Nitrogen remote diagnosis in a creeping bentgrass golf green

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Abbreviations: DGCI, dark green color index; SI, sufficiency index.

Abstract

Nitrogen fertilization is a key factor of the aesthetics and playability for golf greens. Nitrogen fertilization management is based on predetermined scheduled applications, set rates, or expected improvement in visual quality and green speed. As a consequence, the objective of this study was to obtain seasonal N application models (algorithms) based on remote sensing, optimizing playability and aesthetic quality. A 3-yr field study under Mediterranean conditions was conducted on an experimental ‘L-93’ creeping bent-grass (Agrostis stolonifera L.) USGA green, to examine effects of seasonal N fertilizer rates on color, clipping yields, and ball roll (green speed). The remote sensors used were a digital camera and reflectance meter (FieldScout CM1000 Chlorophyll Meter). From digital photographs, a dark green color index (DGCI) was calculated. All data were normalized (relative). For all seasons, a third-order polynomial response model was the best when using a CM1000 and a digital camera. Clipping yields and ball roll regressions were linear, increasing and decreasing when the N fertilizer rate increased, respectively. Ball roll and clipping relative values were correlated with both sensors. To fit a seasonal optimum N fertilizer rate model as a function of remote sensors and the other measured parameters, the intersection of models obtained from relative values of CM1000 and digital camera with ball roll and clipping was calculated, but ball roll was considered the most suitable. The model of the digital camera with automatic settings was less accurate and underestimated the optimum N rate. However, because the actual values of digital camera and CM1000 were correlated, converting DGCI values and applying CM1000 models enabled the obtaining of practically the same N fertilizer applications. A practical application procedure of these seasonal models for an entire golf course was also shown. Actual N recommendation applications with a quick remote diagnosis (CM1000) for creeping bentgrass golf green are feasible under similar management practices in Mediterranean environments. A digital camera can also be used successfully, but it should be better when its analysis is based on CM1000 models.

Keywords: Turfgrass; Putting green; Green speed; Bermudagrass; Precision agriculture; Normalized difference vegetation index (NDVI); Algorithm

1. Introduction

Of the essential nutrients, N is required in the greatest quantity and generally influences the golf course's green quality and growth rate most significantly (Schlossberg and Schmidt, 2007), alleviating the stress due to intensive maintenance and use (Trenholm et al., 2000). Under optimal growing conditions, N promotes a high-quality shoot density, color, and uniformity (aesthetic quality), vigour (Waddington et al., 1978), root-to-shoot ratios (Schlossberg and Karnok, 2001), recovery from damage, and overall health (Davis and Dernoeden, 2002). Nevertheless, in the same way that poor N fertilization prevents a high quality green, N over-fertilization may cause undesirable effects on green quality. Nitrogen over-fertilization increases unnecessary clipping yields and thatch (Barton and Colmer, 2006; Pease et al., 2011). Davis and Dernoeden (2002), Fu et al. (2009), and López-Bellido et al. (2010) indicated that N fertilization can increase organic matter levels in the upper 2.5 cm soil zone. According to McCarty et al. (2007), Callahan et al. (1998), and Carley et al. (2011), excessive thatch-mat layers (organic matter) in greens, and the limiting of permeability, represent one of the most difficult problems in green management. In addition, creeping bentgrass stems and roots become elevated in thick surface organic layers, and plants can be rendered more susceptible to injury from diseases and summer stresses (Turgeon, 2008). Another negative effect of over-fertilization is related to playability: ball roll distances, i.e., green speed, decrease as N fertilizer rate increases (Streich et al., 2005; Pease et al., 2011). Finally, nitrate leaching through sand-based golf greens, which have a low capacity to retain nutrients and water, can be of particular concern when considering surface and groundwater pollution (Brown, 1982; Petrovic, 1990; Quiroga-Garza et al., 2001; Keskin et al., 2004; Paré et al., 2008).

In most cases, N fertilization is based on predetermined scheduled applications, set rates, or expected improvement in aesthetic quality (Mangiafico and Guillard, 2007) based on a visual examination and on the ball roll distance measured by a stimpmeter. The classic methods to determine the N application rate have usually been either soil samples or plant tissue analysis. However, these techniques require many samples, leading to excessive labor, time, and cost (Keskin et al., 2004); furthermore, data obtained have never been translated into actual N recommendation applications. These disadvantages have reinforced that many superintendents decide on a strict N fertilization program based on previous experience and intuition. This type of management can result in over-fertilization (Mangiafico and Guillard, 2007), and, as a consequence, the negative effects aforementioned can appear, or a suboptimal N fertilization that could affect turfgrass performance negatively to shoot density, associated with wear tolerance, and color (Johnson et al., 2003; Samaranayake et al., 2008). All the same, the superintendents have a margin between excessive and poor N fertilization where they have been working based on their experience, in many cases with success.

In recent years, new techniques to determinate turfgrass N status have arisen, such as the use of colorimeters (Landschoot and Mancino, 2000), measuring soil nitrate with anion exchange membranes (Mangiafico and Guillard, 2007), digital photography (Karcher and Richardson, 2003), and assessing turf color with reflectance meters (Keskin et al., 2004; Bell et al., 2002; Kruse et al., 2006; Xiong et al., 2007; Mangiafico and Guillard, 2007; Pease et al., 2011). These new technologies can quickly and inexpensively determine the N available by indirect measures related to N content (Keskin et al., 2004) in comparison with classical methods. However, some technologies are quicker and more accurate than others. The colorimeter is somewhat more time consuming to use because it requires the clipping of leaf blades, arranging them into a stack, taking a measurement, and then repeating the process (Mangiafico and Guillard, 2005).

