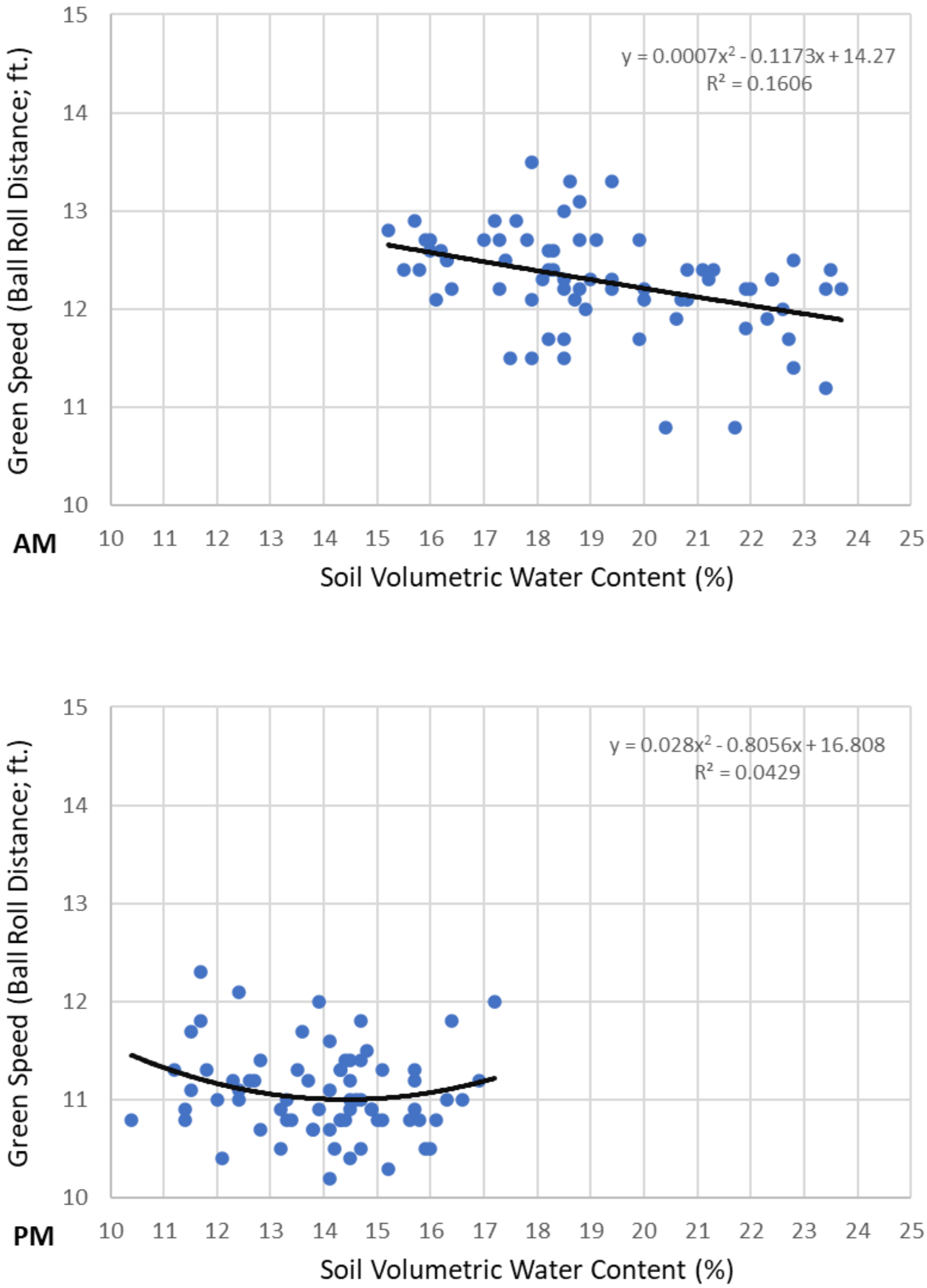
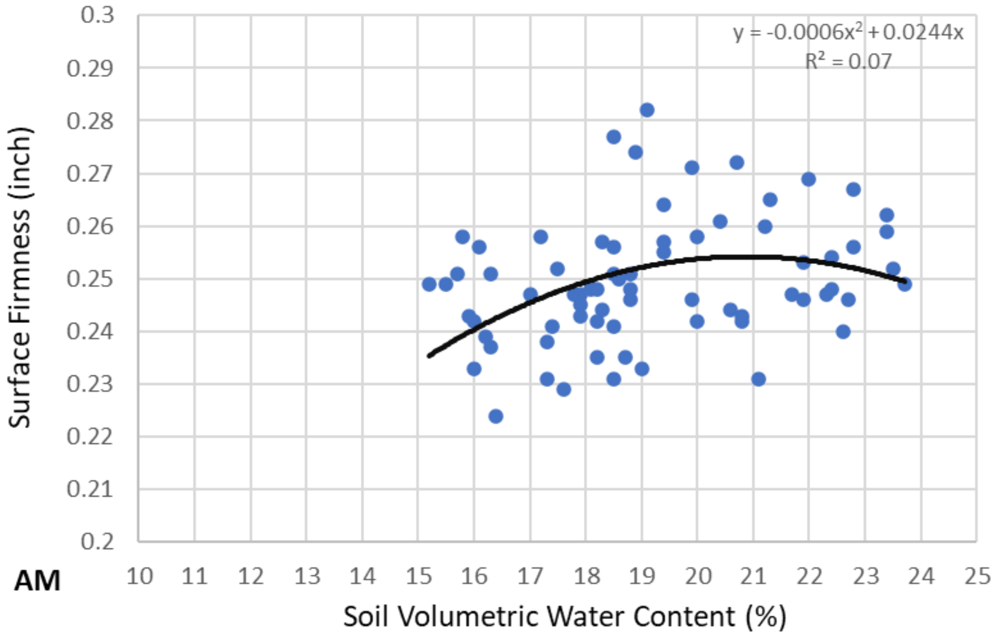


