NUTRIENT RUNOFF FROM GOLF COURSE FAIRWAYS AFTER AERIFICATION AND DEVELOPMENT OF A PRECISION SENSING SPRAYER FOR GOLF COURSE TURF

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Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
May, 2005

NUTRIENT RUNOFF FROM GOLF COURSE

FAIRWAYS AFTER AERIFICATION AND

DEVELOPMENT OF A PRECISION

SENSING SPRAYER FOR

GOLF COURSE TURF

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ACKNOWLEDGMENTS

I would like to thank the Almighty Father, The Son, and The Holy Ghost because without them in my life, I am nothing. I would like to give my special appreciation to my beautiful wife, Teresa, for her patience, kindness, encouragement, understanding, and love during this research. Thanks also go to my parents for their support throughout my life.

I would like to thank my major advisor, Dr. Gregory E. Bell for his help, guidance, time, and friendship throughout this research. I express my sincere appreciation to my other committee members, Dr. Dennis Martin, Dr. John Solie and Dr. Bill Raun, for their time, helpful ideas, and direction during my research. I would also like to thank Dr. Dale Maronek for providing me the opportunity to continue my studies and research at Oklahoma State University.

I express my gratitude to the entire staff of the OSU Turfgrass Research Center for their assistance, direction, and kindness in installing and maintaining my research plots. I would also like to thank Kyungjoon Koh for his friendship and help throughout my program.

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INTRODUCTION

Chapters II, III, and IV of this thesis are to be submitted for publication in Crop Science, published by the Crop Science Society of America.

CHAPTER I

LITERATURE REVIEW

Literature Review

NUTRIENT RUNOFF AND TURFGRASS MANAGEMENT

There are over 16,000 golf courses in operation in the United States (National Golf Foundation, 2005). The average course contains about 12-16 ha of fairways that comprise the majority of maintained grass. Golf course fairways often border creeks, streams, ponds, lakes, and oceans. Consequently, nutrient runoff from golf course turf to surface water is an area of environmental concern. Nitrogen (N) and phosphorus (P) are the most widely used nutrients for the establishment and maintenance of golf course turf (Beard, 2002). Fertilizers allow turfgrass managers to effectively grow healthy and beautiful turfgrass stands. Fertilizers are often “watered in” after application on a golf course either through irrigation or natural rainfall. Irrigation or natural rainfall can cause surface water runoff when irrigation or precipitation rates exceed soil water infiltration rates. Ideally, the turfgrass plants would take up all applied fertilizer nutrients. Unfortunately, sudden heavy rains or irrigation system malfunctions occasionally cause water and nutrient runoff.

Nitrogen can be taken up by the plant, lost to the atmosphere, stored in the soil, leached through the soil, or lost through surface runoff (Brady, 1990). Petrovic (1990) discussed the various fates of N fertilizers applied to turfgrass. There are many factors that influence the amount of N that a turfgrass plant can use. These include temperature, moisture, amount of available N, the source and rate of N applied, mowing height, and genetic makeup of the turfgrass plant.

When more N is applied than the plant can take up, there is a potential for N loss to the environment. Nitrogen may be transported to surrounding streams or other bodies of water even if N is applied correctly. Nitrogen loss through surface runoff depends on such factors as soil moisture content, amount and timing of precipitation or irrigation, method and form of N application, slope, and various soil properties (Walker and Branham, 1992). According to Walker and Branham (1992), the greatest concentration of N in surface runoff will be found during the first significant runoff event after fertilization. Nitrogen is transported in surface runoff from turfgrass areas primarily as nitrate (NO_3^-) and ammonium (NH_4^+).

Nitrogen in surface runoff at concentrations as low as 1 mg L^{-1} may lead to eutrophication. Eutrophication can be accelerated by an overabundance of P and N nutrients in surface waters. High nutrient levels cause an abundance of algae and aquatic plant blooms that deplete oxygen in the water body and may cause fish kills. High NO_3^- levels in drinking water are also a human health hazard. The United States Environmental Protection Agency (USEPA) has established a drinking water standard of 10 mg L^{-1} for NO_3-N (USEPA, 1976).

