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Precision Turfgrass Management (PTM) is a developing information-based approach to managing turfgrass sites. PTM integrates the use of various sensors, mobile sensor platforms, and GPS and GIS technology to more accurately assess the need to apply water and other materials to turfgrass sites and provides information to assess the need for other management operations (i.e. cultivation), as well. Shown above is the Toro Mobile Monitoring device (TMM) mapping soil volumetric water content (VWV) in the surface 4-inch zone, penetrometer resistance, and normalized difference gegetative index (NDVI, a measure of plant health) at Old Colliers Golf Club, Naples, FL.

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PURPOSE

The purpose of *USGA Turfgrass and Environmental Research Online* is to effectively communicate the results of research projects funded under USGA's Turfgrass and Environmental Research Program to all who can benefit from such knowledge. Since 1983, the USGA has funded more than 350 projects at a cost of $29 million. The private, non-profit research program provides funding opportunities to university faculty interested in working on environmental and turf management problems affecting golf courses. The outstanding playing conditions of today's golf courses are a direct result of ***using science to benefit golf***.

Editor

Jeff Nus, Ph.D.
1032 Rogers Place
Lawrence, KS 66049
jnus@usga.org
(785) 832-2300
(785) 832-9265 (fax)

Research Director

Michael P. Kenna, Ph.D.
P.O. Box 2227
Stillwater, OK 74076
mkenna@usga.org
(405) 743-3900
(405) 743-3910 (fax)

Precision Turfgrass Management: A New Concept for Efficient Application of Inputs

Robert N. Carrow, Joseph Krum, and Chris Hartwiger

SUMMARY

Precision Turfgrass Management (PTM) is a developing information-based approach to managing turfgrass sites. PTM integrates the use of various sensors, mobile sensor platforms, and GPS and GIS technology to more accurately assess the need to apply water and other materials to turfgrass sites and provides information to assess the need for other management operations (i.e. cultivation). The focus of this paper is to define the PTM concept and discuss potential applications for the golf industry.

- Site-specific management requires site-specific information. Detailed knowledge of the spatial nature of plant and soil properties is necessary. This requires site data to be acquired on a close-spaced grid - i.e., intensive mapping.
- PTM is based on 1)advanced sensor technology, 2) mobile sensor platforms for site mapping, 3) GPS to define the exact site for each data point, and 4) application GIS technologies to analyze and display spatial data.
- Determining areas that are characterized by similar input requirements is essential for efficient input allocation and are the basis of PTM. Site-specific Management Units (SSMUs) are areas of similar water-holding capacity, soil texture, topography, and microclimate properties that have the same management requirements.
- Software programs with extensive geospatial mapping and analytical capabilities can illustrate spatial variability using the spatial mapping information and help determine how management practices can be modified to increase efficiency and conservation.

"Where, when, and how much" are questions golf superintendents ask about the inputs used on golf courses. A dramatic transformation in traditional agriculture has occurred over the past two decades based on technological advancements that allow a greater degree of site-specific management, and precise and efficient input. This practice of site-specific management is referred to as Precision Agriculture (PA), and its adoption has had positive repercussions involving costs, labor, and environmental impact (1, 5, 7, 18, 20). More recently, the Precision Turfgrass Management (PTM) concept has evolved in the turfgrass industry, based on the PA principle of limiting input application to a site's spatial, temporal, and rate requirements - i.e. application of inputs, such as irrigation water, only where needed, when needed, and at the rate required (15, 16, 22, 23).

Both PA and PTM rely on advanced sensor technology, mobile sensor platforms, use of GPS (global positioning systems), and application of GIS (geographic information systems) to analyze and display the intensive data. The focus of this paper is to define the PTM concept and discuss potential applications for the golf industry, particularly related to efficient application of inputs.

ROBERT N. CARROW, Ph.D., Professor of Turfgrass Science, Dept. of Crop and Soil Sciences, Georgia Experiment Station, University of Georgia, Griffin, GA; JOSEPH KRUM, Graduate Student, Dept. of Crop and Soil Sciences, University of Georgia, Athens, GA; and CHRIS HARTWIGER, Senior Agronomist, USGA Green Section, Birmingham, AL.

Driving Forces

Several factors have recently converged to focus attention on the concept of PTM as a means to improve input efficiencies. Driving forces fostering PTM as a means of improving input efficiency are economic, environmental, and social in nature, and these are likely to continue in the future. These factors include: a) potential for site-specific application to save cost of inputs, labor, and equipment wear related to maintaining acceptable turfgrass quality; b) demand for more precise and efficient irrigation as a key water conservation strategy on turfgrass sites; c) societal pressure for natural resource and energy sustainability; and d) recognition by many businesses that a "green company image" that entails the previous aspects is good business and a necessary factor to be a leader in the industry.

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Experimental Salinity Monitoring Device (SMD) conducting salinity mapping of surface salinity, subsurface salinity, and plant NDVI at Old Colliers Golf Club, Naples, FL in May 2009. Data are GPS-labeled and mapping grid is 5 by 10 feet.