Figure 7. Green speed (i.e., golf ball roll distance) as influenced by soil volumetric water content (VWC) for early morning sampling time (AM) and late afternoon sampling time (PM). Data represents mean of ball roll and VWC for all 18 putting greens combined over four sampling days (11-14 May 2022); Texas, USA; 1 ft = 0.305 m.



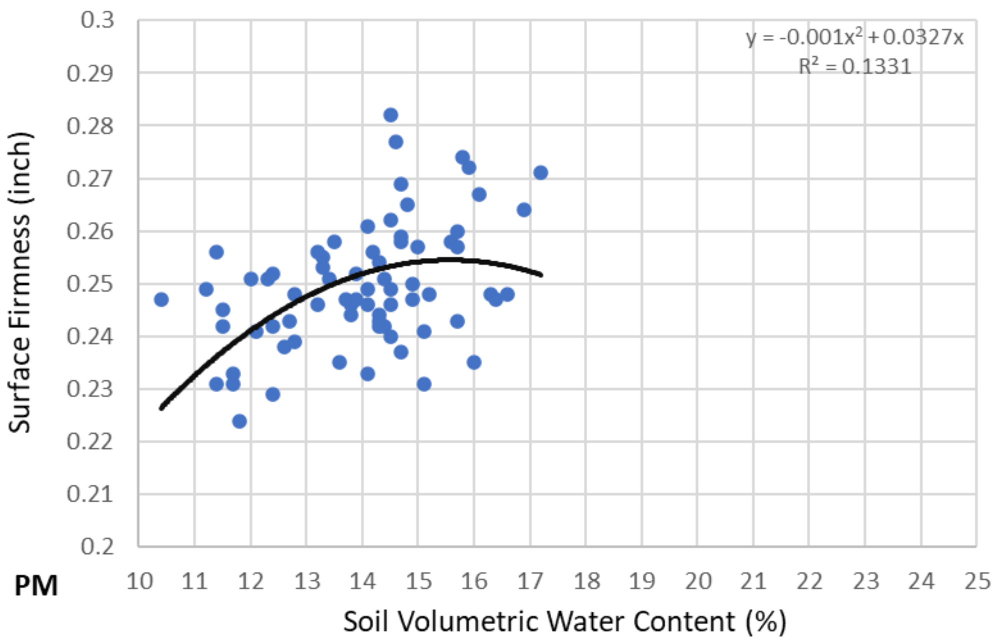


Figure 8. Surface firmness as influenced by soil volumetric water content (VWC) for early morning sampling time (AM) and late afternoon sampling time (PM). Data represents mean of surface firmness and VWC for all 18 putting greens combined over four sampling days (11-14 May 2022); Texas, USA; 1 inch = 25.4 mm.

