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Soil moisture variability on golf course fairways across the United States: an opportunity for water conservation with precision irrigation

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Abstract

Fairways account for an average of 11.3 irrigated hectares on each of the 15,000+ golf courses in the US. Annual median water use per hectare on fairways is between ~2,800,000 and 14,000,000 liters, depending on the region. Conventional fairway irrigation relies on visual observation of the turfgrass, followed by secondary considerations of short-term weather forecasts, which oftentimes lead to “blanket” applications to the entire area. The concept of precision irrigation is a strategy to achieve water use reductions by making applications only where, when, and in the amount needed. The use of technology, such as soil moisture sensors and valve-in-head sprinkler control systems, can further enhance its application. Fairways have the most promise for water conservation through precision irrigation on golf courses due to their more intense management compared to roughs and larger area compared to greens and tees. Soil moisture sensors equipped with GNSS can obtain georeferenced point data for creating soil moisture maps to identify variability, which may be useful for fairway precision irrigation. Previous research conducted in FL and MN has created soil moisture maps to demonstrate variability within fairways can be excessive, but findings are limited to a few golf courses in these states, and only 1 to 2 fairways per course. To further investigate soil moisture variability at larger scales, a golf course fairway soil moisture mapping protocol was developed at the University of Minnesota in 2019. The protocol outlines standard procedures for golf course superintendents to collect georeferenced soil moisture data (% volumetric water content; VWC) with a commercially available, GNSS-equipped, handheld soil moisture meter. The objective of this case study was to report fairway soil moisture variability findings from nine golf courses in eight states (AZ, CA, CO, FL, KS, MN, NH, and TX) that completed the protocol during 2019-2022. The courses exhibited varying course types (i.e., public versus private), turfgrass species, soil types, irrigation system ages and control, and irrigation philosophies. Approximately 80-315 georeferenced soil moisture data points were collected per fairway using either a FieldScout TDR 300 with an external GNSS receiver or FieldScout TDR 350 with an internal GNSS receiver. All data at an individual course were collected the same day, and 7 to 14 fairways were considered depending on course. Cumulative rainfall and irrigation 7 days prior to data collections were recorded. Soil moisture variability was determined through summary statistics, box and whisker plots, and ordinary kriging to create spatial maps. The mean soil moisture on fairways across courses was 22.4 to 48.8% VWC, the range was 27.6 to 43.7% VWC, and the coefficient of variation was 7.5 to 39.4%. Box and whisker plots and spatial maps of soil moisture aided in visualizing variability within and between fairways at all courses. Results suggest that golf course fairway soil moisture variability is inevitable, regardless of climatic region and course characteristics, which further reiterate the need for advanced irrigation practices and technologies for water conservation via precision irrigation.

Keywords

Irrigation, golf courses, turfgrass, soil moisture sensors, variability

Introduction

Unlike other agricultural crops, the goal of turfgrass management on golf courses is not increasing yield; instead, the goals are to optimize aesthetic and playability characteristics such as uniform density, color, and high-quality green coverage (Carrow et al., 2010). Thus, golf courses are intensively managed landscapes typically requiring high levels of inputs, with irrigation being one of the primary determinants required to meet those goals (Turgeon & Kaminski, 2019). Due to public concern surrounding foreseen potable water shortages, the golf course management industry has been under increasing pressure to reduce water use (Wheeler & Nauright, 2006). This has led to efforts over the past two decades that have resulted in a 21.8% decrease in water usage between 2005 to 2013 on US golf courses (Gelernter et al., 2015). Factors that are believed to contribute to these reductions are water conservation practices (e.g., use of wetting agents, hand watering, increase non-irrigated areas), voluntary reduction in overall irrigation, and decreased number of golf facilities.

Current golf course irrigation scheduling methods rely heavily on visual observation of the turfgrass followed by secondary considerations of short-term weather forecasts (Gelernter et al., 2015). More advanced techniques include factors such as reference evapotranspiration (ET_o) and soil moisture to evaluate golf course irrigation needs more precisely. However, the use of a strict ET_o-based approach is rare and has had widely varying results (McCready et al., 2009; Devitt et al., 2008), and the use of soil moisture sensors is commonly restricted to putting greens (personal communication). Fairways are the largest managed area on a golf course and account for an average of 11.3 irrigated hectares on each of the 15,000+ golf courses in the US. Annual median water use per hectare on fairways is between ~2,800,000 and 14,000,000 liters, depending on the region (Gelernter et al., 2015). Therefore, an opportunity for water use reductions in these areas is apparent by implementing new irrigation strategies.

The concept of precision irrigation is a strategy to achieve reductions in water consumption by making targeted or variable-rate applications only where, when, and in the amount needed. To a certain degree, many golf course superintendents already make site-specific irrigation applications; for example, programing individual sprinkler heads within fairways to irrigate more or less often than others based on turfgrass response in perceived dry or wet areas (Straw et al., 2020). This answers some of the *where* question, but *when* water should be applied and *how much* to apply remains unanswered. ET_o-based irrigation scheduling can answer the *when* and *how much* questions, but it is difficult to account for small-scale spatial variations, which lead to "blanket" applications over entire fairways although certain areas may not require any water at all. GNSS-equipped soil moisture sensors (mostly handheld) are currently available and capable of obtaining georeferenced (i.e., latitudinal and longitudinal location) point data for creating maps to identify soil moisture variability across a golf course. These maps can be utilized to determine soil moisture classes within management zones, where zones with the same class have comparable soil moisture values and can be irrigated similarly (Krum et al, 2010). Combined use of soil moisture sensors and maps, along with valve-in-head (i.e., individual) sprinkler irrigation head control, may assist golf course superintendents with more precise, site-specific irrigation applications that could lead to significant water reductions beyond conventional irrigation scheduling methods.