Several of these driving forces are broader environmental issues and not just turfgrass management related, which reflects a similar trend in traditional agriculture. In PA, the primary focus has been on improved efficiency of inputs related to crop yield via site-specific management, where intensive site mapping was conducted to provide the information to make good decisions. However, the same site mapping information has increasingly been used to foster Precision Conservation (PC), which is the use of spatial mapping of surface conditions to manage for soil and water sustainability (9). For turfgrass sites, use of PTM to enhance irrigation efficiency while achieving acceptable quality turfgrass also has a water conservation goal, illustrating the convergence of PTM and PC.

Another essential driving force has been the limitation hindering progress of PTM for large, complex sites, such as golf courses, namely the development of mobile soil sensor platforms specifically designed for turfgrass situations that are capable of intensive site mapping. A recent review of optical sensing applications in turfgrass management demonstrated that considerable research has been conducted on spatial mapping of turfgrass sites using optical sensors, such as spectral reflectance and infrared canopy temperatures (2). But, the review also revealed the absence of mobile platforms with soil sensors to measure key soil attributes that would relate to turfgrass performance.

Rhoades (18), in the early 1990s, recognized this as a critical limitation in PA, and he developed mobile platforms to spatially determine important soil characteristics, which could then be related to crop data such as end-of-year yield or plant performance indices from satellite spectral information or ground-level optical sensing data. It was the coupling of key soil and plant attributes that has allowed PA to better understand and spatially determine factors that influence plant performance, and this need is also critical for PTM (6, 7, 8, 15, 18, 19, 20, 21). The specific devices developed for turf situations are discussed in the next section.

Key Principles

Knowledge of the key principles of PTM is important in understanding the potential applications for this concept. Although PTM is based on PA, it is beyond the scope of this article to address the current state of PA, but this is discussed in several of the references (1, 3, 5, 8, 9, 18, 20). Both PA and PTM are dependent on the following premises.

Intensive, Site-specific Information

Site-specific management requires site-specific information. To apply inputs more precisely, such as on sub-areas of a fairway, detailed knowledge of the spatial nature of plant and soil properties is necessary. This requires site data to be acquired on a close-spaced grid - i.e., intensive mapping.

Integrated Technology

Acquisition of spatial data required the appropriate technological developments in both PA and PTM; thus both are based on 1) advanced sensor technology, 2) mobile sensor platforms for site mapping, 3) GPS to define the exact site for each data point, and 4) application GIS technologies to analyze and display spatial data. Due to the large quantities of information, these systems must be highly integrated for efficiency.

Spatial Mapping Via Mobile Devices

Development and application of mobile sensing equipment can overcome the inherent time and cost barriers associated with hand-held devices, as well as penetration difficulties for soil sensors. Also, as noted, extensive adoption of PA occurred only after instrumentation was developed that could measure both plant status and soil attributes relating to plant performance. In 2005, the Toro Company developed the Turf Mobile Multi-Sensor (TMM) mapping experimental unit as the first device capable of monitoring key plant and soil attributes on turfgrass landscapes. The TMM allowed intensive and rapid GPS-referenced surface zone (0 to 4 inch) volumetric water content (VWC), turfgrass performance by normalized difference vegetative index (NDVI), and penetrometer resistance (PR) mapping. Spectral reflectance is utilized to determine NDVI, while time-domain reflectrometry is used for VWC data acquisition.

In the absence of topographic maps, the TMM GPS also provides an estimate of topography. With the TMM it was now possible to spatially map a fairway in 30 to 45 minutes with 600 to 1,100 individual VWC measurements on a grid of approximately 10 feet. Consequently, the spatial variability of a site could be characterized and assessed relatively quickly, and it was possible to conduct the necessary research studies to establish PTM on a sound science foundation.

Site-specific Management Units (SSMUs)

Determining areas that are characterized by similar input requirements is essential for efficient input allocation and are the basis of PA as well as PTM (7, 8, 10, 14, 24). SSMUs are areas of similar water-holding capacity (VWC), soil texture, topography, and microclimate properties that have the same management requirements. In PA, SSMUs are sub-field areas, while PTM SSMUs are sub-fairway (golf courses), sub-athletic field, sub-field (sod farms), or sub-areas of general landscapes. Other names for SSMUs are management zones, site-specific management zones, or management classes. Once SSMUs are delineated, additional information on the soil chemical and characteristics within SSMUs can be obtained over time to supplement the initial spatial mapping information.

SSMUs are best defined using stable soil characteristics that relate to plant performance. The use of VWC measurements taken at field capacity is a decided advantage for turfgrass sites

