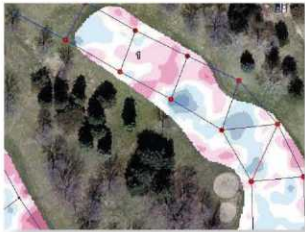# Precision turf management: A new water audit based on soil moisture

The application of principles of precision agriculture to turfgrass management has led to the development of an irrigation audit based on soil moisture.

Precision turfgrass management, a relatively new concept for the golf course industry, is based on the principles of precision agriculture, which has been evolving since the early 1990s (2,3,11,12). Foundational principles are:

- *Site-specific management* means that inputs (water, fertilizer, cultivation operations, salinity leaching fraction, etc.) are applied only where needed, when needed and at the amount needed. The idea is to foster precise, efficient application of inputs on smaller areas, such as the area affected by a single irrigation head.
- *Intensive site-specific information* is necessary to make wise site-specific decisions. Site sampling of soil and plant factors takes place across the whole area on a close-sample grid in order to define the degree of spatial variability of measured parameters.
- *Key soil and plant properties* must be measured to accurately define spatial variability and to investigate relationships of parameters (2,3).
- *Mobile, multiple-sensor devices* are necessary to measure all factors in a timely manner on

close spacing and across large complex areas such as golf courses. Mobile devices developed for precision agriculture are not well adapted to turfgrass situations, and this has hindered the development of precision turfgrass management. On smaller areas, such as golf greens, it is possible to use hand-held units to obtain spatial data.

- *All site data are GPS-labeled* (global positioning system), which allows the data to be imported into powerful geographic information system (GIS) programs for geostatistical analysis, for comparison of measured parameters at specific locations to explore relationships, and for development of detailed GIS maps.

A new device

The Toro Co. recently developed a mobile, multiple-sensor unit specifically designed for use on turfgrass sites (3,8). The Toro Precision Sense 6000 device has a mapping speed of 2 mph (3.2 kilometers/hour) and covers 2.5 acres (1 hectare)/hour using an 8 × 8-foot (2.4 × 2.4-meter) sample grid or

Toro Precision Sense 6000 mobile, multiple-sensor device (**left**) and mapping a golf course fairway (**right**). Photos courtesy of The Toro Co.

Robert N. Carrow, Ph.D.
Van Cline, Ph.D.

600 to 700 samples per acre. With a close-sample grid, GIS programs can accurately calculate the estimated value of measured parameters between sample locations, which effectively increases the spatial data four-fold. The multiple-sensor device measures the following GPS-labeled data:

- soil moisture as volumetric water content (%VWC) in the surface 0- to 4-inch zone (0-10 centimeters)
- soil salinity in the surface 0 to 4 inches
- surface hardness by penetration resistance as force to insert the probes in the top 0 to 4 inches
- plant performance based on spectral reflectance and reported as normalized difference vegetative index (NDVI), which is a measure of plant density, color and stress
- topography slope and aspect at 1-foot (0.3-meter) intervals.

The traditional water audit

A new water audit for golf courses based on soil moisture is a practical field application of precision turfgrass management concepts, in which the water audit fosters sustainable golf course management practices though improved water-use efficiency and conservation. Before discussing this new water audit approach, it is useful to understand the traditional water audit method based on catch-can methodology (13).

The Irrigation Association (9) says that through a traditional irrigation audit (that is, a water audit), "Information about each area's technical characteristics and controller capabilities should be obtained. An irrigation audit involves collecting data, such as site maps, irrigation plans and water use records. Tuning of the irrigation system is accomplished during the inspection. Field tests are then conducted to determine the system's uniformity and to calculate various zone precipitation rates."

Thus, a water audit has two phases. The first phase is the collection of existing site information that may influence irrigation and the inspection of the system for repairable malfunctions (1,13). Information at this stage may include pressure tests, sources, water-quality tests and flow data.

During system inspection, the Irrigation Association (9) recommends evaluating for:

- valve performance
- sprinklers that are tilted, sunken, broken, missing or clogged
- nozzles that are incorrect, misaligned or have spray deflected by objects
- leak detection and repair

- drainage from low sprinkler locations.

For golf courses, many of the items in this first phase may already be accomplished on a routine basis, because they are part of a good maintenance protocol. However, a high level of system maintenance is not always the case at other turfgrass sites. As will be addressed later, the new water audit based on soil-moisture actually aids in implementing the first phase.