Moreover, Karcher and Richardson (2003) pointed out that measurement area is relatively small (<20 cm^2) and in the absence of uniform surface conditions, numerous subsample measurements would be necessary to accurately represent the color of turfgrass. Digital images quantify turf coverage and color with increased precision over more traditional evaluation methods on a relatively large turfgrass canopy (Richardson, 2001; Karcher and Richardson, 2003). However, digital camera requires more time than reflectance meters because of a subsequent image analysis with software to calculate the dark green color index (DGCI), even though Karcher and Richardson (2005) have developed a batch analysis of digital images to make the process easier. Mangiafico and Guillard (2005, 2007) suggested that reflectance meters may be the best tool to guide the optimum N fertilization of turfgrass, featuring reduced sampling time (Kruse et al., 2006). Correlations between reflectance meter measurements and visual color, visual quality, shoot density, tissue N content, clipping, or chlorophyll concentration have been found in turfgrasses (Trenholm, 1999; Rodriguez and Miller, 2000; Bell et al., 2002; Keskin et al., 2004; Kruse et al., 2006; Mangiafico and Guillard, 2005, 2006, 2007; Bremer et al., 2011), confirming that a remote sensing system can reliably guide N fertilization. However, the information provided by these sensors is unfortunately biased by factors other than N (species, cultivar, soil, water supply, mowing, disease, wear, traffic, etc.) (Johnsen et al., 2009). To overcome this obstacle, normalization (relative) procedures are used (Samborski et al., 2009).

Despite considerable research predicting the N status in greens with remote sensors, no study using a remote device has answered the question of how much N must be applied when needed. The problem is apparently that there is not a defined goal in greens as there is for grain yield in agronomic crops. Carrow et al. (2010) pointed out that in turfgrass, yield is not the goal; rather, the goal is uniform density, color, and quality. These attributes respond to irrigation, fertilizer application, cultivation, climatic stresses, traffic stress, and pests; therefore, turfgrass performance may change with management practices and over seasons. In a golf green, there are several quality goals, mainly cover and color (both related), growth (related with cover), and green speed measures by ball roll. The question is how convert readings from remote sensors in kg N ha^{-1} in order apply in site- and time-specific management (precision turfgrass management) (Carrow et al., 2010). Similar procedures employed in agronomic crops may be applied in golf greens using relative measurements to develop an algorithm. In fact, Richardson et al. (2004) stated that in turfgrasses, we cannot yet make quantitative or even qualitative translations from reflectance data without first calibrating some sort of empirical model.

The purpose of this study was to develop N fertilization models (algorithms) with two remote sensors (digital camera and reflectance meter) for creeping bentgrass USGA greens, optimizing aesthetic and playability quality for the different seasons to improve N use efficiency under Mediterranean conditions.

2. Material and methods

2.1. Site and experimental design

The study was conducted at Rabanales Turfgrass Research Facility at the University of Córdoba, Córdoba, Spain (37° 54´ N, 4° 43´ W, 135 m above sea level) on 2-yr-old 'L-93' creeping bentgrass golf green over 2008, 2009, and 2010. The green was constructed according to USGA specifications (USGA Green Section Staff, 2004). The experimental design was a randomized complete block with treatments replicated three times. Treatments were N fertilizer rates 0, 3–

5, 6–10, and 9–15 kg N ha^{-1} applied every 10 d. Within each N rate, the first value was applied in the summer and winter, and the second one was applied in the spring and fall. Plot size was 1.5 by 3.3 m. Weather-related parameters (30-yr average) for this Mediterranean area are as follows: average annual rain-fall of 584 mm (39% October–December, 37% January–March, 19% April–June, and 5% July–September); average annual evapotranspiration of 1000 mm; average duration of dry period of 4–6 months; average annual temperature of 17.5 °C; average temperature in the coldest month of 9.5 °C; average temperature in the warmest month of 27.5 °C. The total rainfall–evapotranspiration during the study years was 660–1370, 744–1475, and 1165–1316 mm in 2008, 2009, and 2010, respectively. The number of days with daily maxi-mum temperature above 35 and 30 °C (separated by dashes) were 61–102, 67–121, and 60–104 for each study year, respectively.

2.2. Green management

Nitrogen was applied as ammonium nitrate with a CO_2- pressurized backpack sprayer calibrated at 750 L ha^{-1}. The green was irrigated daily at 80% of the previous day's actual evapotranspiration. Actual evapotranspiration was estimated by adjusting the reference evapotranspiration with a crop coefficient of 0.85 as suggested by Allen et al. (1998) for turfgrasses. Reference evapotranspiration was computed by the Penman–Monteith equation. Irrigation was applied at 06:00 h to reduce the effect of wind. Irrigation run times were calculated by multiplying the treatment volume by the irrigation system precipitation rate. Catch cups were used to determine irrigation uniformity two times per year (late spring and mid summer) in order to guarantee irrigation accuracy.

The green was maintained according to standard management practices in the region. The green was mowed to a height of 4.0 mm, 6 d wk^{-1} with a Greensmaster 1000 mower (Toro Co., Bloomington, MN), and clippings were removed. Core cultivation (John Deere Aercore 800, Deere and Co., Moline, IL) and sand topdressing were performed two times yearly in the early fall and mid-spring, and the cores were removed. About 15–20 d after core cultivation, no measurements were taken and 0 kg N ha^{-1} plots received N fertilizer to facilitate their recuperation. Before recommencing the experiment, over-irrigations were applied in these plots to reduce the soil nitrate content by leaching. Plant-available P and K levels were tested and supplemented accordingly. A total of 80–110 kg P_2O_5 ha^{-1} yr^{-1} and 180–220 kg K_2O ha^{-1} yr^{-1} were applied. The fungicides applied were iprodione [3-(3,5-dichlorophenyl)- N-(1-methylethyl)2,4-dioxo-1-imadazolidine-carboximide], chlorothalonil (2,4,5,6-tetrachloroisophthalonitrile), and azoxystrobin [methyl (E)-2-(2-(6-(2-cyanophenoxy) pyrimidin- 4-yloxy)phenyl)-3-methoxyacrylate]. The insecticide was chlorpyrifos [O,O-diethyl O-(3,5,6-trichloro-2-pyridinyl) phos-phorothioate]. Moreover, sand topdressing, micronutrients, and wetting agent were applied.