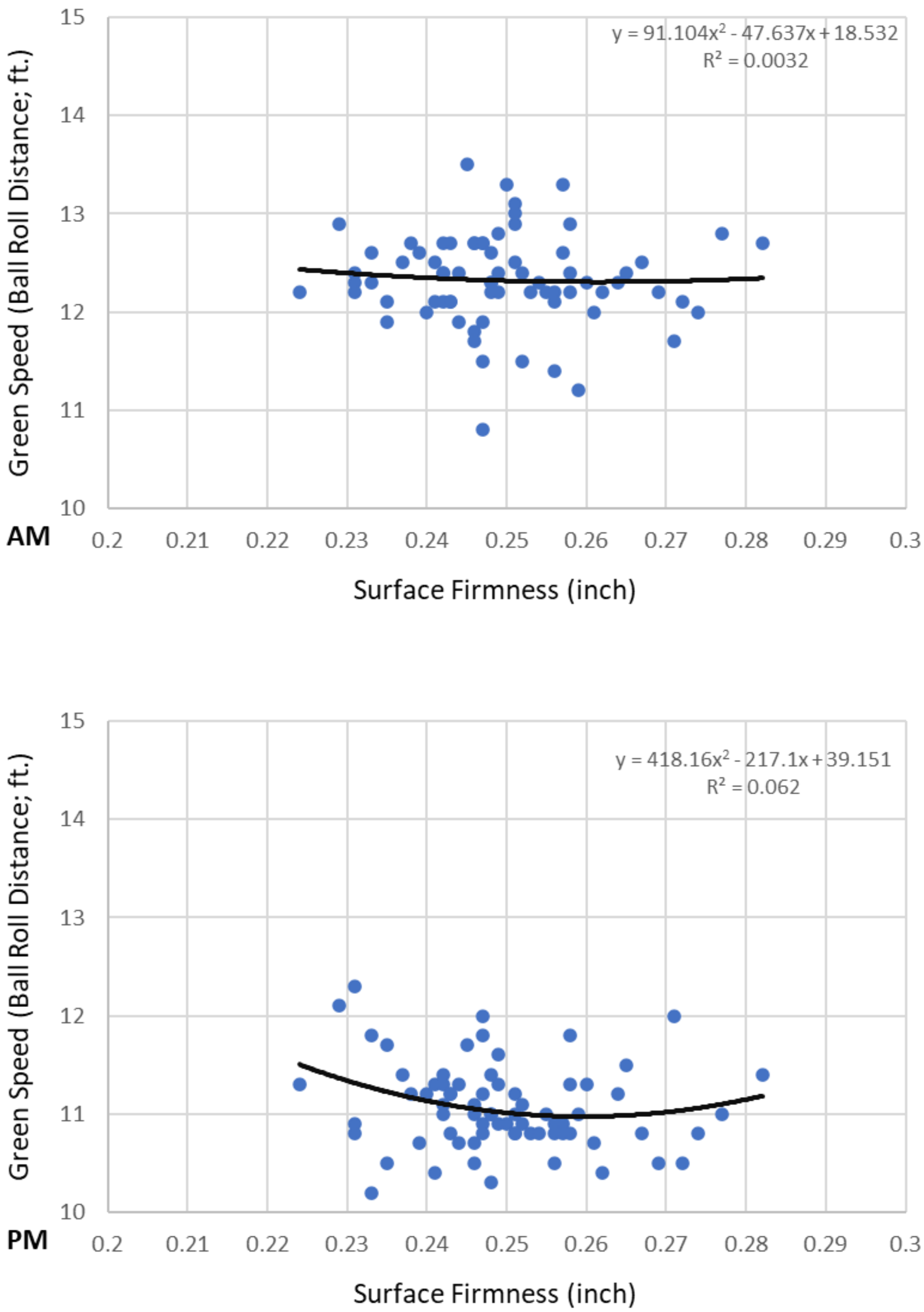


Figure 9. Green speed (i.e., golf ball roll distance) as influenced by surface firmness for early morning sampling time (AM) and late afternoon sampling time (PM). Data represents mean of ball roll and surface firmness for all 18 putting greens combined over four sampling days (11-14 May 2022); Texas, USA; 1 ft = 0.305 m; 1 inch = 25.4 mm.

Table 4. Soil volumetric water content (VWC) of each putting green during early morning monitoring during each day of the professional golf tournament; Fife, Scotland.

Putting Green	a.m.[z] Day 1	Day 2	Day 3	Day 4
	% [y]			
1	9.3	7.5	9.1	9.5
2	7.4	5.6	9.6	7.8
3	7.6	5.7	9.3	7.5
4	7.4	5.7	10.0	7.5
5	7.3	5.2	9.8	6.9
6	6.2	4.3	9.7	6.8
7	7.8	6.2	10.5	7.5
8	7.0	5.5	10.7	7.1
9	7.2	5.0	11.3	5.8
10	7.0	5.5	10.7	7.1
11	7.8	6.2	10.5	7.5
12	6.2	4.3	9.7	6.8
13	7.3	5.2	9.8	6.9
14	7.4	5.7	10.0	7.5
15	7.6	5.7	9.3	7.5
16	7.4	5.6	9.6	7.8
17	9.0	6.8	8.7	8.1
18	8.0	6.7	7.8	8.7

[z]Data represents mean of nine soil VWC sampling points per green, in the early morning (0600 a.m.) during each day of the golf tournament; Day 1 = 14 July, Day 2 = 15 July, Day 3 = 16 July, Day 4 = 17 July 2022.

[y]VWC measured at 5.71 cm root zone depth with a POGO TurfPro (Stevens Water Monitoring Systems, Portland, OR, USA); percent (%) volumetric water content.

Table 5. Green speed (i.e., golf ball roll) of each putting green during early morning monitoring during each day of the professional golf tournament; Fife, Scotland.

Putting Green	a.m.^{z} Day 1	Day 2	Day 3	Day 4
	ft^{y}			
1	10.2	10.3	10.3	10.3
2	10.1	10.1	10.3	10.4
3	10.0	10.3	10.3	10.6
4	10.3	10.0	10.6	10.4
5	9.8	10.0	10.1	10.6
6	10.3	10.1	10.3	10.5
7	10.0	10.2	10.0	10.1
8	10.3	10.1	10.0	10.5
9	9.9	10.1	10.5	10.8
10	10.1	10.1	10.1	10.4
11	9.9	9.8	10.1	10.0
12	10.3	10.3	10.0	10.6
13	9.9	10.3	10.1	10.5
14	10.1	10.1	10.3	10.5
15	10.0	10.3	10.5	10.5
16	9.9	10.1	10.0	10.4
17	10.2	10.0	10.1	10.8
18	10.1	10.1	10.4	10.5

^{z}Data represents mean of nine soil VWC sampling points per green, in the early morning (0600 a.m.) during each day of the golf tournament; Day 1 = 14 July, Day 2 = 15 July, Day 3 = 16 July, Day 4 = 17 July 2022.

^{y}Ball roll distance measured with a StimpMeter (United States Golf Association, Far Hills, NJ, USA); 1 ft = 0.305 m.

Table 6. Surface firmness of each putting green during early morning monitoring during each day of the professional golf tournament; Fife, Scotland.