Recently, a golf course soil moisture mapping protocol was introduced by Straw and Horgan (2019) to increase adoption of GNSS-equipped soil moisture sensors and the concept of precision irrigation. The protocol outlines step-by-step instructions to collect georeferenced soil moisture data from fairways with a commercially available, GNSS-equipped, handheld soil moisture meter. The free protocol is applicable to any type of golf course and follows standard procedures to create fairway soil moisture maps from the georeferenced soil moisture data using open-source GIS software. The soil moisture maps can then be used to act as a guide for in-ground soil moisture sensor placement, delineate fairway irrigation management zones, and/or program an irrigation system to water site-specifically with individual sprinkler head control. Since the protocol's release in Sept 2019, it has been downloaded from golf course superintendents in over half of the states in the US, as well as several other countries. Despite the simplicity of the protocol, less than 20 known golf courses have completed it.

The lack of adoption towards soil moisture sensors and mapping technologies for large-scale precision irrigation could be due to a combination of complex factors that are not fully understood, but research highlighting the existing degree of soil moisture variability within fairways could provide motivation. Therefore, the objective of this case study was to utilize a unique set of soil moisture data collected from golf courses around the US that completed the Straw and Horgan (2019) mapping protocol to quantify soil moisture variability between and within fairways. It is hypothesized that soil moisture variability at large scales may be inevitable in golf course fairways, regardless of climatic region and course characteristics, which will further emphasize the need for advanced irrigation practices and technologies for water conservation via precision irrigation.

Materials and Methods

Nine golf courses that completed the soil moisture mapping protocol by Straw and Horgan (2019) from 2019 to 2022 were selected for the case study. Courses were chosen based on location and characteristics. The goal was to have golf courses in different environmental regions of the US that consisted of varying course type (i.e., public versus private), turfgrass species, soil type, irrigation system age and control, and irrigation philosophies (all self-reported by the superintendent), as well as soil moisture data that were collected from several fairways and within the same day at a course. Following the protocol's standard procedures, georeferenced soil moisture (% volumetric water content; VWC) data were collected from each golf course with an individually owned FieldScout TDR 300 (one course) or TDR 350 (eight courses) Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL). These devices use a similar methodology to indirectly measure soil moisture using time domain reflectometry (Robinson et al., 2003). The manufacturer's reported soil moisture accuracy is ±3.0% VWC when electrical conductivity is <2 mS cm^{-1}. Cumulative rainfall and irrigation amount from seven days prior to soil moisture data collections were documented too.

Soil moisture data were collected from fairways at each golf course by walking and serpentining a fairway, going side-to-side from one end to the other, taking measurements periodically. Two stainless steel tines (5 mm diameter, 3.3 cm spacing, and 7.6 cm length) were inserted into the ground at each sampling location and a button on the soil moisture meter's user interface was pressed to record the measurement. The TDR 300 is compatible with external GNSS receivers, and the manufacturer recommends a Garmin 73H (supported systems include GLONASS and GPS; Garmin Ltd., Olathe, KS), while the TDR 350 is equipped with an internal GNSS receiver [supported systems include Galileo, GLONASS, and GPS, as well as QZSS (where available)]. Therefore, in addition to a soil moisture value, the longitude and latitude at each sampling location were also recorded. The manufacturers' reported locational accuracy for the Garmin 73H and TDR 350 GNSS receivers is <3.7 and 2.5 m, respectively. Approximately 80-315 georeferenced soil moisture data points were collected per fairway from the courses. All data at an individual golf course were collected the same day, and 7 to 14 fairways were considered depending on course. Soil moisture data were collected from fairways at all nine golf courses with no planned timing after rainfall or manipulation to irrigation.

Data were exported from soil moisture meters to a universal serial bus, and then uploaded to individual Google Sheets (Alphabet, Inc., Mountain View, CA) that were shared by each golf course with the researchers. The Google Sheets were downloaded and saved as Microsoft Excel (Microsoft Corp., Redmond, WA) files, which were imported into RStudio 4.1.2 and ArcMap 10.6.1 for further analyses. Soil moisture variability was assessed through descriptive statistics [e.g., min, max, range, mean, standard deviation, and coefficient of variation (CV)], box and whisker plots, and spatial maps generated from ordinary kriging (Cressie, 2015). Descriptive statistics and box and whisker plots were generated in RStudio using the 'summary' and 'boxplot' functions, respectively. Box plots were made for individual fairways within each course, where the top whisker is the max, the lower whisker is the min, the top of a box is the third quartile, the bottom of a box is the first quartile, and the line through a box is the median. Spatial maps were generated in ArcGIS by first digitizing fairway boundaries using a basemap. The boundaries and georeferenced soil moisture data were projected to each course's respective state plane coordinate system. Ordinary kriging was then conducted to interpolate the data using Geostatistical Wizard. Semivariogram models for interpolation were either exponential or spherical and selected primarily based on lowest root mean square error. Ten geometric interval legend classifications were calculated from each golf course's respective soil moisture ranges to display spatial variability in the maps. Statistical procedures to determine the relationship of soil moisture variability and golf course characteristics between the courses were not conducted due to the small sample size, differences in the number of fairways evaluated per course, and in-situ nature of data collections under natural scenarios at different times of year. Rather, anecdotal comparisons were made given the reported golf course characteristics and soil moisture data collected at the specific date at each course.

Results

The nine golf courses considered were in AZ, CA, CO, FL, KS, MN, NH, east TX, and west TX (all in the US), which consisted of four public and five private (Table 1). Creeping bentgrass was the most common turfgrass species in fairways in the northern US [three courses, including one that had a blend with annual bluegrass (*Poa annua*), Kentucky bluegrass (*Poa pratensis* L.), and perennial ryegrass (*Lolium perenne* L.)] and bermudagrass (*Cynodon* spp.) was the most common turfgrass species in fairways in the southern US [four courses, including one that overseeded with perennial ryegrass]. Other courses in the central US had fine fescue (*Festuca* spp.) or zoysiagrass (*Zoysia* spp.) fairways. Self-reported soil types were clay (four courses), silty clay (one course), sandy loam clay (one course), sandy loam (two courses), and sand-capped (i.e., layer of course sand atop native soil; one course) (Table 1). The age of the irrigation systems ranged from 14 to 35 years, and six of the nine courses reported having individual head control capabilities. Fairway irrigation decisions were based primarily on ET_o and other weather variables (e.g., rainfall, temperature, wind). Only one of the courses reported using soil moisture when making the decisions to irrigate fairways (Table 1). Rainfall and/or irrigation amounts the seven days prior to data collections are presented in Table 2 and courses either received no rainfall or irrigation (one course), only rainfall (two courses), only irrigation (two courses), or both (three courses; one course did not report irrigation) prior to their data collection.