2.3. Measurements

To determine aesthetic quality a FieldScout CM1000 Chloro-phyll Meter (Spectrum Technologies, Plainfield, IL) and an Olympus Camedia C-5060WZ digital camera (Olympus Optical Co., London, UK) were used. Measurements of both devices were taken on 272 dates during the experiment at approximately every 4 $\pm$ 1 d. Five readings per plot (averaged per plot) were taken with the CM1000, and one image per plot was taken with the digital camera. All measurements were taken in full sun between 12:00 and 14:00 h with the surfaces of turf leaves dry. The CM1000 readings were obtained facing away from the sun and holding it approximately 1.5 m from the turf canopy (Mangiafico and Guillard, 2007). Images were collected in automatic mode set by a researcher standing immediately next to the plot while holding the camera directly over the center of the plot ≈1.5 m above the turf canopy. Care was taken to avoid casting shadows on the turf inside the plot (Karcher and Richardson, 2003). Digital images were transferred to a personal computer and analyzed with Corel Photo-Paint (v. 11, Corel Corp., Fremont, CA) to determine the DGCI (Karcher and Richardson, 2003). The CM1000 and DGCI values were normalized to adjust for variation not associated with N nutrition. The values from all treatments were divided by the maximum value from all N rates within replication and each date to obtain a relative, normalized or sufficiency index (SI), which is expressed as a decimal (Peterson et al., 1993). The ball roll distance was measured 9 $\pm$ 1 d (total average), using a PELZmeterTM stimpmeter (PelzGolf, Independent Golf Research, Inc., Spicewood, TX). The procedure consisted of three balls rolled three times in one direction, three times in the opposite direction, and the average distance recorded. Ball roll was measured when the turf canopy was dry at midday. Clipping yield measurements were taken 13 $\pm$ 2 d (total average) with the mower aforementioned. The sampling area was 1.44 m^{-2}. The clippings were dried at 80 °C for 48 h and then weighed.

2.4. Statistical analysis

Orthogonal polynomial contrasts (linear, quadratic, cubic) were used to test the type of response to N fertilization for all data. The steps followed to obtain an algorithm were: (i) determining N fertilizer response models for measured parameters (actual and relative values); (ii) determining the optimal or maximum N fertilizer rate when models obtained from relative values were not linear; (iii) checking the existence of a relationship among remote sensor measurements and other measured parameters (i.e., ball roll distance and clipping yield); (iv) models optimization for both remote sensors, determining intersection points between their models and clipping and ball roll models obtained from relative values; and (v) relationships between DGCI and CM1000 values. Statistical analyses were performed using Version 9.1 of SAS (Statistical Analyses System, SAS Institute, 2003).

3. Results

The regression analyses performed showed for all cases that the third-order polynomial response model was the best. Other response models were significant in CM1000, but third-order polynomial models were selected due to maximum N rates were slightly lower in comparison with second-order polynomial. In this way, intersection points with ball roll response models matched with lower N rate values in order to reduce the negative effect of N rate on green speed. For digital camera the only significant response models that allowed to obtain a maximum N rate were third-order polynomial. The CM1000 values and DGCI from digital camera responded similarly, but the response to N fertilizer was much greater in magnitude in CM1000 values than in DGCI values (Fig. 1). Although, the initial hypothesis was based on two models of N fertilization, summer–winter and spring–fall, following the usual practice in southern Spain, the results showed that a different significant model could be obtained for each season. The maximum relative values varied from season to season in both devices. For the CM1000 were 10.7, 13.3, 15.8, and 16.1 kg N ha^{-1} in winter, summer, spring, and fall, respectively, whereas they were lower for the digital camera (DGCI), at 8.5, 9.6, 13.9, and 13.9 kg N ha^{-1}, respectively. For both devices, the model with least precision was in fall, showing a lower regression coefficient (Fig. 1). The CM1000 models showed a greater range of relative values than digital camera. For the CM1000, the range varies from 1 to 0.52, 0.48, 0.58, and 0.48 in spring, summer, fall, and winter, respectively, whereas for digital camera was from 1 to 0.81, 0.76, 0.81, and 0.81, respectively (Fig. 1). The actual values of digital camera and CM1000 were correlated for each season (Fig. 2). In all seasons, ball roll distance decreased when the N fertilizer rate increased (Fig. 3). In all cases, the linear response model showed the best fit. The narrowest variation between data was in winter. The fall showed the lowest variation of relative ball roll distance with N rate. Clipping yield increased with the N fertilizer rate (Fig. 4). Clipping was greatest in the spring, followed by the fall, the summer, and the winter. The response model for all seasons was linear. The ball roll distance and clipping relative values were significantly correlated with both sensors in all seasons (Table 1), a requirement needed to build an algorithm.

To fit a seasonal model as a function of remote sensors and the other measured parameter, the intersection of models obtained from relative values of CM1000 and digital camera with ball roll distance and clipping yield was calculated. Both remote sensors showed a greater intersection point, in the terms of N fertilizer rate, with relative clipping yield models (data not shown) than with the ball roll distance. Because the differences between intersection points of ball roll distance and clipping were not great and therefore did not harm clipping production, ball roll distance was considered the most important parameter with which to build the model. Moreover, this is because ball roll distance can be reduced if the N rate is higher and is the most important parameter of playability. Considering the intersection points, the SIs that optimized aesthetic and playability quality of the green, the optimum seasonal N fertilizer rates of both sensors were reduced (Table 2). For the CM1000 the optimum N rates were 6.7, 7.2, 11.1, and 11.6 kg N ha^{-1} in the winter, summer, spring, and fall, respectively. For digital camera, they were 5.8, 6.7, 8.6, and 9.6 kg N ha^{-1} for the same seasons, respectively.