The second or field-test phase of a traditional catch-can water audit is to assess irrigation system uniformity, where catch-cans are placed in a grid pattern, the irrigation system is operated under low wind conditions and water distribution is determined. Only selected sites, such as problem sites, are evaluated in this manner. Major design issues are of special interest, such as:

- improper sprinkler spacing — if only a few heads are too close or too far apart, they can be moved, but a consistent pattern of wide spacing that cannot be corrected by installing different heads or nozzles is a major design issue
- inadequate zoning or scheduling capability
- inadequate piping, pressure or flow rate for system operation
- outdated or worn-out equipment.

Test results are used to calculate factors important for efficient irrigation operation such as (13):

- *lower-quartile distribution uniformity (DU$_{lq}$)*, a measure of how uniformly water is applied over an area, where a DU$_{lq}$ greater than 80 is good; the DU$_{lq}$ is based on the average of all catch-can samples and the average of the lowest 25% of readings
- *run-time modifier (RTM)*, which is used to adjust timing in an irrigation zone to allow adequate water over the whole site where the run-time modifier increases as DU$_{lq}$ decreases
- *a densogram* that visually shows the wettest and driest areas within the test area and is valuable for making corrective measures such as changing nozzles to obtain greater uniformity (4).

New soil-moisture-based water audit

The new soil-moisture-based water audit has been formulated as a *decision-support system*, which adds value to the data by combining site-data acquisition, traditional and geostatistical analysis, and GIS map displays into a practical decision-making package for the end-user (5). For data acquisition, the Toro Precision Sense 6000 determines soil moisture (%VWC) and the other parameters during a dry period when the irrigation system uniformity of water application would
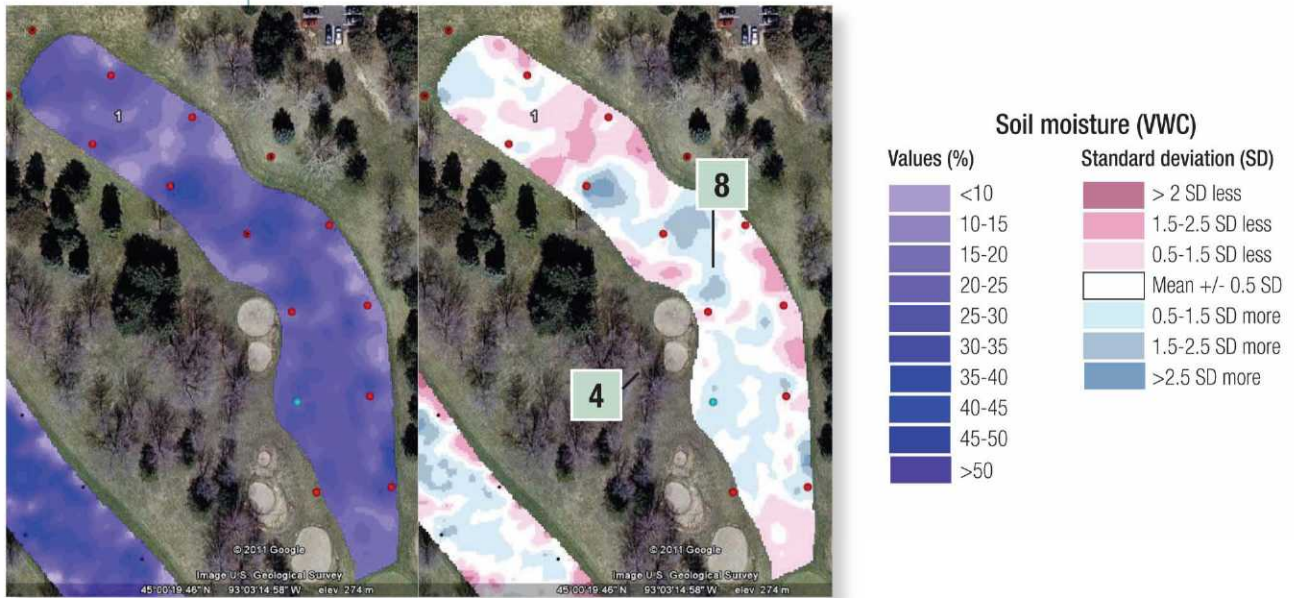
Figure 1. GIS maps of fairway 1 of a golf course presented as soil volumetric water content (VWC) (**left**) and in standard deviation format (**right**), which highlights the driest (pink) and wettest (blue) areas. Tables 2 and 3 and Figures 2 and 3 contain information on irrigation heads 4 and 8. Note the four-fold difference in soil volumetric water content from <15.1% to >59.4% VWC (**see Table 1**).