Overall mean fairway soil moisture values were from 22.4 to 42.8% VWC. The overall fairway ranges were from 27.6 to 43.7% VWC and CVs were from 7.5 to 39.4% (Table 2). There appeared to be no trend in the degree of fairway soil moisture variability between the amount of rainfall and/or irrigation before data collection, course type, turfgrass species, soil type, irrigation system age and sprinkler head control, and irrigation philosophies. Courses that received only irrigation prior to data collection were among the highest (west TX) and lowest (AZ) CVs, whereas comparable trends were observed with those who received only rainfall (e.g., MN and NH) or both (e.g., KS and east TX). Among public and private courses, the average range was 22.9 and 21.0% VWC and the average CV was 35.3 and 36.4%, respectively. Courses that had the same turfgrass species or soil type did not always exhibit the same level of soil moisture variability. For example, the AZ and west TX courses both had bermudagrass, but the AZ course had one of the lower CVs and the west TX course had the highest CV. Similar trends were observed with MN (lower CV) and NH (higher CV), which had creeping bentgrass (Table 2). Furthermore, the four courses that reported having clay soil were among those with the lowest (AZ, CO, and MN) and highest (FL) CVs. The sand-capped fairways in NH interestingly exhibited the highest range and second highest CV of soil moisture (43.7% VWC and 31.1%, respectively). Courses with older irrigation systems were generally ranked amongst those with the highest CVs, but KS (tied for the third oldest system at 27 years) had the lowest overall CV. Since minimal golf courses had paired heads and based their irrigation decisions on anything other than ET and weather, it is difficult to make any comparisons between the reported alternatives (Table 2).

Fairway soil moisture maps and box and whisker plots from each golf course are presented alphabetically by location in Figures 1-9. All golf courses exhibited some degree of soil moisture variability between their fairways, as well as within individual fairways. The three courses with the lowest standard deviation and CV (AZ, CO, and KS) even displayed noticeable soil moisture variation within fairways (Figures 1, 3, and 5). Most courses had differences in median soil moisture between some fairways by at least 10% VWC (Figures 4, 6, 7, 8, and 9), and every course had fairways containing considerable amounts of outlier values within fairways. There were also recognizable differences in the magnitude of soil moisture between single or groups of fairways within some of the golf courses. For example, fairways that were clearly drier than others are shown in the soil moisture maps from FL (fairways 7 and 9; Figure 4), MN (fairway 6; Figure 6), NH (fairways 7 and 11; Figure 7), and west TX (fairways 2, 4, and 8; Figure 9), while apparent wetter fairways are shown in maps from FL (fairway 1; Figure 4), MN (fairways 13, 14, 16, 17, and 18; Figure 6), NH (fairway 4; Figure 7), east TX (fairways 14 and 15; Figure 8), and west TX (fairways 5 and 11; Figure 9).

Summary

Soil moisture variability on fairways at nine US golf courses was evaluated using a mapping protocol. To the authors' knowledge, this is the first report of large-scale golf course soil moisture mapping in several climatic regions and under a wide array of golf course conditions. Results confirmed the hypothesis that soil moisture variability at large scales is inevitable between and within fairways, since every course considered in this study exhibited some degree of variability. These findings agree with other studies that have evaluated fairway soil moisture variability at much smaller scales (Carrow et el., 2010; Krum et al. 2010; Straw et al., 2019), and further justifies the need for advanced practices and technologies to reduce water use in these areas with precision irrigation. Future research should consider developing a method for precision irrigation applications on fairways using spatial soil moisture data, and then compare that to conventional irrigation strategies to quantify potential water use reductions and other benefits (e.g., energy savings, playability characteristics). Furthermore, additional exploration is needed to better understand the underlying issues that drive soil moisture variability on golf course fairways so that agronomic practices can be applied in attempt to improve uniformity (e.g., aerification, wetting agents, soil amendments).

Farm-scale precision irrigation methodologies have been considered in other areas of agriculture with promising water conservation results (Headley & Yule, 2009; Vellidis et al., 2013). It is reasonable to speculate similar benefits of precision irrigation in golf course management, but familiarity with spatial soil moisture data among golf course superintendents is needed, as is simplifying the data collection and processing steps that result in beneficial information to trigger irrigation decisions (Straw et al., 2020). There is growing interest in golf course management to utilize remote sensing (i.e., vegetation indices, thermal) from equipment mounted or unmanned aerial vehicles for irrigation decisions (Jiang et al., 2009; Hong et al., 2019a, b), which has also been used for other agricultural crops (Cohen et al., 2017; Stone et al., 2016). This approach could accelerate data collection without disrupting play, and strong correlations between soil moisture and vegetation indices/thermal measurements have been documented in turfgrass (both proximal and aerial) (Jiang et al., 2009; Hong et al., 2019a, b; McCall et al., 2017). Most studies to-date were conducted on small plots or in a greenhouse, but recent literature has reported an attempt to make similar correlations in-situ at larger scales (i.e., actual fairways) and found conflicting results, warranting additional research (Friell and Straw, 2021; Hejl et al., 2022). Ultimately, the golf course management industry should strive towards employing a combination of technologies that provide spatiotemporal climatic, turfgrass, and soil information for predicting real-world conditions, perhaps using advanced artificial intelligence and machine learning techniques, to develop decision support tools to implement precision irrigation at large scales for water conservation.

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Table 1. Course type, turfgrass species, soil, irrigation system age, irrigation head control, and influences on irrigation decisions at each golf course used in the study from the United States.