The application procedure of these seasonal models is next: (i) establish an over-fertilized plot in the green where maximum values shown in Fig. 1 for CM1000 has been applied every 10 d, i.e., 10.7, 13.3, 15.8, and 16.1 kg N ha^{-1} in the winter, summer, spring, and fall, respectively; (ii) have the superintendent take readings with the FieldScout CM1000 in the over-fertilized plot and a representative sample in the rest of green at all times, averaging the readings of both areas separately; (iii) divide the green reading by the over-fertilized plot reading to obtain SI; (iv) if the SI obtained is higher than the values shown in Table 2 for the season, no N fertilizer application is necessary; (v) if the SI is lower, e.g., using a random date in spring with a SI 0.72 (Fig. 5), use the equation in Table 2 to determine the N available in the green in kg ha^{-1} of N fertilizer; (vi) finally, subtract this quantity from the optimum N fertilizer rate for the season (Table 2), obtaining the quantity to apply (Fig. 5), i.e., 6.6 kg N ha^{-1}. If the digital camera is used, DGCI must first be calculated according to Karcher and Richardson (2003). Using the data from the same date with the digital camera model, if the SI is 0.85, according to the model, 5.4 kg N ha^{-1} are necessary (Table 2).

4. Discussion

The increase of clipping yield and/or aesthetic quality and/or decrease of ball roll in greens with the N fertilizer rate showed in this work agrees with studies carried out by Keskin et al. (2004), Streich et al. (2005), Kruse et al. (2006), Koeritz and Stier (2009) and Pease et al. (2011). Most studies showed how different reflectance meters varying their readings with the N rate. Keskin et al. (2004) showed that reflectance values in the green band (520–580 nm) and the NIR band (770–1050 nm) increased as the nitrogen content increased, but they used a dual-type spectroradiometer, which is somewhat more time consuming to use because it requires clipping and subsequent measurement in a lab. Kruse et al. (2006) used a remote field portable fibreoptic spectrometer (Model S2000, Ocean Optics, Winter Park, FL), finding an effect of fertilizer N on canopy N concentration, biomass production, chlorophyll concentration, and visual quality ratings. They noted a normalized difference vegetation index variability between years, suggesting a partial least square analysis to improve the accuracy. However, they also pointed that this index might be better suited for determining the relative values of the measures. Using a CM1000, Pease et al. (2011) measured the effects of the N rate on clipping yield, ball roll, and quality. Other works mentioned in the introduction also found the same results for reflectance meter and clipping in response to N fertilizer, but they did not do so under green conditions.

Indeed, no study on golf course greens has related actual or relative values of reflectance meters with clipping, color or ball roll. Equally, digital cameras have not been used for greens in spite of high quality studies carried out by Karcher and Richardson (2003, 2005). However, the comparison of the sensitivity of models (SI range) of CM1000 and digital camera was different. The CM1000 exhibited a wider range of SI, and therefore a greater possibility of application (Table 2). This fact allows us to state the CM1000 is more accurate than digital camera. Moreover, chlorophyll meters were specifically designed to measure the reflectance in chlorophyll wavelength as a result of plant N status (Samborski et al., 2009). According to Lebourgeois et al. (2008), the acquisition of digital images performs with automatic settings has generally too low accuracy due to suffer from signal distortions. They suggested cameras have to be modified and settings have to be specifically adjusted. This could be the reason for differences in precision between both sensors. Furthermore, one of the objectives was simplified, so as possible, the superintendents work, in such a way as, they do not need a great knowledge about photography. Moreover, digital camera requires more time for the subsequent image analysis. However, in order to correct the difference between both sensors, DGCI values can be converted to CM1000 values by the equations in Table 2 and apply CM1000 models. If we take up again the example of Section 3, we obtain SI is 0.73, and 6.4 kg N ha^{-1} is the necessary application according to the CM1000 model, i.e., the result is practically the same.

Even though, the CM1000 was more accurate than the digital camera, and because actual DGCI values can be converted to a CM1000 index and obtain results similar to those using CM1000 models, digital cameras are not worthless for this purpose. Although, it takes more time and the application of this approach is limited because the SI range is smaller (Table 2). Using digital camera models, the evaluated N application and color are lower, but ball roll is likely to be greater. However, these results will be enough to satisfy the color perception of golfers, and reduces nitrate leaching, and this approach can reduce costs. When Karcher and Richardson (2003) developed a method to use a digital camera to determinate turfgrass quality, evaluating many camera settings. In this work, the digital camera was used in a fully automatic mode, and the results are satisfactory, making the measurement process easier for the superintendent. Today, most digital cameras have great resolution, and their sensitivity is much more than that of the human eye. We do not dismiss that, in the future, an iPhone application can be developed to take a photograph and immediately obtain the quantity of N fertilizer to be applied to greens.

These models have been developed based on “spoon feeding” because sand-based golf greens have a low capacity to retain N, and nitrate leaching can be significant (Paré et al., 2008). Our experience using these models has shown us that the range of days between applications is from 8 to 13, depending on the season, irrigation, and rainfall events. Therefore, superintendents must not prolong the time between applications because quality could be affected significantly, and the application rate might be too high, reducing N fertilizer use efficiency and increasing the risk of nitrate leaching (Petrovic, 1990). In fact, sometimes after 8 d, the model can recommend a low application about 1 kg N ha^{-1}; in these cases, they should delay the application to maximize economic profitability. Therefore, the timing frequency should be about 10 d. This follows a study by Bowman (2003), who pointed out that the method of using frequent/light fertilizer applications optimizes plant health and nutrient recovery. A specific model of N fertilization for each season was emphasized by Mangiafico and Guillard (2006), who showed that critical values for each date may be retained to determine seasonal or environmental effects on critical values. According to Schlossberg and Schmidt (2007) increased clipping yield is often an undesirable effect of increased N fertility on golf greens, as decreasing ball roll distance is a function of shoot growth. Green speed results shown by Pease et al. (2011) also reinforce the use of ball roll rather than clipping to develop the models. They pointed out that differences in ball roll distances between N rates have practical significance to golfers.