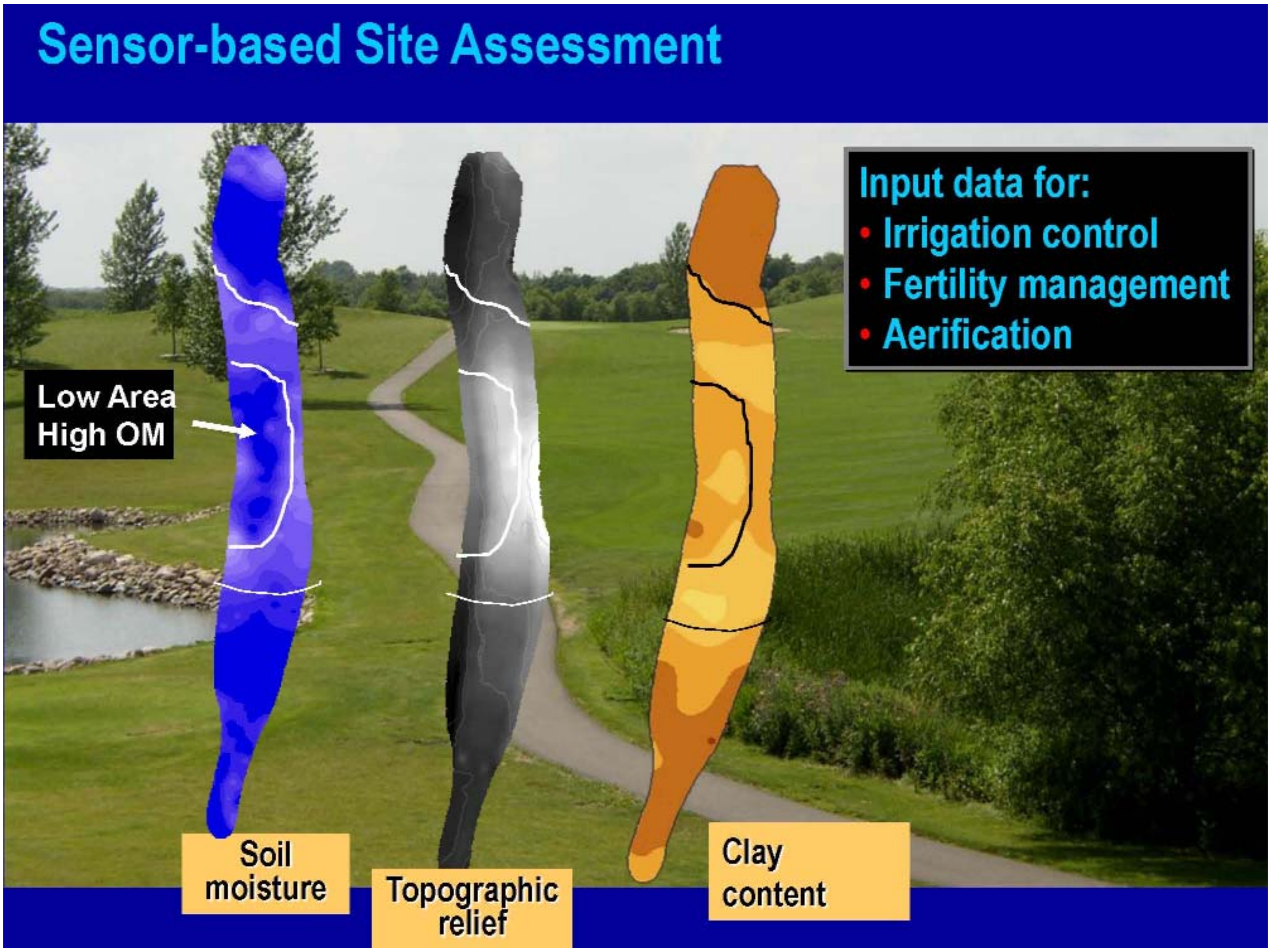

Figure 1. Spatial mapping of soil volumetric water content (left, dark blue = highest VWC) with SSMU boundaries along with topographic map and clay content (determined by soil sampling within SSMU areas.

compared to the most common means of determining SSMUs in PA, since VWC is directly related to stable soil properties such as texture, organic matter content, and structure (20, 21).

Topography, another stable landscape feature, is also included when defining SSMU boundaries since it influences rain and irrigation distribution. However, in PA the most common means to estimate soil properties has been apparent soil electrical conductivity (ECa) measurements by electromagnetic (EM) devices on a mobile sensor platform, while yield mapping or spectral reflectance via ground level or remote devices provide crop performance information (6, 7, 8, 19, 24).

The EM readings are indirect estimates of the combined effects of soil moisture, structure, and bulk density in non-saline soil, and separation of which factor is most important is not always clear. Also, the normal soil depth zone of determination by EM is approximately 30 cm compared to the 10 cm (4 inch) zone of VWC by TMM. Volumetric water content as determined by TDR, while greatly desired in PA, has not been widely used since a deeper soil zone is required for measurements than for turfgrass, and this precludes an on-the-go system for data acquisition.

Visualizing, Characterizing, and Analyzing Spatial Mapping Results

In the field, important differences in soil and plant attributes that could determine input allocation are oftentimes difficult to distinguish. One area of a landscape could have water, fertilizer, and/or cultivation requirements that are substantially different from another location within close proximity. ArcGIS or similar software programs with extensive geospatial mapping and analytical capabilities can illustrate spatial variability using the spatial mapping information and help determine how management practices can be modified to increase efficiency and conservation. Furthermore, GIS is a powerful tool that can be used by turf managers to demonstrate to decision-makers the need for particular resources by visually illustrating the nature, degree, and implications of spatial differences so that budget priorities can be adjusted accordingly.