Location	Type[a]	Turfgrass species	Soil	Irrigation system age (years)	Irrigation sprinkler head control	Influences on irrigation decisions
Arizona	private	bermudagrass, perennial ryegrass	clay	21	individual	ET and weather[b]
California	private	fine fescue	amended sandy loam	14	individual	ET and weather
Colorado	private	annual bluegrass, creeping bentgrass, Kentucky bluegrass, perennial ryegrass	clay	14	individual	ET and weather
Florida	public	bermudagrass	clay	35	N/A	visual observation
Kansas	public	zoysiagrass	silty clay	27	individual	ET
Minnesota	public	creeping bentgrass	clay	27	paired	ET and irrigation system capabilities
New Hampshire	private	creeping bentgrass	sand-capped	22	paired	ET and soil moisture
Texas – east	private	bermudagrass	sandy loam	33	individual	ET, weather, and visual observation
Texas – west	public	bermudagrass	sandy clay loam	27	individual	weather and instinct

[a] All information was reported by the golf course superintendent at each location. N/A indicates that a response was not given.
[b] Weather includes rainfall, temperature, wind, etc.

Table 2. Location, the number of fairways considered, date of data collection, cumulative rainfall and irrigation amount prior to data collection, data count, and soil moisture (% volumetric water content) summary statistics at each golf course used in the study from the United States.

Location (# of fairways)	Date	Rainfall (cm)[a]	Irrigation (cm)	Area (m^2)	Data count[b]	Min	Max	Range	Mean	SD	CV
						%					
Arizona (14)	11/24/2021	0.0	1.8	104,616	1513	21.4	53.8	32.4	42.6	4.4	10.3
California (7)	1/30/2022	0.0	0.0	69,273	565	8.4	41.3	32.9	25.6	5.5	21.5
Colorado (8)	5/19/2020	2.7	3.8	66,169	2510	17.2	53.4	36.2	37.4	4.3	11.5
Florida (7)	2/21/2021	4.3	N/A	57,506	823	8.0	47.7	39.7	24.0	7.4	30.8
Kansas (8)	9/2/2020	6.3	1.9	55,007	1948	29.8	57.4	27.6	42.8	3.2	7.5
Minnesota (14)	4/30/2019	1.2	0.0	113,134	1274	15.7	48.0	32.3	33.6	4.7	14.0
New Hampshire (14)	5/13/2020	0.8	0.0	111,577	1566	9.0	52.7	43.7	28.0	8.7	31.1
Texas – east (7)	7/13/2020	1.4	2.3	38,603	1510	6.6	49.3	42.7	22.4	6.9	30.8
Texas – west (10)	9/27/2021	0.0	2.5	51,350	853	8.2	49.9	41.7	28.2	11.1	39.4

[a] Cumulative rainfall and irrigation amounts were from seven days prior to data collection, as reported by a nearby weather station and/or the golf course superintendent at each location. N/A indicates that a response was not given.
[b] The total number of data point locations across the sampled fairways.

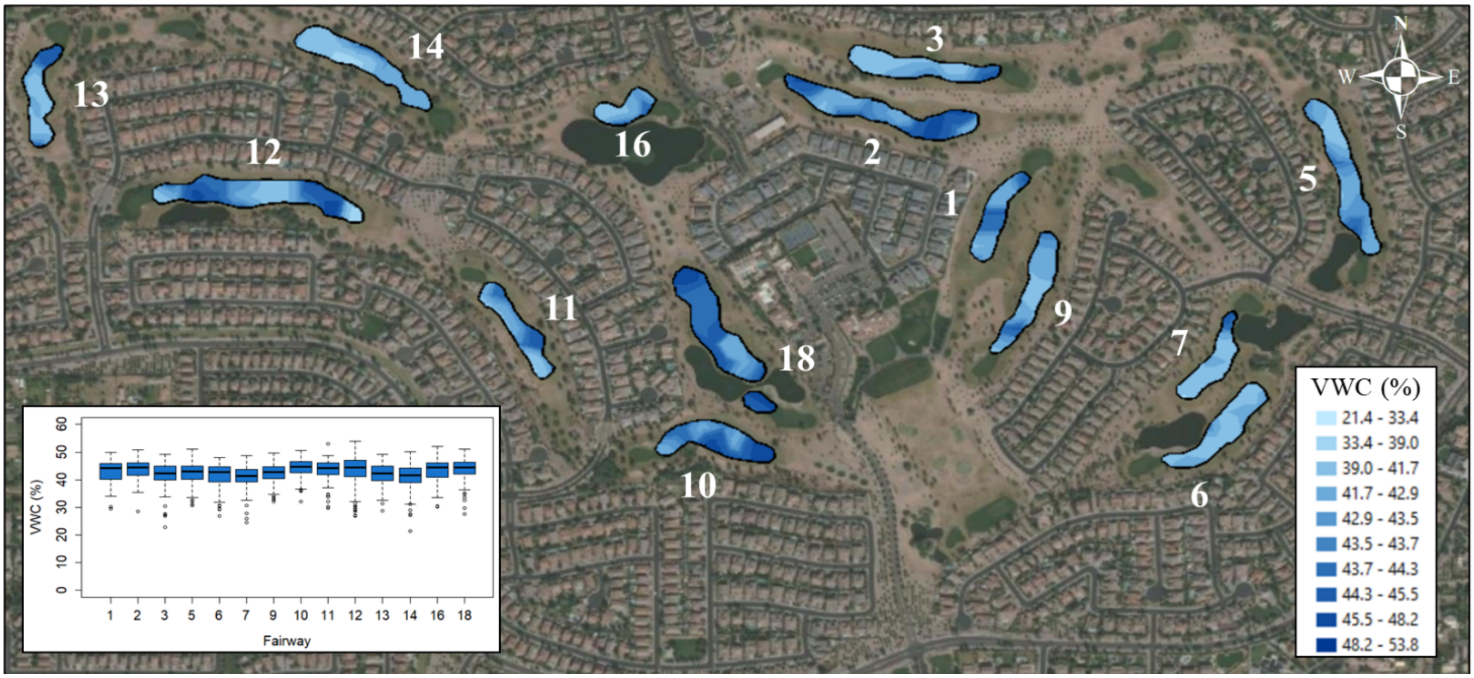

Figure 1. Fairway box and whisker plots and soil moisture maps from a golf course in Arizona.