Generally, about 99% of the P in soils is unavailable for plant growth because less than 1% of soil P is in the soluble or available form for plant uptake (Brady, 1990). The availability of P depends on the following: soil pH; the amount of soluble iron (Fe), aluminum (Al), and manganese (Mn) in the soil; the amount of Fe, Al, and Mn-containing minerals in the soil; the amount of calcium (Ca) and Ca minerals in the soil; the amount and rate of decomposition of

organic matter; and the microorganisms in the soil (Brady, 1990). Fertilizers are thus important as a source of plant available P. There is no significant loss of soil P due to leaching or through gaseous forms, but the addition of soluble P fertilizers increases the risk of P loss in surface runoff. Phosphorus transport in surface runoff is affected by factors including rainfall or irrigation amount, intensity and duration of rainfall or irrigation, soil moisture, soil texture, slope, fertilizer application rate, and fertilizer formulation (Walker and Branham, 1992). Walker and Branham (1992) state that P transport will be greatest following the first significant precipitation event after fertilization. The researchers agree that P in surface runoff from golf course turf areas is primarily transported as HPO_4^{2-} and $H_2PO_4^-$ which may also be called dissolved reactive phosphorus (DRP) and can contribute to eutrophication of surface waters at concentrations as low as 25 $\mu g\ L^{-1}$. Most research has focused on the reduction of P loss to surface waters because P is typically the limiting factor for eutrophication of surface waters (Sharpley et al., 2000). Research has suggested that P loss from agricultural fields may represent a large amount of P input to surface waters and therefore control of P transport to surface waters is vital to reducing eutrophication (Sharpley and Rekolainen, 1997).

FERTILIZER AND TURFGRASS MANAGEMENT

Kunimatsu et al. (1999) studied the loading rates of nutrients discharged from a golf course in Japan. Samples were taken from a stream that ran from a forested basin through the golf course. They found that an increase in nutrient

discharge from the stream was due primarily to the N, P and K applied to the golf course as fertilizer. They also found that loading rates of total N and total P on the golf course were 2.5 and 23 times greater, respectively, than those found on the forested basin.

Walker and Branham (1992) thoroughly reviewed the impact of fertilization on golf course areas. Nitrogen fertilizer is divided into two groups: quick release and slow release. Quick release N is the most soluble form of N fertilizer. Urea, ammonium nitrate, ammonium sulfate, ammonium phosphates, and potassium nitrates are examples (Turgeon, 1999). Urea is commonly applied to bermudagrass (*Cynodon* spp.) golf course fairways and contains about 46% N. Typically on a bermudagrass golf course fairway, N will be applied at a rate of 196 kg ha^{-1} yr^{-1}. Urea is highly soluble in water and N loss may occur by leaching (Petrovic, 1990), surface water runoff (Cole et al., 1997), or volatilization. Phosphorus fertilizers are primarily derived from rock phosphate. Triple superphosphate, a common fertilizer P source, is made by treating rock phosphate with phosphoric acid and contains about 46% phosphorus pentoxide (P_2O_5) or 20% P (Brady, 1990). Triple superphosphate is highly soluble in water and may be found in surface water runoff when applied to bermudagrass golf course fairways (Cole et al. 1997). Phosphorus fertilizers may be applied to bermudagrass golf course fairways at rates as high as 24.4 kg P_2O_5 ha^{-1} mo^{-1} during the growing season.

NUTRIENT RUNOFF FROM TURFGRASS

Turfgrass is effective at reducing nutrient runoff into surface waters (Krenitsky et al., 1998; Linde et al., 1995), especially if the fertilizer is “watered-in” (Shuman, 2004). However, nutrient concentrations in runoff from turf were high enough to contribute to eutrophication in previous studies (Harrison et al., 1993). Research has demonstrated that vegetative filter strips, commonly called buffers, may reduce nutrient runoff from golf course fairways (Cole et al., 1997; Moss, 2002), but in both studies nutrient concentrations were high enough to contribute to the degradation of surface water quality. Additional research is required to determine management practices that further reduce nutrient runoff from turf.