Field Applications

Since there may be several reasons to conduct spatial mapping, it is important to a) initially determine the specific purposes for mapping, and b) to ensure that the mapping protocols or conditions are appropriate to achieving the stated purposes (6, 7, 15). Inattention in these areas can result in nice-looking spatial maps where the results cannot be explained and are, therefore, of little practical use. For PA, site mapping of soil parameters is conducted before planting and often without regard to soil moisture status. However, for turfgrass sites, access is more flexible and soil moisture status can be altered to maximize results for each mapping purpose. Our purpose in this article is to outline field applications that are achievable based on the current level of knowledge and technology, and note some basic protocols.

Emphasis on environmental stewardship has intensified in recent years. In times of water shortages, golf courses are among the first entities criticized for wasteful water management practices. Moreover, under current economic circumstances, cost-cutting measures are being explored more extensively throughout the turfgrass industry, involving water and pumping/energy expenditures. For these reasons, a focus on practices targeted toward increasing irrigation efficiency and other water conservation strategies is gaining popularity and recognition.

The precision of site-specific irrigation is dependent upon the degree of control offered by the irrigation system. In older irrigation systems that are associated with zoned irrigation heads (multiple irrigation heads per zone), the ability to allocate variable irrigation rates to specified areas is severely limited. However, the versatility offered by newer irrigation systems capable of single-head irrigation control is much greater. Therefore, as irrigation system versatility/control increases, a higher degree of site-specific irrigation becomes possible. As advances in the irrigation head itself come to fruition, water-use efficiency and irrigation precision will increase according.

Water-use efficiency/conservation, including the energy associated with water movement, can be enhanced through at least three different types of mapping. First is to define SSMUs by mapping at field capacity to determine the spatial patterns of soil VWC, which is a good estimate of soil texture and organic matter content patterns (20, 21). Initial SSMU areas based on soil VWC may be refined to consider topography, such as degree of slope, where strongly sloped areas may require different irrigation programs (e.g. pulse irrigation cycles) to allow water to infiltrate.

Also, if VWC is mapped during dry-down from field capacity, conditions within an initial SSMU that would influence spatial plant water use in the SSMU may be identified. For example, a strongly sloped area facing the southwest may exhibit more rapid dry-down than other locations within the SSMU, even though the initial field capacity VWC is similar; or there may be shade patterns that influence ETc. Thus, in terms of water relationships, it is important to identify SSMU boundaries based on the stable landscape factors of soil texture and organic matter content (both reflected in VWC field capacity measurements) and topography. It may also be useful to identify transient factors within a SSMU, such as shifting shade patterns that may require some seasonal adjustment of irrigation scheduling.

The emphasis on soil VWC is key, since soil water characteristics are primary causes for spatial variation in crops and turfgrass (14, 20, 21). As Sadler et al (20) noted, "no prime candi-