An issue that arises is what happens if a superintendent uses a different N fertilizer source or has another cultivar. Pease et al. (2011) showed the highest reflectance values with ammonium sulphate, ammonium nitrate, and urea. On the other hand, Schlossberg and Schmidt (2007) indicated that the form of N had little influence on moderate levels of clipping yield. Moreover, Davis and Dernoeden (2002) showed after testing 9 types different fertilizers that no N source was consistently associated with higher levels of soil microbial activity, so we can deduce that the N fertilizer source does not modify N available for the plant. Nevertheless, Pease et al. (2011) found that the N source had a significant effect on ball roll in a 1 of 2 yr study, with urea treatments producing a lower ball roll distance than all other N sources. In any case, the N fertilizer source seems not to have an important effect. In relation with the cultivar used, if we speak in terms of actual values, obviously, there will be differences, but for relative values, the most important differential is between the over-fertilized plot value and green value. This differential tends to be constant in most cases, as has been demonstrated in agronomic crops in a literature review conducted by Samborski et al. (2009). However, potential sources of error, such as genotype, water status, irradiance, disease and pests, should be researched specifically for golf greens to resolve any doubts. Obviously, a right irrigation management is basic to use the models due to an over-irrigation could affect N available and, as a consequence, sensor readings.

These N fertilization models based on remote sensing follow and contribute to the practical development of the concepts and challenges proposed by Carrow et al. (2010) regarding precision turfgrass management as inspired by precision agriculture. Therefore, these models enhance the efficiency, sustainability and economic benefits of N fertilization in golf greens. Although Carrow et al. (2010) studied a fairway, our approach with regard to the number of site-specific green management units per golf course does not differ significantly from their proposal. They recommended that a typical golf course have 4–6 or more distinct fairway site-specific management units that are scattered across a golf course with 2–3 being located on any single fairway. Obviously, a golf green must not be divided in management units due to its small area and the soil homogeneity. A reasonable balance between site-specific management units and working time to manage them must thus be achieved to maximize economic profitability.

For the application of these models in a golf course, we suggest the following protocol: (i) take measurements with the remote sensor of the variability within and between greens; (ii) establish a reasonable number of site-specific green management units, e.g., 3–5 in an 18-hole golf course; (iii) establish reference or over-fertilized plots in one green for each site-specific green management unit; (iv) the reference plot area may be about 1 $\times$ 1 m or lightly smaller; (v) the reference plot area must be moved within a green or to another green every season to avoid negative effects of N over-fertilization; (vi) before using a new reference plot, this must be previously over-fertilized across at least 20 d to reach maximum values with the remote sensor; (vii) the superintendent should take measurements every 5–10 d.

5. Conclusions

All of the previous studies on remote sensor use in turfgrass focused more on measurement considerations than on the actual N recommendation applications. This is the first time that quick N remote diagnosis for golf green is developed, and this approach enables avoiding strict N fertilization programs or mere intuitive approaches using visual quality and ball roll distance measurements. The FieldScout CM1000 Chlorophyll Meter can be used to determine the actual amount of N needed to optimize playability (green speed) and aesthetic quality in a creeping bentgrass (cv. L-93) USGA green under similar management practices in Mediterranean environments. A digital camera with automatic settings can also be used by DGCI, but because it is less accurate, the best way is to convert actual DGCI values to CM1000 values and apply the models derived from this sensor. Future research is necessary to develop similar models on other climate and management conditions.

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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration. In: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56. FAO-Food and Agriculture Organization of the United Nations, Roma.

Barton, L., Colmer, T.D., 2006. Irrigation and fertiliser strategies for minimizing nitrogen leaching from turfgrass. Agric. Water Manage. 80, 160–175.

Bell, G.E., Martin, D.L., Stone, M.L., Solie, J.B., Johnson, G.V., 2002. Turf area mapping using vehicle-mounted optical sensors. Crop Sci. 42, 648–651.

Bowman, D.C., 2003. Daily vs. periodic nitrogen addition affects growth and tissue nitrogen in perennial ryegrass turf. Crop Sci. 43, 631–638.

Bremer, D.J., Lee, H., Su, K., Keeley, S.J., 2011. Relationships between normalized difference vegetation index and visual quality in cool-season turfgrass: II factors affecting NDVI and its component reflectances. Crop Sci. 51, 2219–2227.

Brown, K.W., 1982. Nitrogen source effect on nitrate and ammonium leaching and runoff from greens. Agron. J. 74, 947–950.

Callahan, L.M., Sanders, W.L., Parham, J.M., Harper, C.A., Lester, L.D., McDonald, E.R., 1998. Cultural and chemical controls of thatch and their influence on rootzone nutrients in a bentgrass green. Crop Sci. 38, 181–187.

Carley, D.S., Goodman, D., Sermons, S., Shi, W., Bowman, D., Miller, G., Rufty, T., 2011. Soil organic matter accumulation in creeping bentgrass greens: a chronosequence with implications for management and carbon sequestration. Agron. J. 103, 604–610.

Carrow, R.N., Krum, J.M., Flitcroft, I., Cline, V., 2010. Precision turfgrass management: challenges and field applications for mapping turfgrass soil and stress. Precis. Agric. 11, 115–134.

Davis, J.G., Dernoeden, P.H., 2002. Dollar spot severity, tissue nitrogen, and soil microbial activity in bentgrass as influenced by nitrogen source. Crop Sci. 42, 480–488.

Fu, J., Dernoeden, P.H., Murphy, J.A., 2009. Creeping bentgrass color and quality, chlorophyll content, and thatch–mat accumulation responses to summer coring. Crop Sci. 49, 1079–1087.

Johnsen, A.R., Horgan, B.P., Hulke, B.S., Cline, V., 2009. Evaluation of remote sensing to measure plant stress in creeping bentgrass (Agrostis stolonifera L.) fairways. Crop Sci. 49, 2261–2274.

Johnson, P.G., Koenig, R.T., Kopp, K.L., 2003. Nitrogen, phosphorus, and potassium responses and requirements in calcareous sand greens. Agron. J. 95, 697–702.

Karcher, D.E., Richardson, M.D., 2003. Quantifying turfgrass color using digital image analysis. Crop Sci. 43, 943–951.