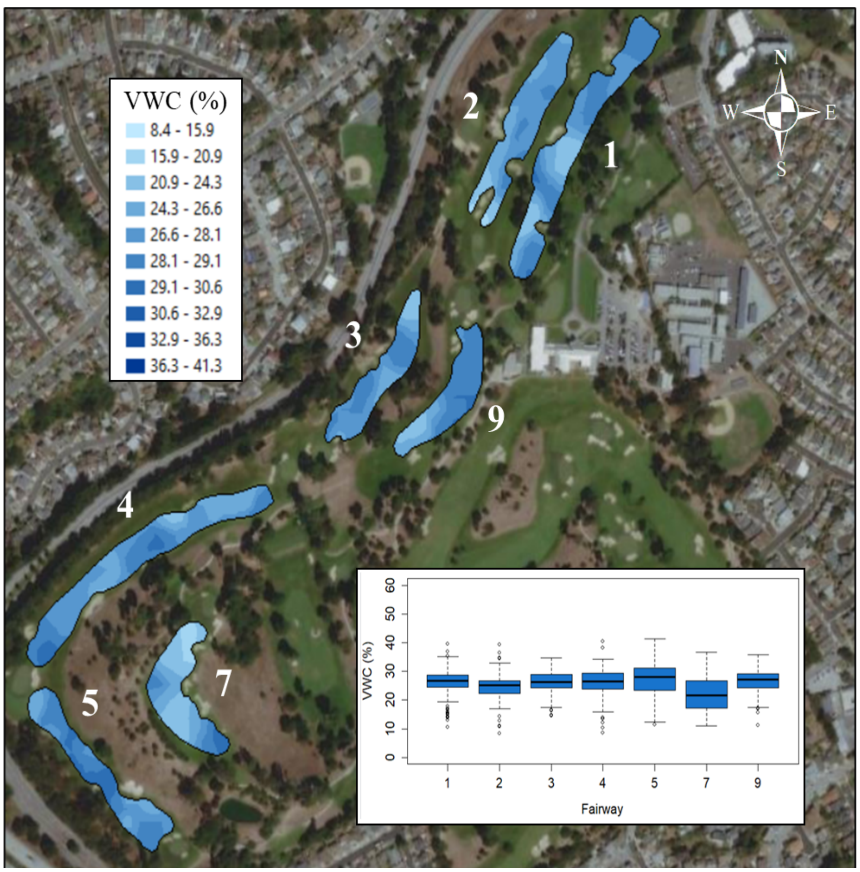

Figure 2. Fairway box and whisker plots and soil moisture maps from a golf course in California.

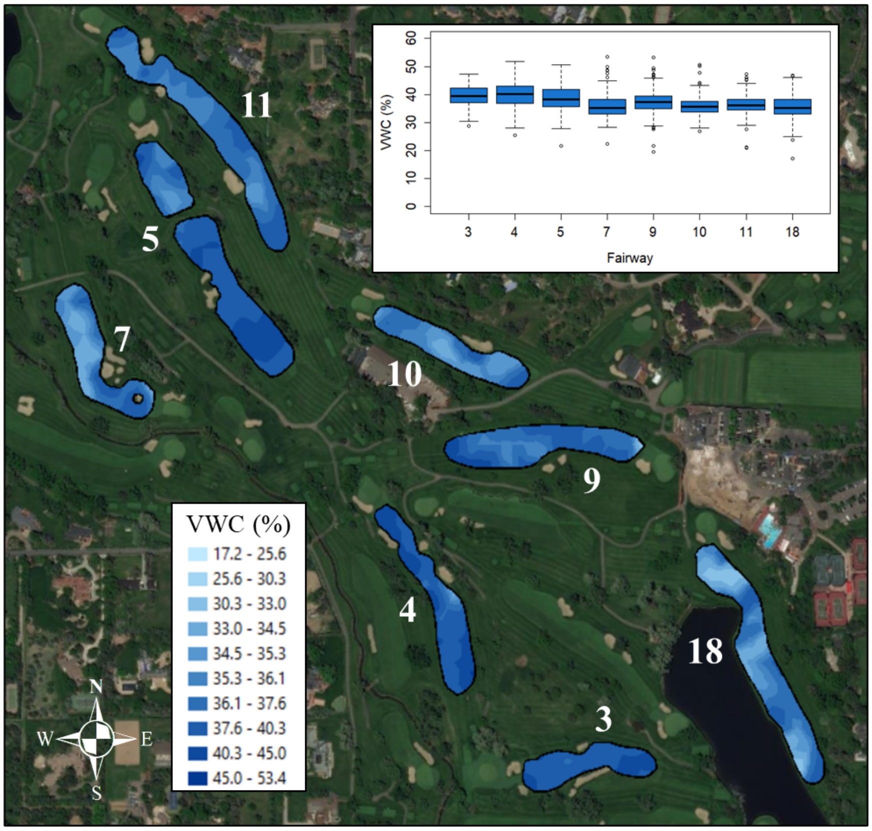

Figure 3. Fairway box and whisker plots and soil moisture maps from a golf course in Colorado.