Putting Green	a.m.[z] Day 1	Day 2	Day 3	Day 4
	gravities[y]			
1	151	156	158	152
2	151	158	159	151
3	149	158	160	156
4	147	157	157	153
5	146	156	155	151
6	155	164	162	158
7	144	154	152	150
8	141	154	150	148
9	140	154	147	147
10	141	154	150	148
11	144	154	152	150
12	155	164	162	158
13	146	156	155	151
14	147	157	157	153
15	149	158	160	156
16	151	158	159	151
17	162	162	167	158
18	143	161	157	150

[z]Data represents mean of nine soil VWC sampling points per green, in the early morning (0600 a.m.) during each day of the golf tournament; Day 1 = 14 July, Day 2 = 15 July, Day 3 = 16 July, Day 4 = 17 July 2022.
[y]Surface firmness measured with Klegg 0.5 kg Meter (Precision USA, Pompano Beach, FL, USA).

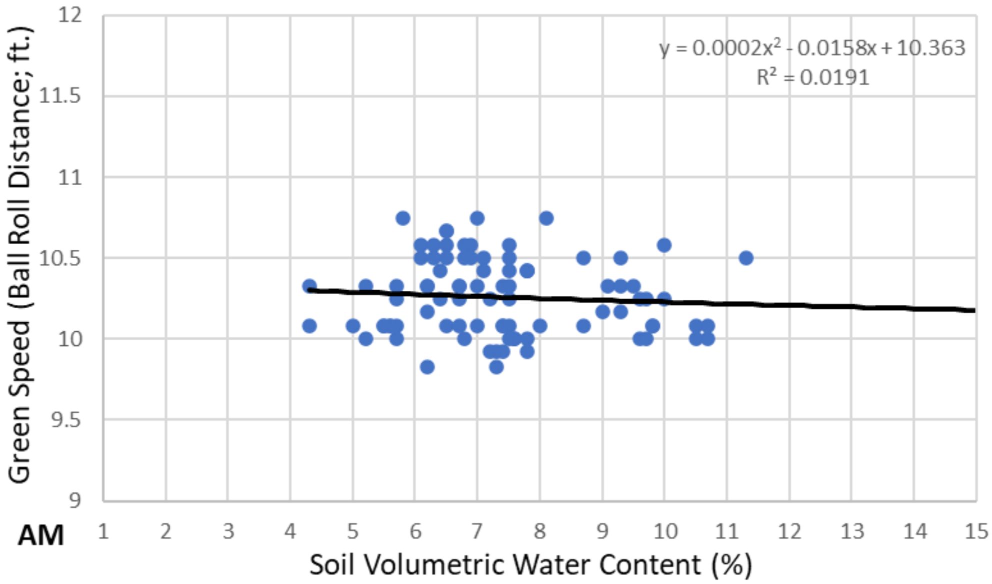


Figure 10. Green speed (i.e., golf ball roll distance) as influenced by soil volumetric water content (VWC) for early morning sampling time (AM). Data represents mean of ball roll and VWC for all 18 putting greens combined over four sampling days (11-14 May 2022); Fife, Scotland; 1 ft = 0.305 m.

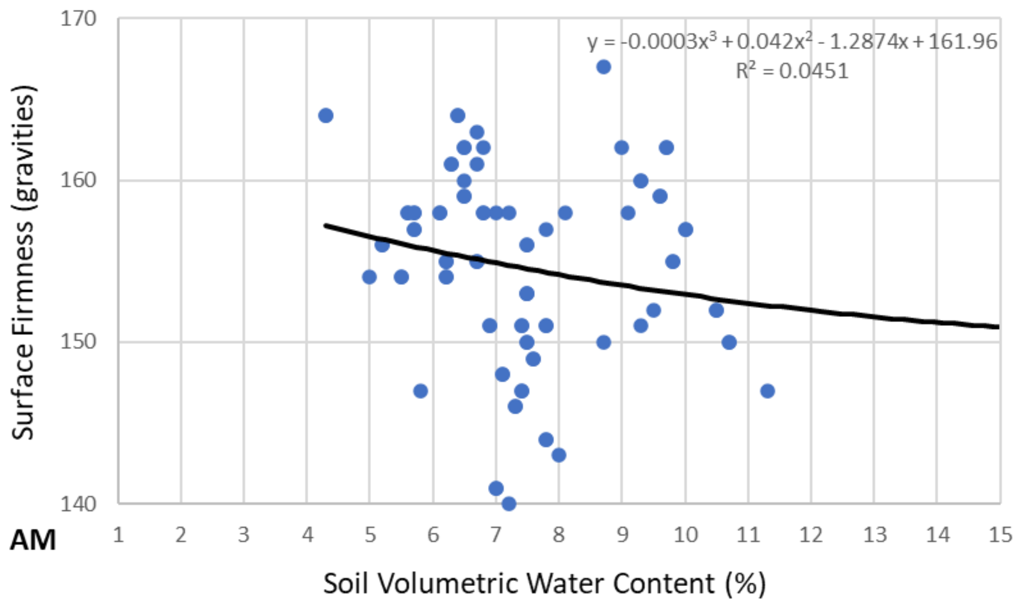


Figure 11. Surface firmness as influenced by soil volumetric water content (VWC) for early morning sampling time (AM). Data represents mean of surface firmness and VWC for all 18 putting greens combined over four sampling days (11-14 May 2022); Fife, Scotland.