Karcher, D.E., Richardson, M.D., 2005. Batch analysis of digital images to evaluate turfgrass characteristics. Crop Sci. 45, 1536–1539.

Keskin, M., Dodd, R.B., Han, Y.J., Khalilian, A., 2004. Assessing nitrogen content of golf course turfgrass clippings using spectral reflectance. Appl. Eng. Agric. 20, 851–860.

Koeritz, E.J., Stier, J.C., 2009. Nitrogen rate and mowing height effects on velvet and creeping bentgrasses for low-input putting greens. Crop Sci. 49, 1463–1472.

Kruse, J.K., Christians, N.E., Chaplin, M.H., 2006. Remote sensing of nitrogen stress in creeping bentgrass. Agron. J. 98, 1640–1645.

Landschoot, P.J., Mancino, C.F., 2000. A comparison of visual vs. instrumental measurement of color differences in bentgrass turf. HortScience 35, 914–916.

Lebourgeois, V., Bégué, A., Labbé, S., Mallavan, B., Prévot, L., Roux, B.AT Can commercial digital cameras be used as multispectral sensors? A crop monitoring test, 2008. Sensors 8, 7300–7322.

López-Bellido, R.J., Lal, R., Danneberger, T.K., Street, J.R., 2010. Plant growth regulator and nitrogen fertilizer effects on soil organic carbon sequestration in creeping bentgrass fairway turf. Plant Soil 332, 247–255.

Mangiafico, S.S., Guillard, K., 2005. Turfgrass reflectance measurements, chlorophyll, and soil nitrate desorbed from anion exchange membranes. Crop Sci. 45, 259–265.

Mangiafico, S.S., Guillard, K., 2006. Anion exchange membrane soil nitrate predicts turfgrass color and yield. Crop Sci. 46, 569–577.

Mangiafico, S.S., Guillard, K., 2007. Cool-season turfgrass color and growth calibrated to leaf nitrogen. Crop Sci. 47, 1217–1224.

McCarty, L.B., Gregg, M.F., Toler, J.E., 2007. Thatch and mat management in an established creeping bentgrass golf green. Agron. J. 99, 1530–1537.

Paré, K., Chantigny, M.H., Carey, K., Dionne, J., 2008. Leaching of mineral and organic nitrogen from putting green profiles supporting various turfgrasses. Crop Sci. 48, 2010–2016.

Pease, B.W., Koeritz, E.J., Soldat, D.J., Stier, J.C., 2011. Nitrogen source and rate effects on velvet bentgrass putting green turf. Crop Sci. 51, 342–352.

Peterson, T.A., Blackmer, T.M., Francis, D.D., Schepers, J.S., 1993. Using a chlorophyll meter to improve N management. Nebguide G93-1171A. Coop. Ext. Ser., Univ. of Nebraska, Lincoln.

Petrovic, A.M., 1990. The fate of nitrogenous fertilizers applied to turfgrass. J. Environ. Qual. 19, 124–130.

Quiroga-Garza, H.M., Picchioni, G.A., Remmenga, M.D., 2001. Bermudagrass fertilized with slow-release nitrogen sources. I. Nitrogen uptake and potential leaching losses. J. Environ. Qual. 30, 440–448.

Richardson, M.D., 2001. Quantifying turfgrass cover using digital image analysis. Crop Sci. 41, 1884–1888. Richardson, A.D., Reeves, J.B., Gregoire, T.G., 2004. Multivariate analyses of visible/near infrared (VIS/NIR) absorbance spectra reveal underlying spectral differences among dried, ground conifer needle samples from different growth environments. New Phytol. 161, 291–301.

Rodriguez, I.R., Miller, G.L., 2000. Using a chlorophyll meter to determine the chlorophyll concentration, nitrogen concentration, and visual quality of St. Augustinegrass. HortScience 35, 751–754.

Samaranayake, H., Lawson, T.J., Murphy, J.A., 2008. Traffic stress effects on bentgrass putting green and fairway turf. Crop Sci. 48, 1193–1202.

Samborski, S.M., Tremblay, N., Fallon, E., 2009. Strategies to make use of plant sensors-based diagnostic information for nitrogen recommendations. Agron. J. 101, 800–816.

SAS Institute. 2003. SAS/STAT user’s guide. Release 9.1 ed. SAS Inst., Cary, NC.

Schlossberg, M.J., Karnok, K.J., 2001. Root and shoot performance of three creeping bentgrass cultivars as affected by nitrogen fertility. J. Plant Nutr. 24, 535–548.

Schlossberg, M.J., Schmidt, J.P., 2007. Influence of nitrogen rate and form on quality of putting greens cohabited by creeping bentgrass and annual bluegrass. Agron. J. 99, 99–106.

Streich, A.M., Gaussoin, R.E., Stroup, W.W., Shearman, R.C., 2005. Survey of management and environmental influences on golf ball roll distance. Int. Turfgrass Soc. Res. J. 10, 446–454.

Trenholm, L.E., 1999. Relationship of multispectral radiometry data to qualitative data in turfgrass research. Crop Sci. 39, 763–769.

Trenholm, L.E., Schlossberg, M.J., Lee, G., Parks, W., 2000. An evaluation of multispectral responses on selected turfgrass species. Int. J. Remote Sens. 21, 709–721.

Turgeon, A.J., 2008. Turfgrass management, 8th ed. Pearson Prentice Hall, Upper Saddle River, NJ.

USGA Green Section Staff, 2004. USGA recommendations for a method of putting green construction. USGA Green Sect. Rec. 31 (2), 1–3.

Waddington, D.V., Turner, T.R., Duich, J.M., Moberg, E.L., 1978. Effect of fertilization on Penncross creeping bentgrass. Agron. J. 70, 713–718.

Xiong, X., Bell, G.E., Solie, J.B., Smith, M.W., Martin, B., 2007. Bermudagrass seasonal responses to nitrogen fertilization and irrigation detected using optical sensing. Crop Sci. 47, 1603–1610.