AERIFICATION

Aerification is the process of drilling, spiking or punching holes in turf and its underlying soil to alleviate soil compaction. Golf course superintendents often aerate bermudagrass fairways one or more times during the growing season. Cole et al. (1997) found that aerification of golf course buffer strips (roughs) did not affect nutrient runoff from simulated golf course fairways, but little is known about the effects of aerifying the fairway itself. Hollow-tine aerification transfers soil from beneath to above the turfgrass surface. Portions of the soil located on the surface of the turf could potentially be lost to surface runoff. The aerification holes could increase water infiltration and decrease potential nutrient runoff or could contribute to nutrient runoff by exposing nutrient-charged soil particles.

OPTICAL SENSING

Optical sensing provides an indirect and non-destructive method to measure plant nutrients. While optical sensing is a valuable tool that can be used to assess plant health, variability in plant nutrient status can exist over very short distances. Agricultural researchers recently learned that significant differences in soil test results can occur at distances less than 1 meter (Raun et al., 1998), and Solie et al. (1999) suggested that soil, plant and indirect measurements should be made at the meter or submeter level. Raun et al. (2002) conducted a study to determine the validity of using optically sensed in-season estimates of grain yield (INSEY) and a response index in winter wheat (*Triticum aestivum* L.) at the 1 m^2 level. Nitrogen use efficiency was improved by >15% when N fertilization was based on optically sensed INSEY determined for each 1 m^2 and a response index compared to traditional practices at a single N rate. Also, Raun et al. (2002) determined that variable rate N application at the 1 m^2 spatial resolution could result in an increased profit of \$30 ha^{-1} when compared with traditional single rate N applications. The use of optical sensors may help golf course managers increase or maintain adequate turfgrass quality while reducing the total amount of N fertilizer applied. Turfgrass managers are not concerned with increasing yield, but are concerned with improving or maintaining adequate turfgrass quality for their particular playing conditions.

TURFGRASS AND OPTICAL SENSING

Bell et al. (2002b) conducted a study to evaluate the use of vehicle-mounted optical sensing (VMOS) for mapping large turf areas of creeping bentgrass (*Agrostis stolonifera* L.). The VMOS was mounted on a cart and manually pushed across the turf. Results indicated that VMOS measurements that were constructed into maps using normalized difference vegetative index (NDVI) were correlated with turf response to N fertilizer and turf cover during construction or grow in. Normalized difference vegetative index relies on the spectral contrast between the near-infrared and red regions of the spectrum to measure plant status. Normalized difference vegetative index can be defined as the difference between the reflectances in the near infrared region and red regions of the spectrum normalized to the sum of these reflectances (Tucker, 1979). These maps could possibly be used to identify areas of poor fertility and/or the amount of fertilizer needed. Bell et al. (2002a) conducted a study that used VMOS of plant reflectance to evaluate turfgrass quality of tall fescue (*Festuca arundinacea* Schreb.) and creeping bentgrass. The VMOS was mounted on a utility tractor and driven at speeds between 5 to 8 km hr^{-1}. Data collection was slower with VMOS than by human evaluators because vehicle speed had to be slow for data collection but the researchers concluded that turfgrass color ratings could be reliably predicted using the VMOS system. Trenholm et al. (1999) conducted a study that used a multispectral radiometer to evaluate turf quality, turf density, percentage of shoot tissue injury, and shoot growth of seashore paspalum (*Paspalum vaginatum* Swartz) and hybrid

bermudagrass (*Cynodon dactylon* L. x *C. transvaalensis* Burtt-Davy) that were exposed to simulated wear treatments. The researchers concluded that spectral radiometry was reliable for distinguishing between wear-treated and untreated plots. Bell et al. (2004) provided some evidence that NDVI may be useful for determining turf chlorophyll content, which is highly correlated to turf N content. Therefore, NDVI may be very useful for turfgrass managers to measure turf quality and obtain an indirect measurement of turf N status.