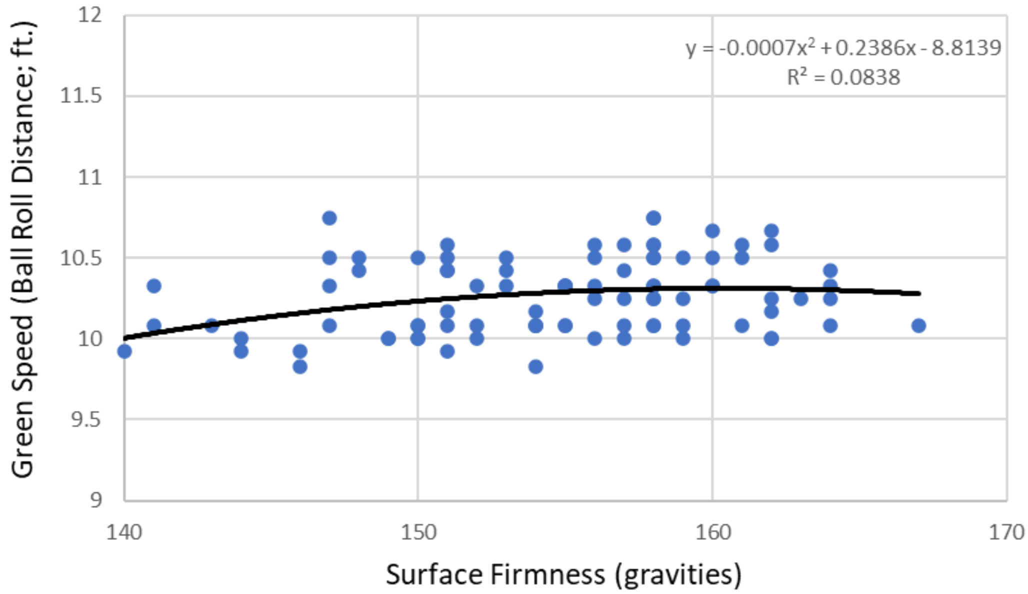


Figure 12. Green speed (i.e., golf ball roll distance) as influenced by surface firmness for early morning sampling time (AM). Data represents mean of ball roll and surface firmness for all 18 putting greens combined over four sampling days (11-14 May 2022); Texas, USA; 1 ft = 0.305 m.

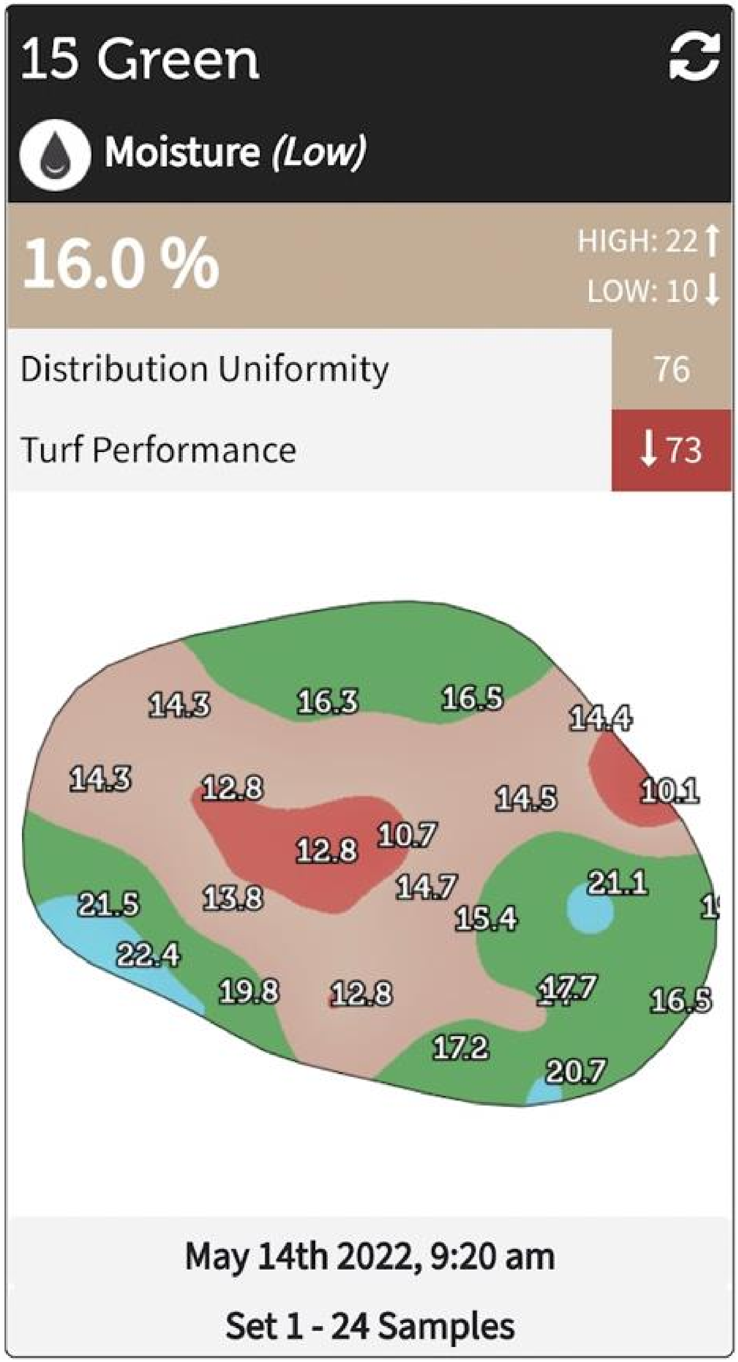


Figure 13. Visual Insight Analysis by the POGO TurfPro monitoring platform (Stevens Water Monitoring Systems, Portland, OR, USA). This image illustrates soil moisture variability across the putting green, and that information is utilized for targeted spot-applications of irrigation water to produce optimum or uniform soil moisture conditions across the entire putting green (Carminati, 2016).