Table 1
Seasonal linear correlation coefficients (r) of relative ball roll distance and clipping yield with relative FieldScout CM1000 reading and relative dark green color index (DGCI) value of digital camera.

Measurement and sensor	Season[a]			
	Spring	Summer	Fall	Winter
Ball roll distance				
FieldScout CM1000	0.87	0.87	0.79	0.81
Digital camera	0.81	0.83	0.72	0.79
Clipping yield				
FieldScout CM1000	0.87	0.85	0.75	0.88
Digital camera	0.87	0.72	0.89	0.83

[a] All correlations were significant at the 0.001 probability levels. The number of data used (n) is the same as showed in Figs. 4 and 5 for each season.

Table 2
Seasonal models to diagnose the amount of N fertilizer needed to optimize the aesthetic and playability quality in creeping bentgrass golf green. Models developed by means of remote sensors (FieldScout CM1000 and digital camera) and stimpmeter measurements. Models are based on the concept of the sufficiency index (SI) (Peterson et al., 1993). Seasonal correlations among remote sensors are also shown.

Season	Sensor and correlation	Model	Adjusted SI[a]	Optimum N rate (kg ha^{-1})
Spring	CM1000	$SI = -5 \times 10^{-5}N^3 - 3 \times 10^{-4}N^2 + 0.047N + 0.52$	0.88	11.1
	Camera	$SI = -1 \times 10^{-4}N^3 + 1.8 \times 10^{-3}N^2 + 0.008N + 0.81$	0.90	8.6
	Correlation	$CM1000 = 1310 \times DGCI - 252$	–	–
Summer	CM1000	$SI = -2 \times 10^{-4}N^3 + 1.6 \times 10^{-3}N^2 + 0.064N + 0.48$	0.89	7.2
	Camera	$SI = -4 \times 10^{-4}N^3 + 5.1 \times 10^{-3}N^2 + 0.011N + 0.76$	0.90	6.7
	Correlation	$CM1000 = 1314 \times DGCI - 266$	–	–
Fall	CM1000	$SI = -6 \times 10^{-5}N^3 + 3 \times 10^{-4}N^2 + 0.037N + 0.58$	0.90	11.6
	Camera	$SI = -7 \times 10^{-5}N^3 + 0.001N^2 + 0.013N + 0.81$	0.91	9.6
	Correlation	$CM1000 = 1369 \times DGCI - 266$	–	–
Winter	CM1000	$SI = -7 \times 10^{-5}N^3 - 0.0031N^2 + 0.091N + 0.48$	0.88	6.7
	Camera	$SI = -4 \times 10^{-4}N^3 + 0.0045N^2 + 0.001N + 0.81$	0.89	5.8
	Correlation	$CM1000 = 1631 \times DGCI - 352$	–	–

[a] Adjusted SI is the intersection among sensors and ball roll relative values N response models minus 0.05 according to Peterson et al. (1993) SI theory. The adjusted SI is obtained from the optimum N fertilizer rate (see Fig. 5).

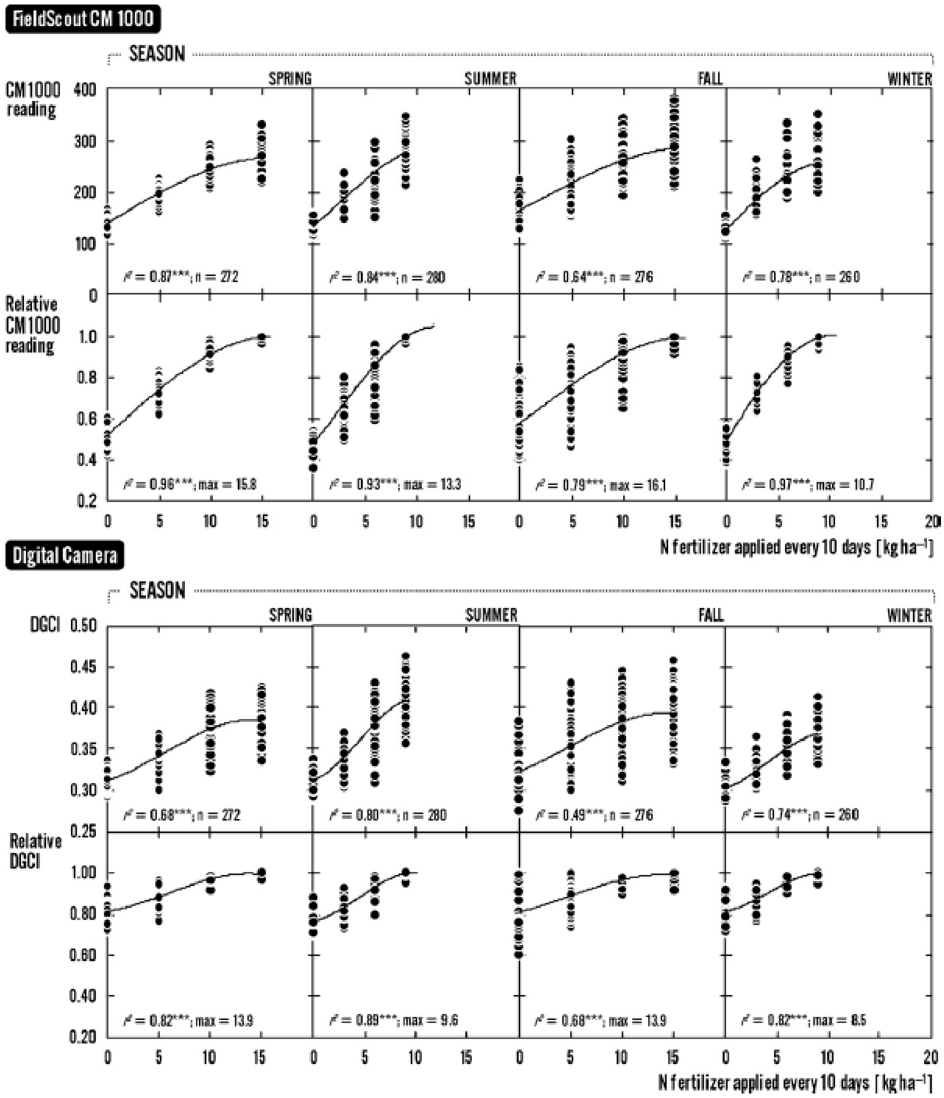

Fig. 1. Seasonal aesthetic quality response models (actual and relative values) to N fertilizer applications measured by FieldScout CM1000 and digital camera in a creeping bentgrass golf green. Digital camera values were obtained calculating dark green color index (DGCI). *** Significant at the 0.001 probability level.