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CHAPTER II

NUTRIENT RUNOFF FROM BERMUDAGRASS GOLF COURSE FAIRWAYS AFTER AERIFICATION

Nutrient Runoff From Bermudagrass Golf Course Fairways After Aerification

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ABSTRACT

Golf course superintendents may aerate fairways one or more times during the growing season but little is known about the relationship between soil aeration and nutrient runoff. The objective of this study was to investigate the influence of hollow-tine aerification and core removal on nutrient runoff from a bermudagrass (*Cynodon dactylon* L. [Pers.]) golf course fairway under natural rainfall conditions. Collection troughs and automated samplers were positioned at the bottom of six 12.3 x 24.4 m plots (5% slope) for surface runoff collection. Three plots received hollow-tine aerification (1.6 cm diameter tines, 7.6 cm long, and hole spacing of 6.4 cm) with core removal and three plots served as control in a randomized complete block design. Aerification and fertilizer (49 kg N ha^{-1} mo^{-1} and 24 kg P_2O_5 ha^{-1} mo^{-1}) were applied at the beginning of each month during the study. Runoff samples were collected and tested for NO_3-N, NH_4-N, and dissolved reactive phosphorus (DRP) after seven natural rainfall events. Aerification delayed runoff by 4 min but did not significantly reduce runoff volume or nutrient losses when compared to control plots. For both treatments, the total amount of applied fertilizer lost to surface runoff was extremely low (<1%). Nutrient concentrations were not statistically different between treatments and had an average concentration of 0.54 mg L^{-1} NO_3-N, 0.44 mg L^{-1} NH_4-N, and 1.20 mg L^{-1} DRP. The practice of hollow-tine aerification with core removal neither reduced nor contributed to a loss of nutrients to natural rainfall runoff.

Golf course fairways often border lakes, streams, and other water features. Nitrogen (N) and phosphorus (P) are two of the most important nutrients used for the establishment and maintenance of golf course turf (Beard, 2002). Bermudagrass (*Cynodon* spp.) is a commonly used turfgrass for golf course fairways and may be fertilized at rates as high as 49 kg N ha^{-1} mo^{-1} and 24 kg P_2O_5 ha^{-1} mo^{-1} during the growing season. Both N and P have the potential for off-site movement in surface runoff.

High nutrient levels in surface water enable an undesirable growth of algae and aquatic plants that can deplete oxygen and affect plants and animals in the area. This process is called eutrophication and can be accelerated by an overabundance of P and N in surface waters. Nitrogen is transported in water runoff from turfgrass areas primarily as nitrate-N (NO_3-N) and ammonium-N (NH_4-N) and may contribute to eutrophication at concentrations as low as 1 mg L^{-1} (Walker and Branham, 1992). Phosphorus in surface runoff from golf course turf areas is primarily transported as HPO_4^{2-} and $H_2PO_4^-$ which may also be called dissolved reactive phosphorus (DRP) and can contribute to eutrophication at concentrations as low as 25 µg L^{-1} (Walker and Branham, 1992). Many blue-green algae can assimilate atmospheric N_2. Consequently P, opposed to N, is typically the more important contributing factor for eutrophication of surface water (Sharpley et al., 2000).

Turfgrass is effective at reducing nutrient runoff (Krenitsky et al., 1998; Linde et al., 1995), especially if the fertilizer is “watered-in” (Shuman, 2004). However, nutrient concentrations in runoff from turf were high enough to

contribute to eutrophication in previous studies (Harrison et al., 1993). Research has demonstrated that vegetative filter strips, commonly called buffers, may reduce nutrient runoff from golf course fairways (Cole et al., 1997; Moss, 2002), but in both studies nutrient concentrations were high enough to contribute to the degradation of surface water quality. Additional research is required to determine management practices that further reduce nutrient runoff from turf.

Aerification is the process of drilling, spiking or punching holes in turf and its underlying soil to alleviate soil compaction. Golf course superintendents often aerate bermudagrass fairways one or more times during the growing season. Cole et al. (1997) found that aerification of golf course buffer strips (roughs) did not affect nutrient runoff from simulated golf course fairways, but little is known about the effects of aerifying the fairway itself. Hollow-tine aerification transfers soil from beneath to above the turfgrass surface. Portions of the soil located on the surface of the turf could potentially be lost to surface runoff. The aerification holes could increase water infiltration and decrease potential nutrient runoff or could contribute to nutrient runoff by exposing nutrient-charged soil particles.

The objective of this study was to investigate the influence of hollow-tine aerification and core removal on nutrient runoff from bermudagrass golf course fairways under natural rainfall conditions.