5 References

Amazon. (2022). *Amazon Web Services*. Retrieved from Amazon Web Services: https://aws.amazon.com/

Balogh, J. W. (1992). *Golf Course Management & Construction.* Chelsea MI, USA: Lewis Publishers.

Beard, J. B. (2002). *Turf Management for Golf Courses.* Hoboken, New Jersey: John Wiley & Sons, Inc.

Brady, N. W. (2004). *Elements of the Nature and Properties of Soils.* Upper Saddle River, NJ, USA: Pearson Prentice Hall.

Burns T., A. J. (n.d.). Laboratory calibration of the Hydra Probe soil moisture sensor: comparison of infiltration wet-up vs. dry-down. *Vadose Zone Journal, 13*(12), 1-10.

Campbell, J. (1990). Dielectric Properties and Influence of Conductivity in Soils at One to Fifty Megahertz. *Soil Science Society of America Journal, 54*, 332-341.

Campbell, J. (2018, June 12). Interview with Dr. Jeff Campbell on HydraProbe and sensor technology performance. (C. Magro, Interviewer)

Carminati, A. Z. (2016). Engineering Rhizosphere Hydraulics: Pathways to Improve Plant

Adaptation to Drought. *Vadose Zone Journal, DOI: 10.2136/vzj2016.09.0090* (https://www.researchgate.net/publication/311486187).

Fidanza, M. (2023). *Achieving Sustainable Turfgrass Management*. Cambrige, UK: Burleigh Dodds Science Publishing.

Fry, J. H. (2004). *Applied Turfgrass Science and Physiology.* Hoboken, N.J, USA: John Wiley & Sons, Inc.

Gelernter, W. S. (2015). Documenting trends in water use and conservation practices on. U.S. golf courses. *Crop, Forage and Turfgrass Management, 1*, 1-10.

Grabow, G. G. (2013). Water application efficiency and adequacy of ET-based and soil moisture-based irrigation controllers for turfgrass irrigation. *Journal of Irrigation and Drainage, 139*(2), https://doi.org/10.1061/(ASCE)IR.1943-4774.0000528.

Haley, M. A. (2012). Validation of landscape irrigation reduction with soil moisture sensor irrigation controllers. *Journal of Irrigation and Drainage, 138*(2), https://doi.org/10.1061/ASCE)IR.1943-4774.0000391.

Harivandi, A. B. (2012). Golf's use of water: Solutions for a more sustainable game. *USGA Turfgrass and Environmental Research Online, 11*(12), 1-70.

Hartwiger, C. (2014). The big three of putting green setup: firmness, slope, and speed. *USGA Green Section Record* 52(4).

Havlin, J. B. (1999). *Soil Fertility and Fertilizers.* Upper Saddle River, New Jersey, USA: Prentice Hall.

International Soil Moisture Network. (2022). *ISMN*. Retrieved from International Soil Moisture Network: https://ismngeo.tuwien.ac.at/en/

Karcher, D. R. (2019). What the tech? Moisture meters for greater efficiency, healthier turf. *Golf Course. Management*, http://www.gcmonline.com/tags/moisture-meters-golf.

Kowalewski, A. M. (2014, December). Relationship between distribution uniformity and soil moisture content. *Golf Course Management, issuu.com/golfcoursemanagement/docs/dec-2014-gcm/105*, pp. 84-87.

Lawrence, P. R. (2020). Guiding soil sampling strategies using classical and spatial statistics: A review. *Agronomy Journal, 112*(4), https://doi.org/10.1001/agj2.20048.

Mead, R. C. (2003). Statistical Methods in Agriculture and Experimental Biology.

Moeller, A. (2012). Identify soil moisture status more accurately than ever before! *USGA Green*

Section Record, 59(9), 1-5.

Pathan, S. B. (2007). Evaluation of a soil moisture sensor to reduce water and nutrient leaching in turfgrass (Cynodon dactylon cv. Wintergreen). *Australian Journal of Experimental Agriculture, 47*, 215-222.

POGO. (2022). *POGO TurfPro*. Retrieved from POGO TurfPro: www.pogoturfpro.com

Radko, A. and Bengyfield, W.H. 1975. The agronomics of course preparation for major championships. USGA Green Section Record 13(4):1-5.

Roberson, T. B. (2021). Improving soil moisture assessment of turfgrass systems utilizing field radiometry. *Agronomy, 11*(1060), https://doi.org/10.3390/agronomy11101960.

Seyfried, M. G., Grant, L. E., Du, E. and Humes, K. (2005). Dielectric Loss and Calibration of the Hydra Probe Soil Water Sensor. *Vadose Zone Journal, 4*, 1070-1079.

Shaffer, M. (2021, December 8). Retired, Director of Golf Course Operations, Merion Golf Club, Ardmore PA. (C. Magro, Interviewer)

Soilsensor.com. (2022). *Soilsensor.com*. Retrieved from https://soilsensor.com

Stevens Water Monitoring Systems. (2022). *Stevens Water Monitoring Systems*. Retrieved from https://stevenswater.com

Throssell, C. L. (2009). Golf course environmental profile measures water use, source, cost, quality, management and conservation strategies. *Applied Turfgrass Science, 6*, 1-16.