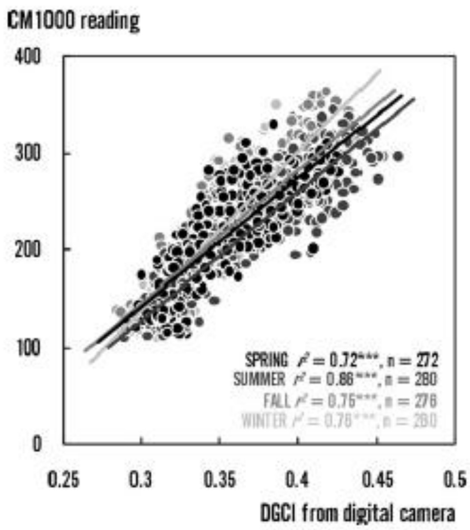

Fig. 2. Seasonal relationship between FieldScout CM1000 readings and dark green color index (DGCI) values obtained by digital camera. *** Significant at the 0.001 probability level.

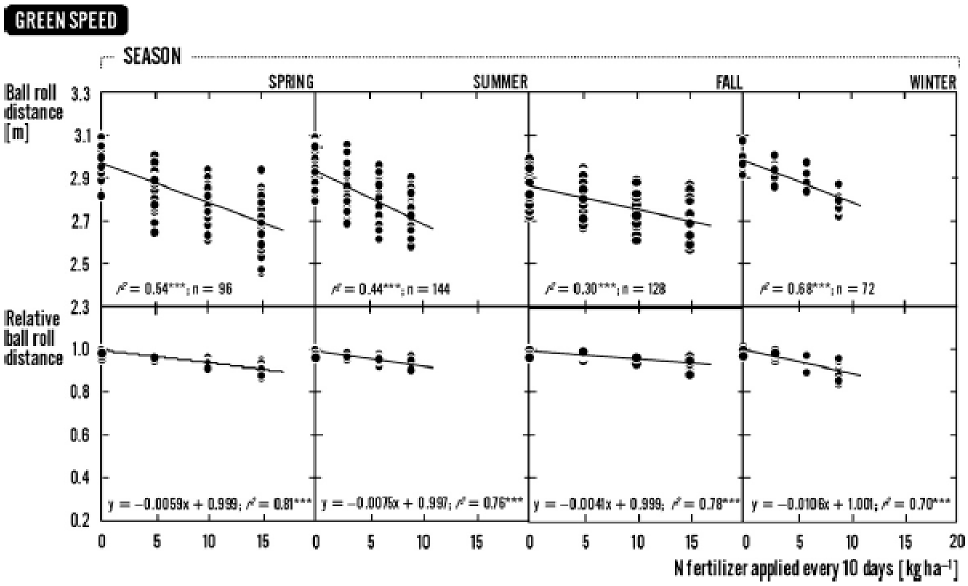

Fig. 3. Seasonal playability quality (ball roll distance) response models (actual and relative values) to N fertilizer applications measured by stimpmeter in a creeping bentgrass golf green. *** Significant at the 0.001 probability level.

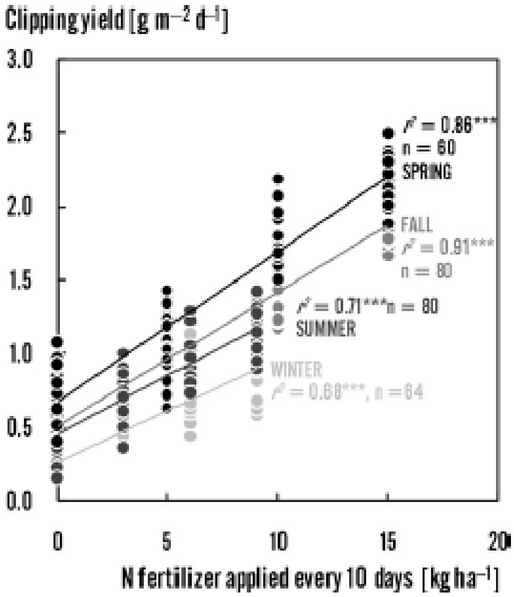

Fig. 4. Seasonal clipping yield response models to N fertilizer applications in a creeping bentgrass golf green. *** Significant at the 0.001 probability level.

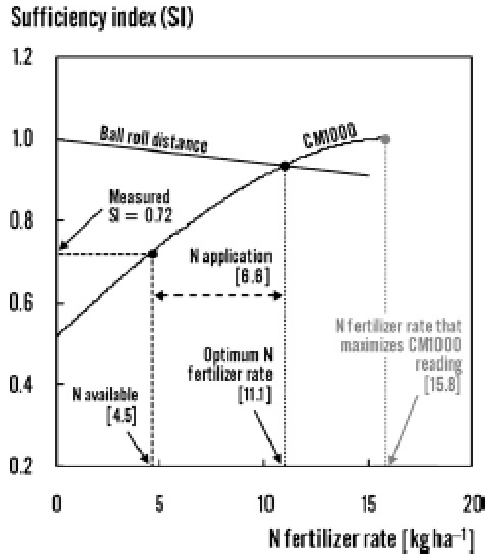

Fig. 5. Spring aesthetic and playability (ball roll) quality response model (sufficiency index or relative value) to N fertilizer applications measured by stimpmeter and FieldScout CM1000 in a creeping bentgrass golf green. Example of an N application calculation.