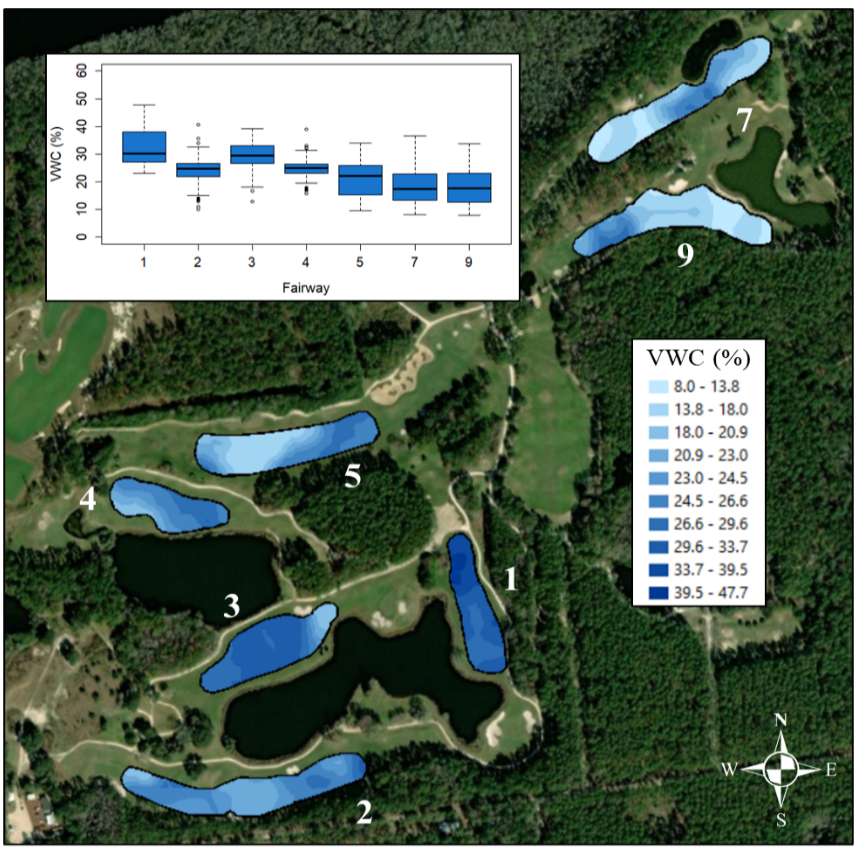

Figure 4. Fairway box and whisker plots and soil moisture maps from a golf course in Florida.

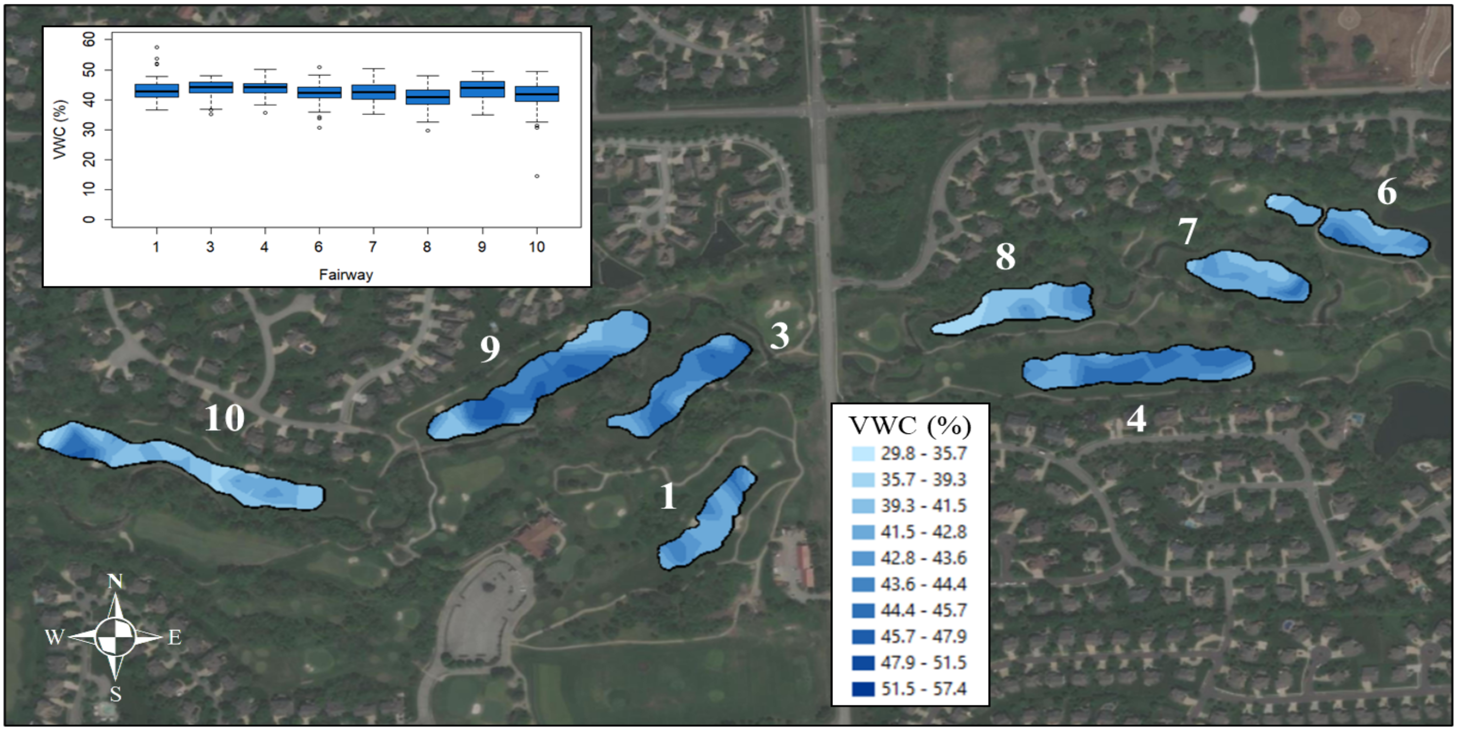

Figure 5. Fairway box and whisker plots and soil moisture maps from a golf course in Kansas.