Turgeon, A. (2005). *Turfgrass Management, 7th ed.* Upper Saddle River, NJ, USA: Pearson Education.

United States Golf Association. (2021). Preparing greens for a USGA championship. USGA Green Section Record 59(10).

United States Golf Association. (2022). *USGA Putting Green Construction Resources.* Retrieved from Recommendations for a Method of. Putting Green Construction: https://www.usga.org/course-care/specialty-articles/usga-putting-green-construction.html

Waters, G. (2020). The truth about green speeds. USGA Green Section Record 58(12).

Zontek, Z. (2010). Understanding and appreciating firmness. USGA Green Section Record 48(22).

Chapter 6

General conclusions.

Turfgrass science and management in recent years has been positively influenced by the use of sensor technology designed to help monitor, measure, and assess environmental conditions that affect plant and soil health, and surface playability and performance. Soil moisture, and the ability to rapidly and conveniently determine the volumetric soil water content using a portable hand-held sensor, is of particular importance to turfgrass practitioners for developing and maintaining sustainable turfgrass management practices. However, an understanding of how best to use or optimize sensor technology is needed.

In an analysis of various sampling densities and foci within a 372 m^2 (equivalent to 4000 ft^2) area of close-cut creeping bentgrass (*Agrostis stolinifera* L.) maintained on a sand-based rootzone, and measuring percent volumetric soil water content using a portable hand-held soil moisture meter, it was determined from the standard error of the mean that a minimum or optimum of 3 to 4 sampling points per 93 m^2 (equivalent to 3 to 4 sampling points per 1000 ft^2) was necessary to assess the variability and reliability of monitoring soil moisture for intensively managed turfgrass ecosystems. In other words, to make an informed decision about the whole of a turf surface, one must take a representative sampling of that turf zone. Therefore, to gain an understanding and insight into the environmental soil conditions of a turfgrass site (i.e., golf course putting green or fairway, sports pitch, lawn and landscape), representative sampling should be utilized frequently and consistently over time. At this time, it is important to note that in all of the studies and data collection referenced throughout this thesis, an average of two to three minutes was needed per putting green to collect the data in the POGO TurfPro platform for immediate analysis. At the Texas site, when two individuals were deployed for data collection, data was collected in under ninety seconds per green. From experience of the author, it appears that representative sampling of a sport pitch such as a football pitch requires approximately ten to fifteen minutes.

Portable hand-held soil sensors and devices are mostly utilized to measure soil moisture (percent volumetric water content) and soil salinity (electrical conductivity). A collection of soil cores from 30 sand-based golf course putting greens were collected from nine countries in three continents. The soil samples were partitioned into 3 cm layers or segments from 0 to 18 cm depth, and a second set of soil samples were partitioned into 6 cm segments also from 0 to 18 cm depth. All soil samples were subjected to laboratory measurements of the soil moisture saturated index test, electrical conductivity of saturated soil-paste extract solution, and electrical conductivity of soil pore water solution. Those measured parameters confirmed that those turfgrass soils were not uniform, but highly variable within that 0 to 18 profile. However, the ideal or optimum depth or layer for monitoring and measuring soil moisture and soil salinity would be at the 0 to 6 cm depth. Of equal interest is that moisture and salts leading to EC activity in the rootzone were not static given the insights into the layers. It is likely that moisture, for instance, rises and falls due to the pull upward of evaporation and transpiration processes while gravitation and capillary movements can move water down or in other directions. Similarly, as the data suggests, salts, or ionic substances of cations or anions, follow a similar pattern in the overall profile as water. This 0 to 6 cm depth is clearly dominant for moisture and

EC as the turfgrass system sees it. With experience examining the macro climates of properties that are utilizing monitoring practices, there seems to be a hold in the turfgrass system against losses downward (drainage) and losses upward (Evapotranspiration, or ET). This further indicates the significance of the upper 6 cm region of the turfgrass system. More research is needed to examine this phenomenon that has influence on turfgrass performance and irrigation practices.

Monitoring the soil moisture and soil salinity at this depth would provide turfgrass practitioners with useful information to support their decisions about irrigation inputs and other cultural turfgrass management practices. An understanding of where in the rootzone that soil water and salinity has the most influential impact with turfgrass function, performance, and quality would help the turfgrass practitioner with developing a sustainable turfgrass management program.

A recently developed and manufactured soil moisture sensor that utilizes coaxial impedance dielectric permittivity technology has gained acceptance globally in the golf course and sports pitch industries. This technology has been commercialized as the HydroProbe™ sensor and is available as a portable hand-held device marketed as the POGO TurfPro system (Stevens Water Monitoring Systems; Portland, OR, USA). The device that has the HydroProbe™ affixed to it is called the POGO Pro+, and this device requires no routine or daily calibration by the end-user. An assessment of POGO TurfPro global customer utilization was conducted from end-user data during 2014-2021. End-users included golf course superintendents, greenkeepers, course care managers, and sports pitch managers from every continent except Antarctica. The total number of global soil volumetric water content samples were only 135 in 2014, but this increased to

>10,000,000 in 2021. From 2014 to 2017, there was an exponential increase in soil sampling from 135 to nearly 4,000,000, and reaching >10,000,000 in 2021, thus representing a 29.25% annual average increase during 2017-2021. In 2014, the majority of soil sampling occurred during July and August, and in 2015, soil sampling occurred during April through December. From 2016-2021, soil sampling occurred consistently from January through December, with the majority or > 50% of sampling observed during May through September. This survey of end-user use characteristics confirmed that portable hand-held sensor technology has become an accepted and heavily relied upon tool for supporting sustainable turfgrass management practices and programs.