Soil moisture metrics for fairways

Fairway	Min	Mean	Max	Range	SD	CV	Moisture uniformity
1	15.08	33.67	59.37	44.3	7.27	21.6%	72%
2	7.24	27.2	66.72	59.48	8.62	31.7%	64%
3	12.92	33.93	57.61	44.68	7.47	22%	71%
5	12.25	31.89	54.62	42.37	7.94	24.9%	70%
7	7.8	28.58	52.92	45.12	10.83	37.9%	51%
8	12.72	31.66	45.3	32.58	6.02	19%	76%
9	15.9	33.86	51.87	35.97	6.23	18.4%	76%
10	12.87	33.92	57.79	44.92	7.82	23.1%	70%
11	10.02	37.94	66.05	56.03	9.25	24.4%	67%
12	9.27	33.62	80.98	71.71	12.53	37.3%	62%
14	12.63	37.48	69.98	57.35	11.7	31.2%	60%
16	11.34	37.53	64.85	53.51	7.34	19.6%	75%
17	13.33	43.85	91.08	77.74	7.56	17.2%	79%
18	14.36	38.9	92.85	78.5	9.37	24.1%	70%

Table 1. Soil moisture (%volumetric water content [VWC]) metrics for each fairway area. Standard deviation (SD) and coefficient of variability (CV) are statistical measures of soil VWC variability, where low values of each are best. SM-DU is a measure of soil moisture distribution uniformity across the fairway, where SM-DU (based on lower quartile) is normally somewhat higher than lower quartile catch-can distribution of uniformity results. An SM-DU above 85% is good. The irrigation system on this site is an older one with poor distribution because of irrigation head spacing, head and nozzle issues. Note the data for fairway 1, which is discussed in Tables 2 and 3 and Figures 1, 2 and 3.

be exhibited. The audit based on the volumetric water content of the soil considers any factor influencing soil-moisture distribution (irrigation system design, system performance, wind distortion, runoff, high evapotranspiration [ET] areas, soil texture, etc.), and the entire area is mapped. Mapping of fairways is especially important for maximizing water-use efficiency, but greens and their surrounds and tees can also be mapped as individual units. In this paper we emphasize fairways.

A proprietary software program based on ArcGIS allows traditional and geostatistical analyses of spatial variability of measured parameters (6,7). Analysis of spatial data, presentations of maps and quantitative metrics are applied at three spatial levels: across the whole fairway, green/surrounds or tee; within the influence zone of each irrigation head; and analysis of head-to-head spacing related to system performance. GIS map and data presentation and transmittal to the end user is assisted by Google Earth as well as a written report.

Whole-area spatial maps and analysis

When spatially mapping soil and plant attributes on a golf course, it is imperative to first have a GPS-tagged map of golf course features — boundaries of fairways, greens, tees, bunkers, water features, topography, etc. Such maps can be entered into an irrigation control system. If a golf course does not already have this GPS information, then it can be obtained as part of the water audit.

% VWC metrics for fairway 1 irrigation heads

Head ID No.	Min	Mean	Max	Range	SD	CV	Moisture uniformity
5	24.75	34.86	43.28	18.52	4.72	13.6%	81%
6	23.58	32.85	53.1	29.53	7.16	21.8%	78%
4	28.66	38.06	46.79	18.13	2.81	7.4%	90%
7	19.06	34.82	48.17	29.11	5.57	16%	78%
3	23.23	36.15	48.41	25.18	5.57	15.4%	81%
8	18.11	30.11	50.56	32.45	7.11	23.6%	71%
2	20.48	36.33	51.45	30.97	8	22%	70%
9	18.71	32.79	47.57	28.86	5.87	17.9%	76%
1	15.79	36.73	59.37	43.59	10.34	28.1%	61%
10	15.63	30.24	43.47	27.85	6.96	23%	72%
313	16.85	29.98	41.31	24.46	4.63	15.5%	80%
11	15.08	24.92	31.76	16.68	3.6	14.5%	80%
314	21.42	37.33	48.37	26.95	6.78	18.2%	72%
12	18.57	31.76	40.62	22.05	5.27	16.6%	77%
13	21.46	34.66	39.81	18.35	5.02	14.5%	78%