MATERIALS AND METHODS

Site Description

This research was conducted on the Oklahoma State University Turfgrass Runoff Research Site, Stillwater, OK. The soil at the site was Norge silt loam (fine-silty, mixed, active, thermic Udic Paleustolls) with a bulk density of 1.50 g cm^{-3}. The runoff site was divided into three large blocks. Each block consisted of two experimental units that measured 12.3 m wide with a uniform 5% slope that measured 24.4 m long. The site was graded and sodded with 'U-3' bermudagrass (*Cynodon dactylon* L. [Pers.]) in the summer of 1998. Plots were mowed three times a week at 1.3 cm during the growing season. Earthen berms that confined runoff to the area under investigation separated experimental units and blocks. Covered troughs collected runoff water from each experimental unit and channeled it through calibrated Parshall flumes by gravity flow. The collection troughs were made of polyvinylchloride pipe (15 cm dia.) cut in half length-wise and were mounted on wooden support posts. The posts (10 by 10 by 60 cm long) were buried in concrete below the soil frost line to stabilize the troughs. A galvanized shingle-type attachment was fixed to an aluminum angle along the bottom edge of each plot to channel runoff water into the corresponding collection trough (Cole et al., 1997). The shingle-type attachment was sealed to the soil with paraffin wax to prevent water from running beneath the trough. Stainless steel bolts supported a galvanized cover 7.6 cm above the shingle to allow runoff collection while eliminating the entry of unwanted irrigation or rainfall into the trough.

Isco 6700 portable samplers (Isco, Lincoln, NE) were secured to concrete platforms located between each experimental block. Ultrasonic Modules (Isco 710) mounted over each Parshall flume used ultrasonic reflection to measure water level. The sampler was programmed to determine water flow rate from these water level measurements based on a pre-determined calibration of each Parshall flume. A pump in each sampler provided runoff sample collection through vinyl suction line tubing (0.95 cm) fitted with a screen strainer and secured to the Parshall flume. A Rapid Transfer Device (Isco 581) enabled information transfer from samplers to a computer.

Time-domain-reflex probes were permanently buried along the slope in each experimental unit to assess soil moisture content and to help maintain antecedent soil moisture at uniform conditions prior to natural rainfall. These probes were centered within each experimental unit at 2.1, 10.2, and 18.3 m from the top of the fall line and buried 15.2 cm deep. An in-ground sprinkler-type irrigation system that delivered 51 mm h^{-1} was located along the edges of each block. Plots were irrigated as needed to maintain uniform soil moisture in each plot during the study.

Runoff Sampling Methodology

Treatments consisted of three plots (one plot per block) that were aerated with hollow-tines followed by core removal once per month and three plots that received no aerification. Fertilizer was applied to the plots as urea at 49 kg N ha^{-1} mo^{-1} and as triple superphosphate at 24 kg P_2O_5 ha^{-1} mo^{-1}. Aerification and

core removal were performed at the beginning of each month and were followed immediately by fertilization. Aerification treatments were applied in a single direction using a 9100 Greens Aerator (Toro, Bloomington, MN) with 1.6 cm diameter tines that were 7.6 cm long. Spacing between tines and aeration holes was 6.4 cm in all directions. Plots were irrigated lightly after fertilization to "water-in" the nutrient application. Time from the beginning of rainfall to the initiation of runoff was recorded for each event and runoff water samples were collected in five minute intervals for 60 min.

Analytical Procedures

Water samples were analyzed for NO_3–N and NH_4–N using colorimetric methods by automated flow injection analysis and DRP using the phosphomolybdate colorimetric procedure employed by Murphy and Riley (1962). The detection limit was 0.01 mg L^{-1} for each nutrient in the runoff water samples. The average background levels of nutrients in the natural rainfall samples were 0.58 mg L^{-1} for NO_3-N, 0.29 mg L^{-1} for NH_4-N, and 0.09 mg L^{-1} for DRP. The nutrient mass and concentrations reported in this paper are the background nutrient levels plus fertilizer losses. The actual background nutrient levels were only subtracted from the measured concentrations in collected runoff samples when the proportion of fertilizer loss from plots was determined. Seven natural rainfall events that produced measurable runoff were recorded on 14 May (15 mm), 16 May (41 mm), 10 June (19 mm), 25 June (55 mm), and 30 August in 2003 (17 mm), and on 04 March (64 mm), and 10 April in 2004 (33 mm). Runoff

water nutrient samples were collected following the first significant rainfall event after aerification each month. Therefore, no water samples were collected on 16 May and 25 June 2003. Flow data was recorded for all events.