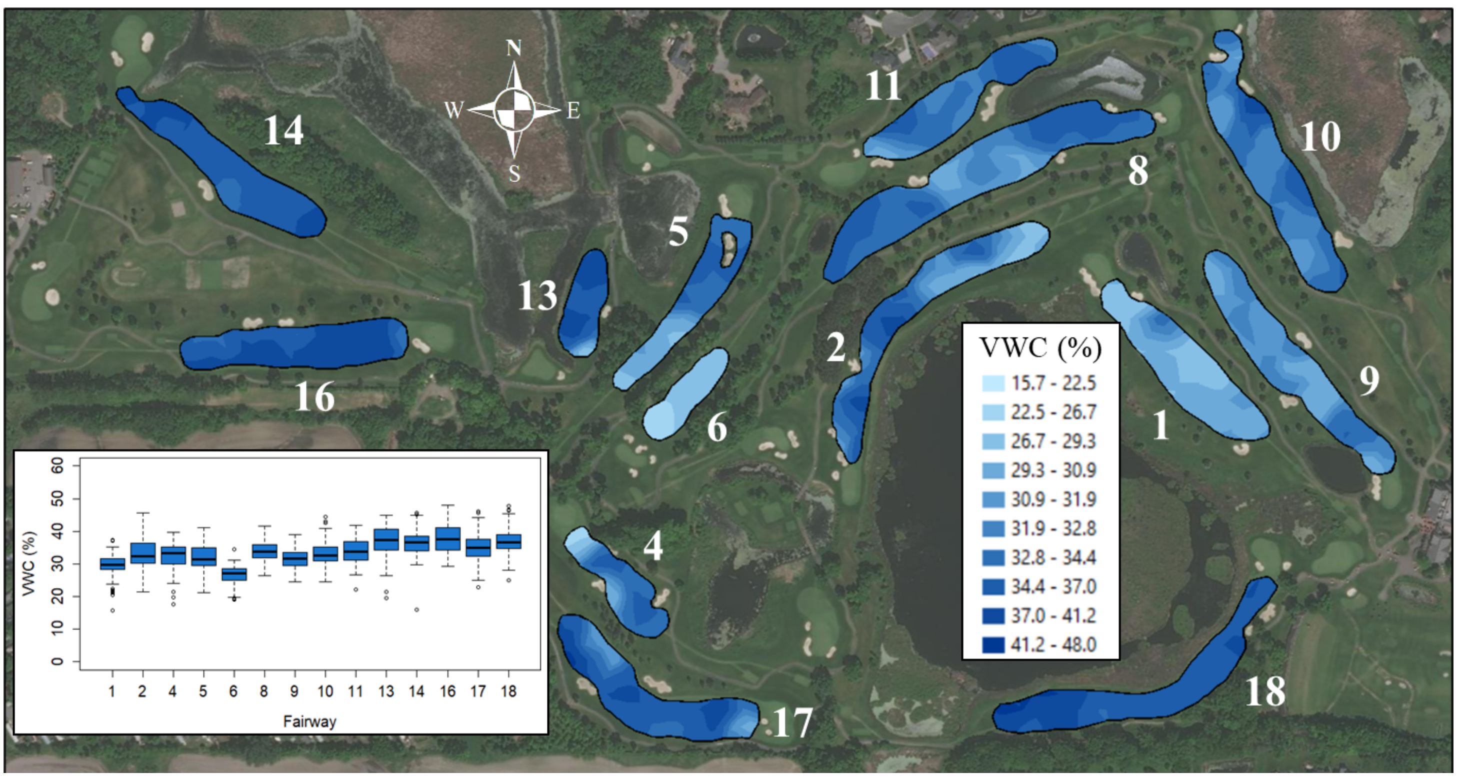

Figure 6. Fairway box and whisker plots and soil moisture maps from a golf course in Minnesota.

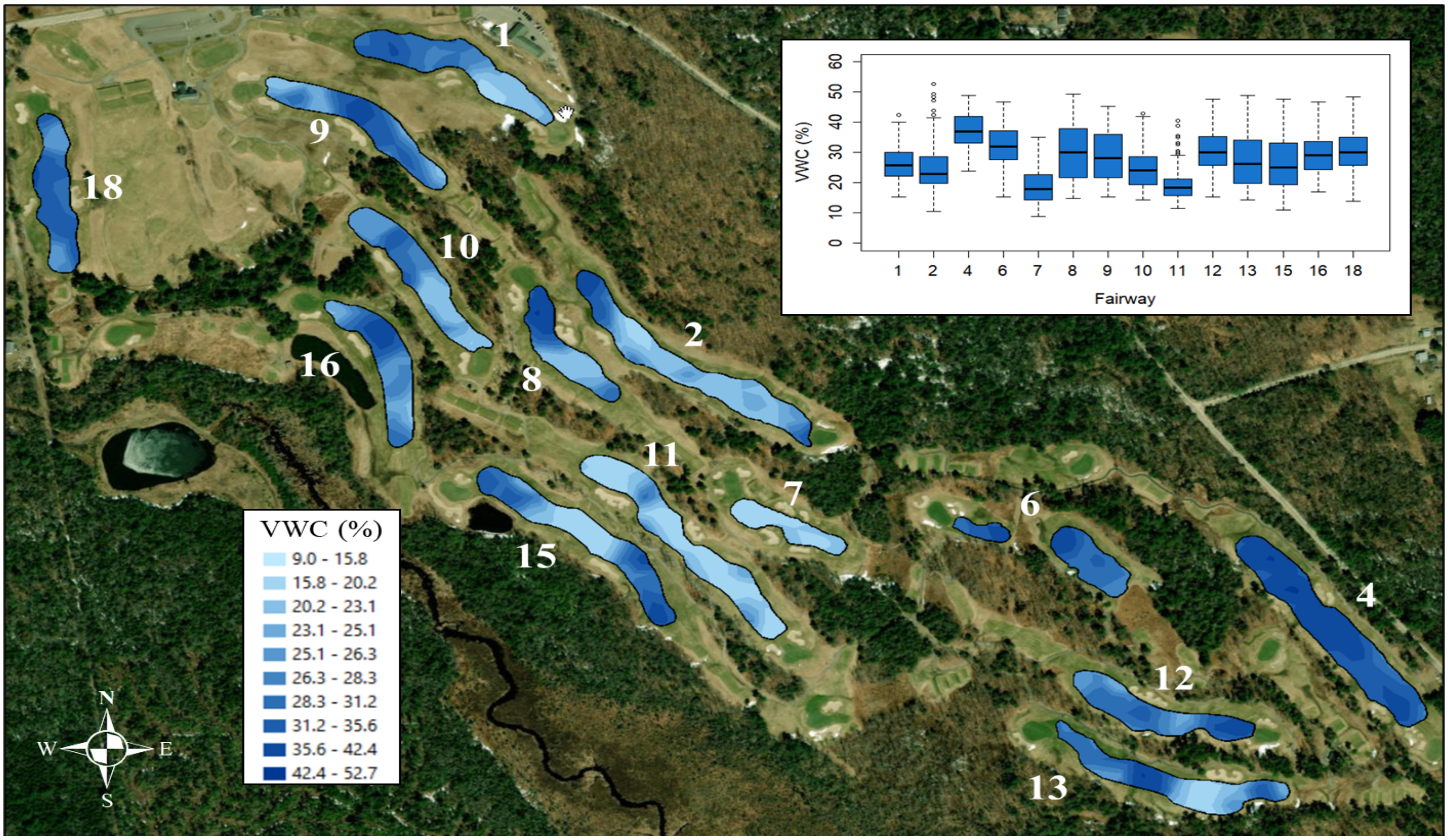

Figure 7. Fairway box and whisker plots and soil moisture maps from a golf course in New Hampshire.