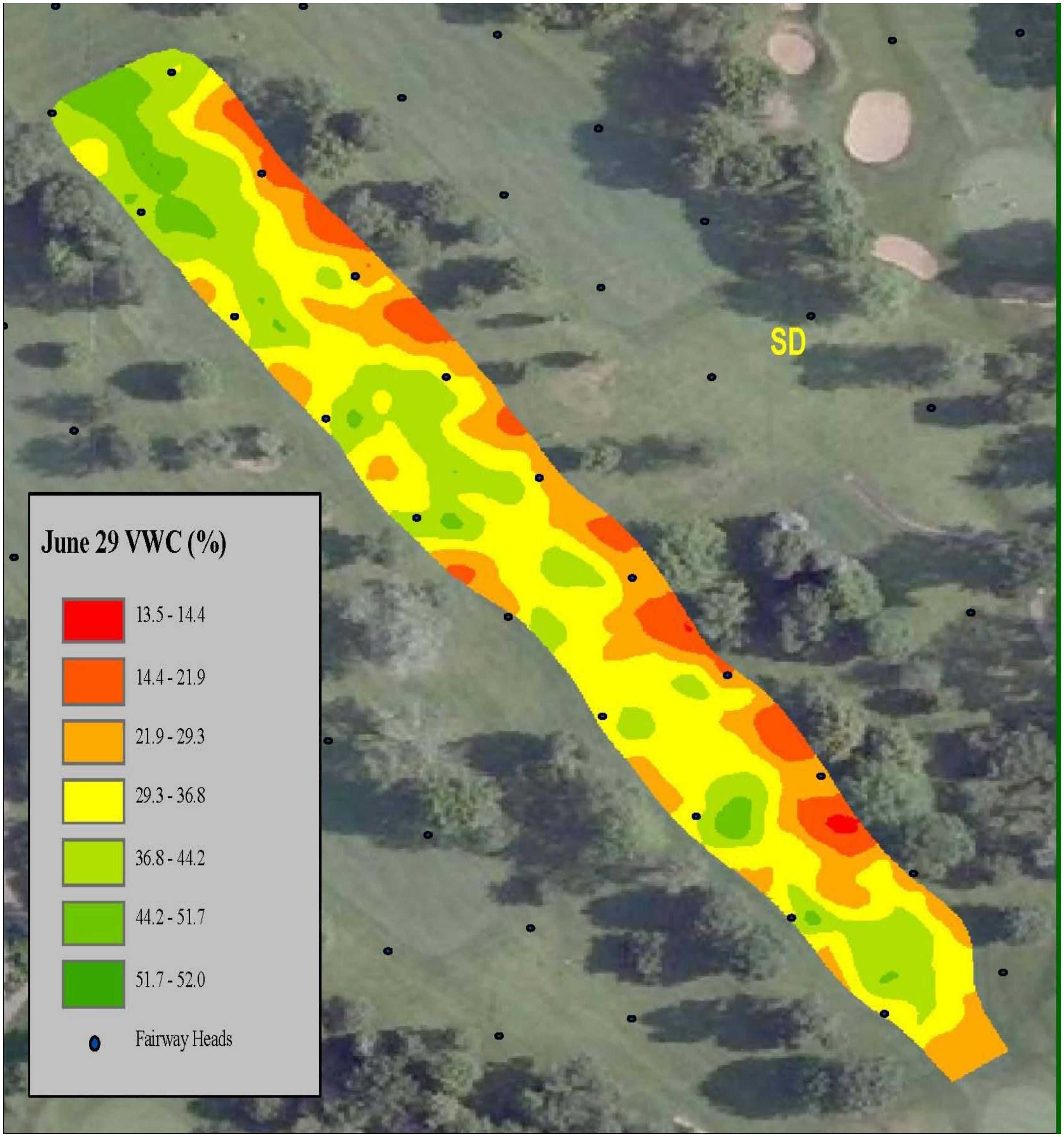

Figure 2. Spatial variability of soil VWC. Note the wind effects from right to left on spatial VWC patterns.

date other than water" exists for explaining the spatial variability of crops in a field, and that "ensuring the success of irrigated farming enterprises will require the development of reliable and more timely information on field and plant status to support the decision-making process."

Appropriate statistics provide a quantitative means to describe spatial data within a SSMU compared to the whole area or other SSMUs - e.g., measures of central tendency (mean); measures of dispersion (range, standard deviation, coefficient of variation); indications of data set shape or relative position (skewness, kurtosis) (6, 7).

A potentially useful means to characterizing spatial variability of VWC at field capacity across a whole fairway or within a SSMU is adaptation of the distribution uniformity (DU) approach used for assessing irrigation water application uniformity, but using soil VWC rather than the traditional catch-can values (10). The value of this approach is:

- Whole fairways or greens can be evaluated versus more limited areas, typical of the traditional catch-can method.

- The DU analysis based on VWC at field capacity would not only reflect the influence of irrigation system distribution, but would also determine the natural variation in VWC when at field capacity. The lower quartile distribution uniformity (DUlq) can be calculated to quantify the variability within a SSMU with a high DUlq indicating good uniformity of VWC within an SSMU. Calculation of the DUlh (lower half distribution uniformity) is commonly used as a run time modifier for irrigation scheduling, and this could be applied to a SSMU for irrigation scheduling on a more site-specific basis (10, 13).

- The 50 to 60 % of field capacity (FC) VWC value (or a value selected by the turf manager to represent the degree of surface drying allowable on their site) is a good estimate for lower VWC limit within each SSMU. The difference between the FC VWC and 50 % FC is an estimate for replacement ET within the SSMU. The actual replacement water needs may be greater if dry-down is sufficient to remove water from below the 0 to 4-inch zone, but the surface values provides an initial ball-park value on a spatial basis across the landscape.

- Spatial mapping at field capacity allows not only variability to be determined and defined within a fairway, but also across a whole golf course. Normally, a golf course may have 6 to 8 distinct SSMUs that are located across different fairways with each distinct SSMU exhibiting similar irrigation needs regardless of location.

- Once SSMUs are characterized within fairways and across a golf course, this information is a good guide for placement of in-ground soil sensors. This is a very important aspect, since where to place soil sensors in complex landscapes has been a major question - along with how to determine the fewest sensors necessary.

The second field application related to water conservation is assessing spatial soil moisture distribution by mapping under drier conditions from a "typical" irrigation cycle used on the site. This mapping would essentially be an alternative water audit method compared to the traditional catch-can method. It is essential that the irrigation system be evaluated for maximum performance before conducting the audit -- all components are operating and adjusted properly, proper pressure to the heads, appropriate scheduling, etc. With these adjustments, the irrigation system distribution capabilities can then be assessed on a wall-to-wall basis with the results reflecting true system capabilities or deficiencies (such as improper head spacing) as well as any other factor that alters spatial distribution of VWC - wind, slope, etc.

The third potential mapping that could assist in irrigation decisions would be to use routine NDVI monitoring on a site by mounting the spectral units on mobile equipment to rapidly go over a site periodically for the purpose of identifying problem areas. Usually, these may be relatively small, representing for example, a misaligned head, malfunctioning head, under/over irrigation on an area, or localized dry spot. Spatial mapping under good irrigation conditions can aid establishing benchmark NDVI values with in SSMUs. Routine NDVI maps can highlight problem areas which the turf manager can then observe for the cause.