Nutrient losses following runoff initiation were calculated by multiplying the average nutrient concentration during each sampling interval [(concentration at time 1 + concentration at time 2) / 2] by the total amount of runoff that passed through the Parshall flume during each specific 5 min sample period. The total nutrient loss for each treatment following runoff initiation was computed by adding the total amount of NO_3-N, NH_4-N, or DRP that were calculated for each 5 min sample period.

Statistical analyses were performed using SAS version 8.1 (SAS Inst., Cary, NC). Analysis of variance procedures were used to determine nutrient runoff as a function of precipitation duration for a randomized complete block design. Repeated measures analysis was performed using PROC MIXED with time as the repeated measure treatment. There was no collection date x treatment interaction so data are presented after averaging over all collection dates. A model for intra-plot variance was determined using an auto regressive variance model. All results were tested at $\alpha = 0.05$.

RESULTS AND DISCUSSION

The minimum rainfall amount required to produce runoff from fairway plots during the course of this study was 15 mm. Aerification had no significant effect on flow rate or nutrient concentration during 60 min of runoff (Figures 2.1, 2.2, and 2.3). There was no significant difference in peak runoff rate between aerated and control plots. Runoff from all plots reached an average maximum flow rate of 61.1 L min^{-1} at 25 min after runoff began. There was no significant difference in nutrient concentrations in runoff samples between aerated and control plots. The average nutrient concentrations in the runoff samples (*n*=360) were 0.54 mg L^{-1} NO_3-N, 0.44 mg L^{-1} NH_4-N, and 1.20 mg L^{-1} DRP. Less than 1% of the urea and triple superphosphate applied were lost to runoff. This was probably due to the fact that the fertilizer was “watered-in” and that rainfall did not occur for an average of 13 d following treatment. These results concur with the findings of Shuman (2004) who demonstrated that nutrient losses from bermudagrass fertilization were lowered after being “watered-in” and reduced as time between application and runoff increased. Aerification significantly delayed runoff initiation by an average of 4.1 min (Table 2.1) when compared to the control plots. The average time to initiation of runoff was 47.9 min for control plots and 52.0 min for aerated plots. This delay may be attributed to an increase in water infiltration due to aerification. However, aerification did not result in a statistically significant reduction in total nutrient loss or in a statistically significant reduction in runoff volume (Table 2.2). Average N and DRP loss from plots were 20.2 and 25.4 g ha^{-1} respectively and average cumulative runoff volume from

plots was 78493 L ha^{-1}. The maximum average nutrient concentrations for N and DRP occurred at 5 min after runoff initiation and were 1.7 and 1.5 mg L^{-1} respectively (Figures 2.1 and 2.2). There was no significant difference in nutrient concentrations at any sample time during this study. If undiluted, these maximum nutrient levels were above the minimum that are capable of enhancing eutrophication of surface waters (Walker and Branham, 1992).

Conclusions

Aeration is a common turf management practice that serves to alleviate compaction, promote new growth, and increase soil oxygen content. Using management practices similar to this study, golf course managers may aerate their fairways one or more times during the growing season without affecting nutrient losses to surface runoff.

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Figure Legends

Figure 2.1. Flow rate during 60 minutes of runoff from bermudagrass fairway plots. The results are an average of seven natural rainfall events that occurred from May 2003 to April 2004. The bars indicate the standard error interval at each collection period.

Figure 2.2. Concentration of N (NO_3-N + NH_4-N) in natural rainfall runoff from bermudagrass fairways for 60 min after runoff began. The results are an average of seven natural rainfall events that occurred from May 2003 to April 2004. The bars indicate the standard error interval at each collection period.

Figure 2.3. Concentration of dissolved reactive phosphorus (DRP) in natural rainfall runoff from bermudagrass fairway plots for 60 min after runoff began. The results are an average of seven natural rainfall events that occurred from May 2003 to April 2004. The bars indicate the standard error interval at each collection period.

Table 2.1. Average time from initiation of precipitation to the beginning of runoff for control and aerated bermudagrass fairways during seven natural rainfall events.