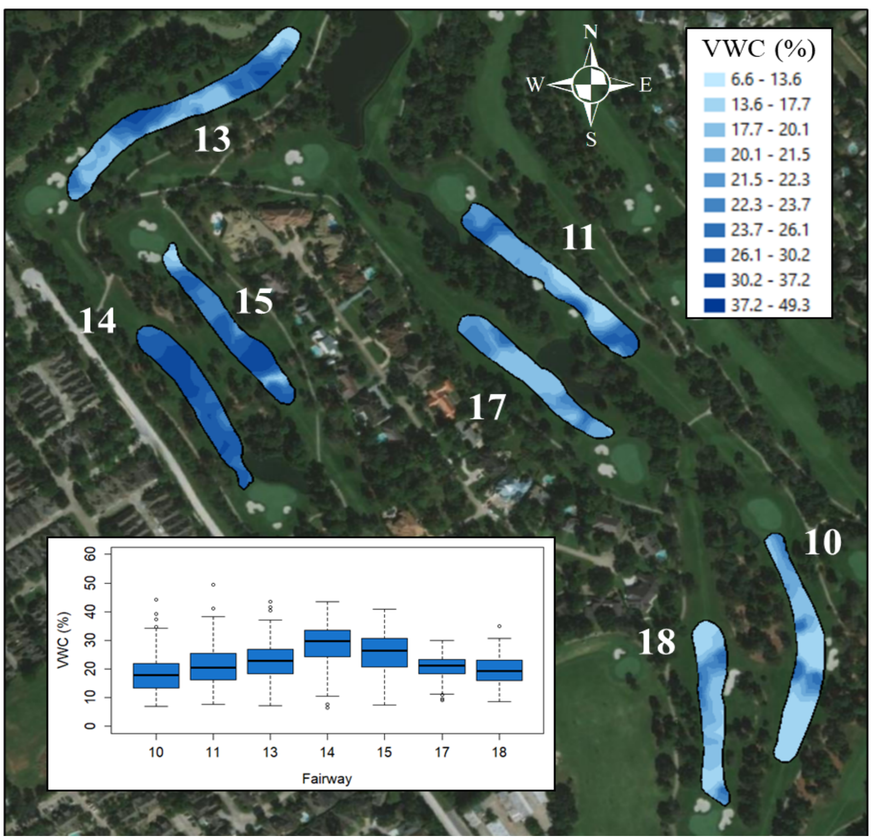

Figure 8. Fairway box and whisker plots and soil moisture maps from a golf course in east Texas.

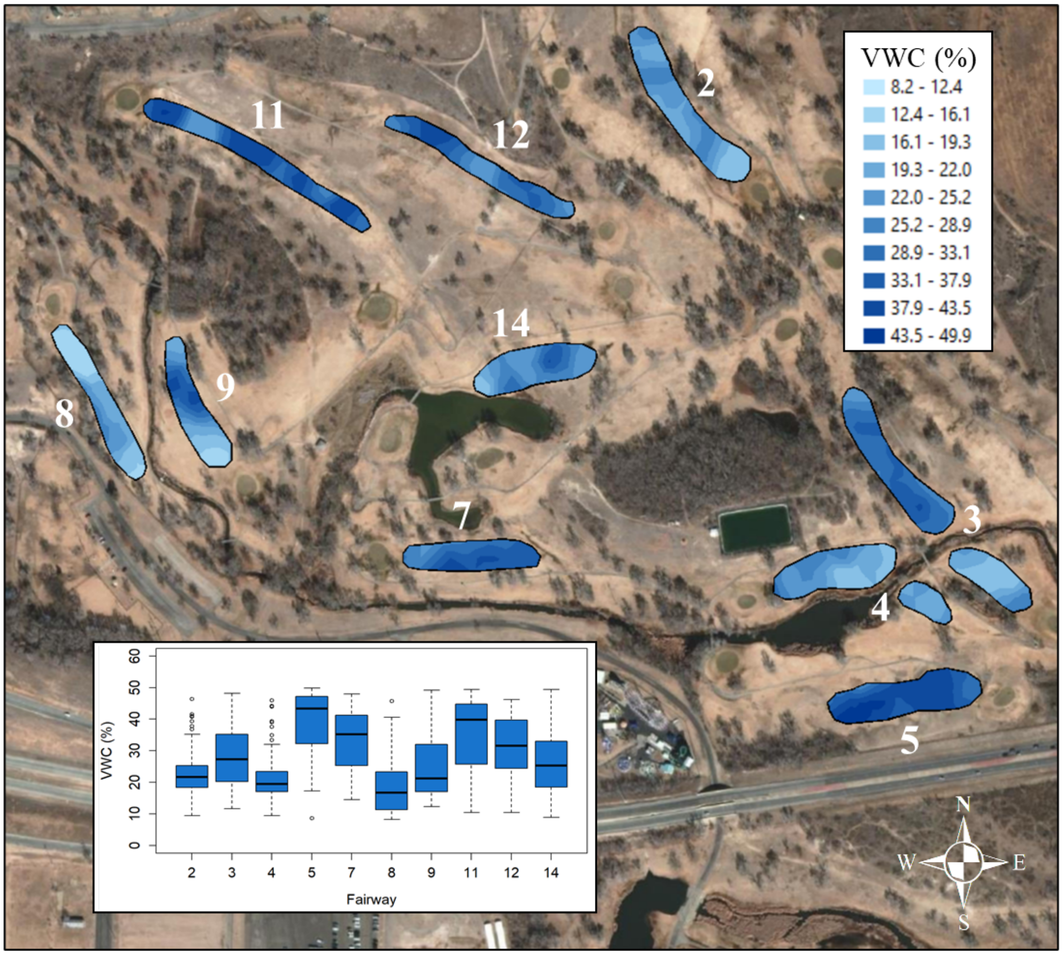

Figure 9. Fairway box and whisker plots and soil moisture maps from a golf course in west Texas.