In a study of golf course putting greens, soil moisture content, green speed (i.e., golf ball roll distance), and surface firmness were measured and evaluated over a four-day period during professional golf tournaments in two countries and in two continents. Although the three variables measured exhibited weak associations, the four-day data trends were consistent and indicated soil moisture influenced firmness and green speed. Overall, the lower soil moisture was related to an increase of green speed and an increase in firmness, however, green speed was not noticeably influenced by firmness alone. The relationship between soil moisture and the putting green surface performance factors of green speed and firmness warrants further study to determine other possible abiotic or biotic factors that may be involved and influenced by soil moisture. However, at both events, micro decisions were made locally, based on the measured conditions, to alter practices to influence conditions for play, further influencing the conditions themselves.

These studies indicate that effective, targeted, and consistent environmental monitoring with appropriate portable hand-held sensor technology can be employed by turfgrass practitioners to accurately measure turfgrass soil or rootzones conditions, and support sustainable turfgrass management practices and programs.

As individuals learn more of what to do with the proper information assessed in monitoring, the shift from a desire to a dependency seems to be evolving. Similarly, to how a standard soil coring probe was something different for managing turfgrass six decades ago as laboratory soil sampling became more popular, it is nearly impossible to find any turfgrass operation anywhere in the world without one of these sampling probes for laboratory soil sampling. Those simply have become a standard need for managing turfgrass systems effectively, and they lead to a change in management practices depending on the results and analysis of the laboratory data. The trend identified here for dramatic increases in proper sampling actions point to this technology becoming as much a necessity to making informed decisions as ever. It is very possible, given the insight identified throughout the discussions here, that proper monitoring will lead to decisions made that otherwise would not be made. As the insight gained from proper monitoring associates turf conditions with ambient conditions and day to day practices and influences, like doctors see while evaluating the whole of one's health, turfgrass practitioners will have insight they otherwise never had and this will surely lead to changes in decisions, including how we utilize and manipulate water in the system among many other things.

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I feel this thesis has been a career in-the-making as I have practiced turfgrass management as much as I have studied it. By having the opportunity to expand that knowledge into agricultural as well as municipal applications, I am continuously reminded that I am a student of this great industry and I hope that never changes. Working with turfgrass practitioners around the globe has truly been one of the greatest learning experiences of my life, and I continue forward every day learning as much as I can from them and hopefully offering them some insight that will help them in their own careers.

As I engaged in my studies at this highest level, I would very much like to acknowledge the help and support of my advisors, Prof. Stefano Macolino and Prof. Mike Fidanza for their guidance and with teaching me the ways of science and how to marry my love for practical turfgrass management with my desire for scientific analysis and improvement of practices. I am often reminded to show me the data. As a group, it is wonderful to see the insight my little piece of the equation gives these seasoned veterans of our profession. Their approachable and insightful characteristics allow me to expand further than I imagined. These two gentlemen are truly mentors and role models in my life that I will surely depend upon as life goes forward.

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to student once again all while remaining very much in touch with the industry and the individuals working in it throughout the world. I was always reminded that one of my best traits, according to Dr Watschke was that no matter what, I remain a student and that will keep me learning forever. I will never forget this lesson and the character both gentlemen instilled in me. Thank you!

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I'll finish with a lesson my father taught me when I wanted to learn how to play baseball. It was a Saturday morning, and I came running through the kitchen with a ball, a bat and glove. My father was reading the newspaper at the table. I was eight years old. He asked, "Where are you going?" I said I'm going to try out for the baseball team. He asked me if I know what it takes to play baseball. I said "Yeah, a ball, a bat and a glove." He smiled and said good luck.

I went to the practice, enthusiastic for sure. But shortly into the practice, the coach put me at second base to try me out at that position. I took a ground ball and threw it to first base properly. On the very next ground ball, with my glove turned in the wrong direction, the ball took a hop, skipped off my glove and hit me in my eye. I came home with a large egg on my head.

My father, still at the kitchen table, looked angry. Without asking what happened, he said "Grab your glove, give me the ball and bat." He took me out to our yard which was only about twenty meters long, and he started hitting balls at me, telling me we'll quit when I catch three in a row. He was hitting the balls hard, and I was hurting from getting hit by the balls and not catching any of them. My mother was asking him to let her look at my eye and he continued to hit balls at me. I realized that I better start catching these balls or I may well die that day. After catching a few balls, he walked up to me, put his arm around me and said, "Carmen, you can have all the tools in the world. But if you don't have this (pointing at my head), and this (pointing at my heart), you will never be successful at this game or in life." My father was a World War II veteran and obviously had a strictness about him that many would frown on today. But that lesson stuck with me throughout my life. Unfortunately, my father died not long after that lesson with my mother passing not long after that from a cancer that today would likely be cared for much differently and successfully than in her time.

The values I learned from my parents and from everyone in my life are in this thesis. I do remain a student and I am very passionate about all I do in life and work as without passion, there is nothing but work. To me, work and life are one in the same, and I'm proud and appreciative of that as it is not work at all but simply life. I hope that this carries through to readers and I can influence others in some positive way as others have done for me. I look forward to all that is to come.