With water-use efficiency/conservation becoming a necessity on golf courses, new concepts and approaches are needed to progress toward true site-specific management. While these PTM concepts may seem rather futuristic, in reality the technology already exists. An interesting question is "what alternatives are there in terms of actually improving irrigation system design and operation for water-use efficiency?"

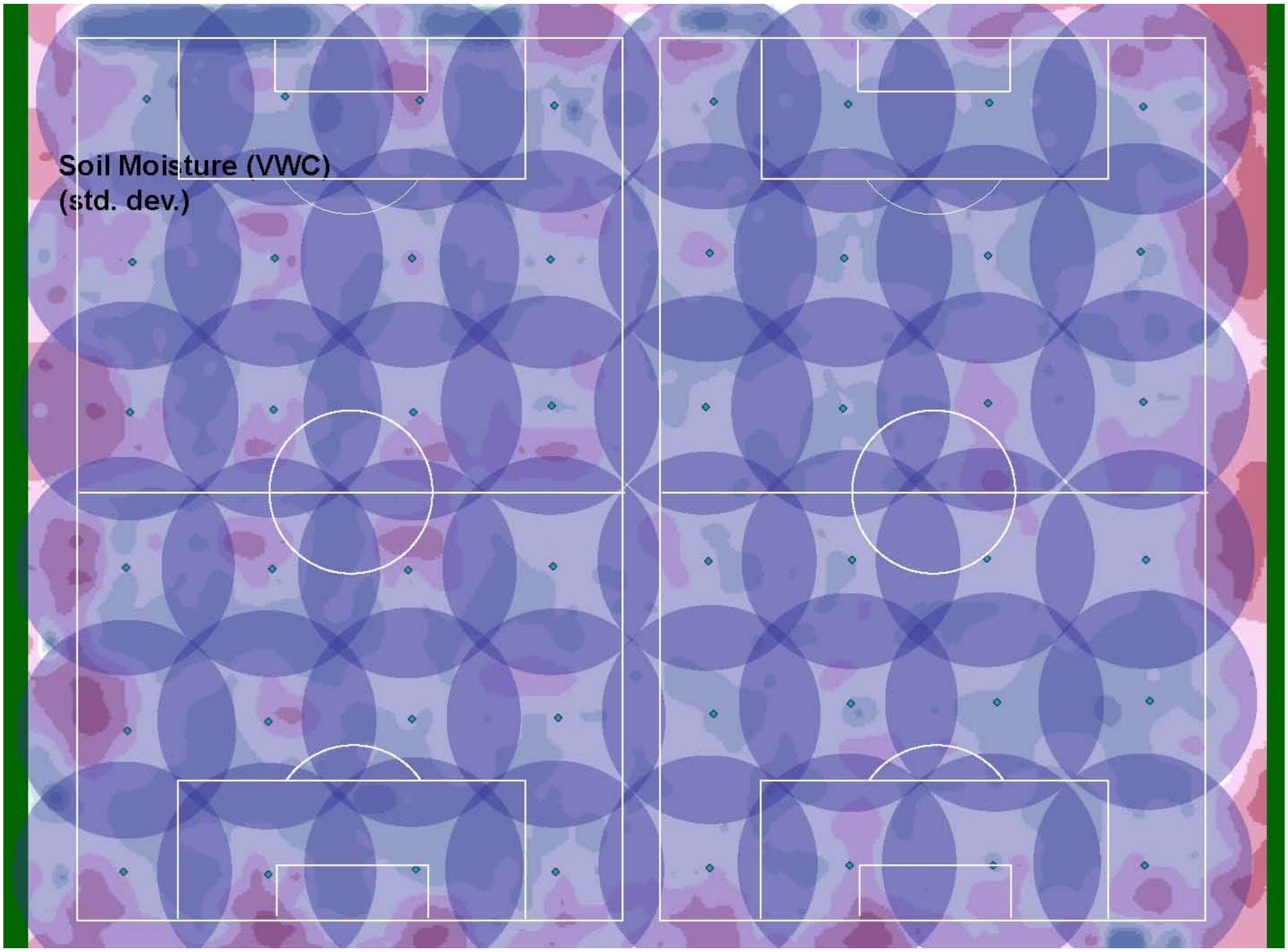

Figure 3. This is a map of soil VWC on two athletic fields but similar results could occur on golf course areas. Irrigation distribution pattern of soil VWC was mapped under drier conditions when the irrigation system uniformity could be expressed. The underlying pink areas denote the the drier sites (dark pink = driest) and are located on the edges and near sprinklers indicating poor overlap of sprinkler areas. However, this system was actually well designed but the operating pressure was too low for the design and resulted in poor overlap. This illustrates the necessity of conducting a good system evaluation to insure optimum performance of a system before assessing spatial soil VWC or the traditional catch-can water distribution uniformity evaluation. System design was for 67 feet head spacing, but the irrigation water only covered 47 feet.

Site-specific Cultivation

Soil hardness is a function of soil moisture content, percent of clay, type of clay, and soil structure (i.e. degree of soil compaction). When sites are mapped at field capacity for penetrometer resistance, the soil moisture aspect is eliminated as a factor contributing to spatial patterns. The resulting penetrometer resistance maps become useful to determine areas with the highest degree of penetrometer resistance, often due to traffic patterns. The potential then exists for site-specific cultivation rather than cultivation of whole areas as means to save labor, energy, and equipment wear. Benchmarking of penetrometer data for acceptable levels is another possibility for determining when to cultivate.