Table 2. Soil moisture (%volumetric water content [VWC]) metrics for each irrigation head on fairway 1 (the data are based on the area of influence or impact for each irrigation head). Standard deviation (SD) and coefficient of variability (CV) are statistical measures of soil volumetric water content variability, where low values of each are best. SM-DU is a measure of soil-moisture distribution uniformity across the area of influence of the irrigation head, where SM-DU (based on lower quartile) is normally somewhat higher than lower quartile catch-can distribution uniformity results. An SM-DU above 85% is good. The irrigation system on this site is an older one with poor distribution caused by problems with irrigation head spacing and irrigation heads and nozzles. Irrigation head 4 has very good SM-DU, whereas head 8 exhibits a lower SM-DU as illustrated by water patterns in Figure 1. See Figure 2 and Table 3 for more information on head 8.

%VWC metrics for head 8

Head 8 impact area statistics	Moisture uniformity: 71.4%		
	Mean	CV	Soil moisture correlation
Soil moisture	30.1%	23.6%	
Compaction	226.5 psi	11.3%	-0.86
Turf vigor	0.867 NDVI	3.1%	0.77

Table 3. Soil moisture (%VWC) metrics for the area of influence of head 8 (see map) on fairway 1. Coefficient of variability (CV) is a statistical measure of soil volumetric water content (VWC) variability, where a low value is best. These data appear as a pop-up on the spatial map for fairway 1 and provide information similar to that in Table 2 as well as information that relates soil volumetric water content values to penetrometer resistance (COMP) values and turf vigor (NDVI). Because of the considerable spatial variability in soil volumetric water content in this irrigation head's area of influence, penetrometer resistance increases as soil volumetric water content declines, and NDVI increases as soil volumetric water content increases. See Figure 2 for soil water distribution away from head 8 by quadrant.
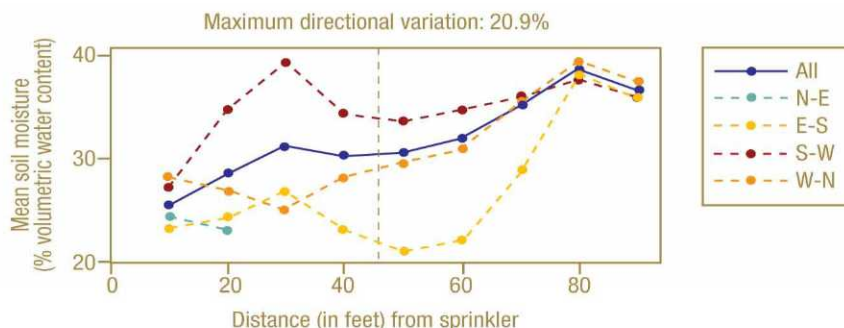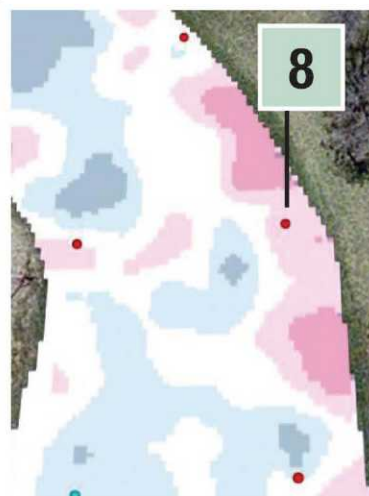

Figure 2. Average volumetric water content at different distances from head 8 for each quadrant and for an average of all quadrants (see Table 2 for additional information provided for each irrigation head).

Figure 3. Assessment of distance between adjacent irrigation heads on fairway 1. Any heads that are more than 92.6 feet apart (which is 1 standard deviation above the mean spacing for the fairway) are red-flagged for closer observation as to whether they are contributing to soil volumetric water content issues. 1 SD would identify distances between heads that are within the highest 16% of all spacings on a course. However, on this fairway, even the mean distance between irrigation heads is large, based on the heads, nozzles and operational pressure used. For this fairway, the mean distance is 85.0 feet (25.9 meters); the minimum distance is 60 feet (18.2 meters); the maximum distance is 116.9 feet (35.6 meters); the standard deviation is 7.6 feet (2.3 meters); and the coefficient of variability is 9%.