Site-specific Fertilizer and Soil Amendment Applications

The cost of fertilizers and soil amendments continue to increase, but cost-effective means of identifying spatial areas for site-specific application of these products have not been developed separate from intensive and costly grid sampling. Delineating SSMUs based on soil VWC at field capacity does offer ability to make more site-specific decisions for these products since the SSMUs reflect soil texture and organic matter differences - both which directly relate to soil cation exchange capacity (ability of soil to retain nutrients). Considerable activity in PA has been directed to the issue of efficient soil and plant sampling (3, 4, 7, 11, 14, 17, 18).

A basic tenant of soil testing is to sample similar areas together, not combining samples from unlike areas. On golf courses, this tenant is not followed; for example, golf course fairways are tested as a whole area rather than sub-areas (SSMUs) within a fairway. Simply by using SSMUs as soil sampling units offers several options for site-specific application of fertilizers and amendments. Recently, NuTec Soil, Inc. (http://www.nutecsoil.com/) applied PA principles to golf courses in the Carolinas for this very purpose. They used grid sampling (about 70 soil samples per fairway on a 50-60 ft grid); put data into ArcGIS maps for display; and used GPS guidance from the GPS tagged ArcGIS maps for site-specific fertilization. NuTec then used GPS-capable fertilizer applicators to make site-specific nutrient applications. This would be costly if there is a analysis charge for each soil sample However, the same thing can be done using the SSMUs concept with several options, such as:

- A typical fairway may have 2 to 3 SSMUs. Taking about 10 samples per SSMU zone (30 total for fairway) would give as much or more accurate data than the NuTec grid sample approach, provided the soil sample locations were selected using appropriate spatial sampling protocols. Statistical programs are available to indicate the least number of soil samples and their location in order to provide the best estimate for assessing the whole SSMU soil chemical and physical properties. Any soil physical or chemical determinations that correlate to the mapping data (especially VWC) can be spatially displayed as ArcGIS maps and used in the same fashion as the grid-based soil sampling procedure on NuTec.

- Collecting 8-10 subsamples per SSMU and combining them within an SSMU (i.e., 3 total soil samples per fairway for the example of a fairway with 3 SSMU) would give data sufficient for site-specific fertilization that would be almost as accurate as either the NuTec or the previous option. This approach would be consistent with good sampling protocols and would result in approximately 54 soil samples from an 18-hole course.

- Another version would be to obtain soil samples from all the same type of SSMU units across different fairways. Thus, if there were 8 distinct SSMU units located across fairways, only 8 soil samples would be taken from the course. This option would allow site-specific fertilization based on SSMU soil test results and would be more sound in terms of soil sampling than the current practice of combining all soil samples within a fairway when there may be major SSMU differences in a fairway.

All methods are versions of PTM, but the approach taken obviously makes a big difference on cost of sampling. Options exist for more site-specific fertilization based on the selected soil sampling scheme, but the critical component is determination of the SSMUs. These options would allow site-specific recommendations to be formulated for site-specific application, with savings possible from reduce product need, energy for application, and labor.

A recent example of considering soil spatial variability for soil nutrients is the paper by Gardner et al. (12), which reported on spatial variability of the Illinois soil N test on golf course fairways. They did not determine SSMUs to use as sampling units, but sampled on a 30-ft grid sample pattern. In this study, the amino sugar N concentrations were not highly variable and sampling by traditional means would be sufficient.

Site-Specific Management of Soil Salinity

Currently, within the turfgrass industry, mobile salinity mapping devices are under development and testing. All would map total soluble salts on a salt-affected site, but spectral devices can map plant performance, and the TDR device may be able to map VWC at the same time. Although salt retention is affected by soil type, in