Soil volumetric water content and other parameters are presented in both raw data and standard deviation (SD) GIS maps. The GIS maps are very useful for identifying areas with the lowest (driest) and highest (wettest) soil volumetric water content values (Figure 1). Descriptive metrics presented for each fairway area aid in evaluating spatial distribution of soil volumetric water content and irrigation system performance (Table 1). Descriptive statistics include measures of central tendency (mean) and data variability (minimum, maximum, range, standard deviation, and coefficient of variability or CV). Also, moisture uniformity (soil-moisture distribution uniformity, SM-DU) is reported based on the lower quarter of soil volumetric water content data for a fairway or irrigation-head area of influence, where

$$SM\text{-}DU = 100(VWC_{lq}/VWC_{tot})$$

and VWC_{lq} is the average of the lowest quarter of soil volumetric water content measurements,

and VWC_{tot} is the average of all soil measurements. The SM-DU value normally is similar to traditional catch-can distribution uniformity (DU_{lq}) but somewhat higher (10).

Additional fairway maps to aid in irrigation decisions or assessing system performance are:

- the lower-quartile soil volumetric water content (driest) sample sites — very useful in determining whether the low volumetric water content is caused by irrigation water distribution or soil texture changes
- the highest quartile soil volumetric water content (wettest)
- the number of heads that cover each area on a fairway
- topography contours, slope and aspect.

Individual irrigation heads

With close-grid mapping, the area of impact of each irrigation head can be characterized using the same metrics as for a whole fairway (Table 2), as well as correlation of soil volumetric water content with plant NDVI and soil penetrometer resistance (Table 3, Figure 2). Standards can be assigned that would red-flag a problem head, where the SM-DU is especially useful for identifying heads with poor uniformity of distribution. This is valuable considering the number of irrigation heads on a golf course. In Table 2, for example, irrigation head 8 exhibits a low SM-DU value of 71% with soil moisture ranging from 18.1% to 50.56% volumetric water content, and the high standard deviation and coefficient of variation values all illustrate considerable variability in soil volumetric water content within the area of head impact. Soil volumetric water content variability at different distances from the head can be evaluated by quadrant and an average of quadrants to aid in understanding distribution problems at the single-head level (Figure 2).

Irrigation head spacing

GIS programs allow distances between adjacent irrigation heads to be determined for a fairway and surrounds (Figure 3). Distances that exceed 1 standard deviation distance of the average distance between irrigation heads are red-flagged for closer inspection. The standard deviation distance would represent about 16% of all the distances between heads. Information about the distances between irrigation heads combined with data and maps of fairways and individual irrigation-head impact areas can determine whether there are just a few head-spacing problems or whether heads are consistently spaced too wide for adequate coverage with existing heads and nozzles. In the latter case,

theoretical distribution from different heads and nozzle choices can determine replacement options or whether the system will be inadequate regardless of reasonable changes. Flagged heads are field-evaluated for possible problems and fixes.

Other features

The new soil-moisture-based water audit focuses on water-use efficiency by assessing and correcting issues related to irrigation system design, maintenance and scheduling, but the NDVI and salinity data obtained during spatial mapping under drier conditions also are very valuable. Relations between soil volumetric water content and plant NDVI or soil salinity can be explored because the decision support system report contains this information. Soil moisture strongly influences turfgrass performance, salinity spatial distribution (when saline irrigation water is used), and salinity leaching efficiency.

In modern turfgrass management, integration of cutting-edge science technologies and concepts is important to maintain efficiency of resource inputs, including water. The new soil-moisture-based water audit is an important step toward improved site-assessment methodology to support sustainable golf course management.

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GCM

Robert N. Carrow (rcarrow@uga.edu) is a professor in the department of crop and soil science at the Georgia Experiment Station, University of Georgia, Griffin, Ga., and Van Cline is manager of turf agronomics and research at The Toro Co., Bloomington, Minn.

The research says

→ A mobile multiple-sensor unit for conducting a soil-moisture-based water audit on large areas of turf, such as fairways, brings precision turfgrass management to golf courses.

→ The soil-moisture-based water audit combines site data acquisition, traditional and geostatistical analysis and GIS displays.

→ Soil volumetric water content is combined with GIS maps to identify the driest and wettest areas of an area such as a fairway.

→ Each irrigation head is evaluated based on soil water content and distribution patterns in the area of influence for each head, which allows individual head problems to be identified.

→ Distances between irrigation heads are recorded for a fairway, and excessive distances are highlighted to call attention to problem irrigation heads and spacing.

→ The focus of the soil-moisture-based water audit is to correct deficiencies in the irrigation system, but NDVI and salinity data can also be helpful to superintendents.