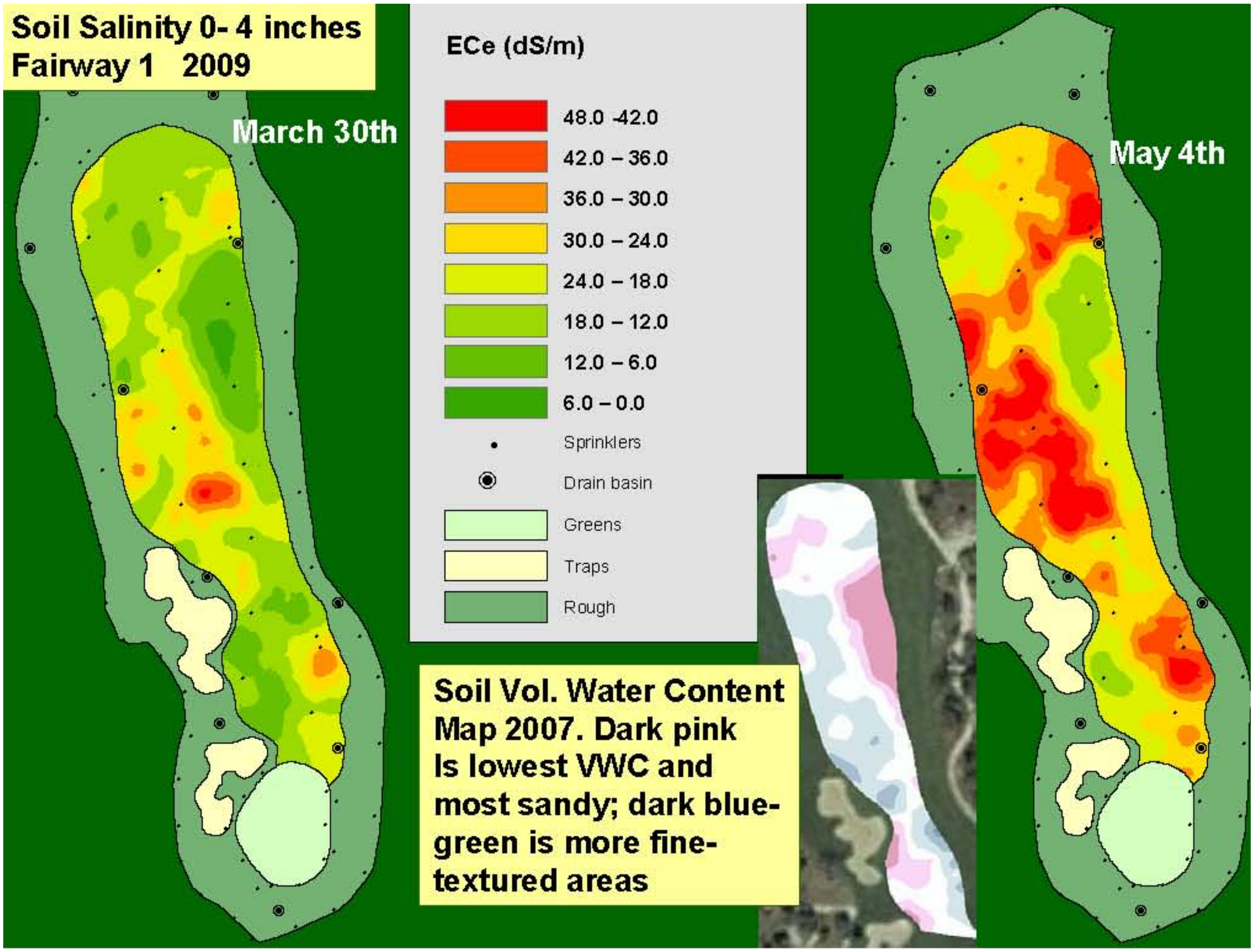

Figure 4. Salinity mapping results from March 30 and May 4 for fairway 1 at Old Collier Golf Club using experimnetal Salt Monitoring Device. ECe saturated past extract salinity is the standard means of reporting soil salinity. Seawater has a salinity level of 45 dS./m or 34,000 ppm salts. The bright red areas are approximately the same salinity as ocean water. Site is irrigated with saline water from 4,000 to 7,000 ppm during winter and spring. Soil VWC data (smal insert map) was mapped by TMM and reflets VWC in the surface 1-inch zone.

turfgrass situations, the most common source of salts is irrigation water. But, any factor affecting water distribution and the quantity of water applied (i.e. degree of leaching occurring at a specific location) are more dominant factors than soil type on spatial salinity patterns. Thus, "salinity SSMUs" often differ from the VWC at field capacity-based SSMUs discussed above. Defining spatial salinity patterns offer several management options for PTM, namely:

- Identification of spatial distribution of salinity levels is an essential requirement to do site-specific leaching, thereby conserving water compared to using the same leaching requirement over a whole site. Instead of using an estimated leaching requirement over a whole area, irrigation can be targeted to the 'hot spots.'

- With appropriate mobile salinity monitoring devices, as well as hand-held units that could determine soil salinity by soil depth, it would be possible to evaluate whether the selected leaching program was effective on a salt SMMU.

- Locations that consistently exhibit the most rapid accumulation of soluble salts would be ideal sites for soil salinity sensor placement to provide real-time data on salt accumulation and leaching.

- Sites highest in soluble salts are also those most likely to be highest in Na, which could allow for site-specific application of gypsum rather than whole-area applications.

● Additionally, sites high in soluble salts will be those receiving or retaining most of the various chemical constituents that may influence spatial fertility requirements.

Other PTM Application on Golf Courses

The field applications previously addressed were based on soil mapping, except for the NDVI routine monitoring example. The review paper by Bell and Xiong (2) present the history and current applications for optical sensing, including pest mapping. When golf courses have basic GPS delineated features, and possibly their own GPS units to define areas that exhibit a history of nematode, disease, or insect activity, this becomes another application for PTM principles.

Conclusion

Precision Turfgrass Management, based on the concepts evolved in PA over the past 25 years but with refinements specific to turfgrass situations, offers another management tool to turfgrass managers seeking a greater understanding of spatial variability of their site and the implications for resource needs. The PTM area will develop over time, with new technologies incorporated; however, there is considerable potential for this concept at the current state-of-the-science to address efficiency questions related to inputs of "where, when, and how much" on a more site-specific basis than the current practices.

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