Treatment	n	Mean	Std error
		min	
Control	21	47.9	1.3
Aerated	21	52.0*	1.3

* significant at α = 0.05 level

Table 2.2. Cumulative volume of natural rainfall runoff from bermudagrass fairway plots for 60 min after runoff began and total mass of N (NO_3-N + NH_4-N) and dissolved reactive phosphorus (DRP) in natural rainfall runoff from bermudagrass fairway plots for 60 min after runoff began. The results are an average of seven natural rainfall events.

Treatment	n	df	Mean	Std error	Mean	Std error	Mean	Std error
			Cumulative volume		N		DRP	
			L ha^{-1}		g ha^{-1}			
Control	21		96034	33032	16.8	4.1	22.8	6.4
Aerated	21		60951 NS†	16583	23.6 NS	7.2	27.9 NS	8.7
			p Value					
Source of variation								
Treatments		1	0.1522		0.1532		0.4733	
Blocks		2						
Error		2						
Total		5						

† NS, not significant at the 0.05 level.

Figure 2.1.

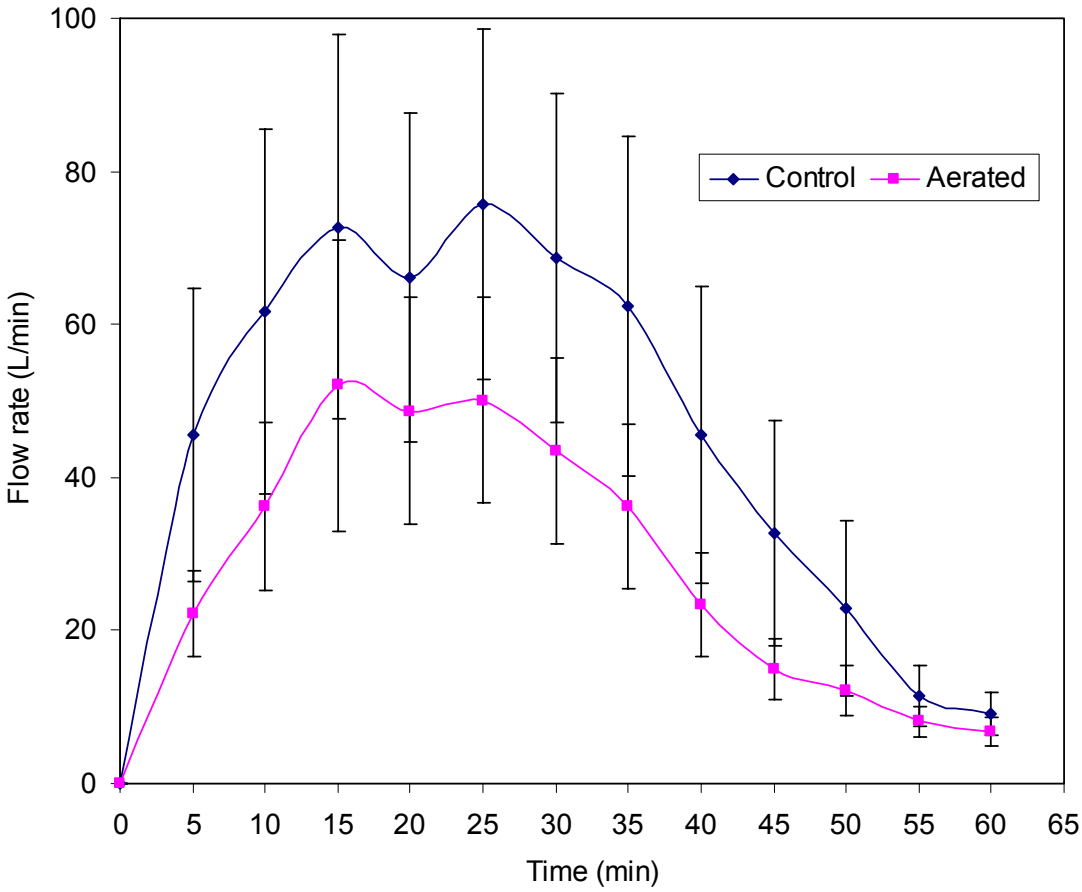

100
80
60
40
20
0
Flow rate (L/min)
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Time (min)
Control
Aerated

Figure 2.2.

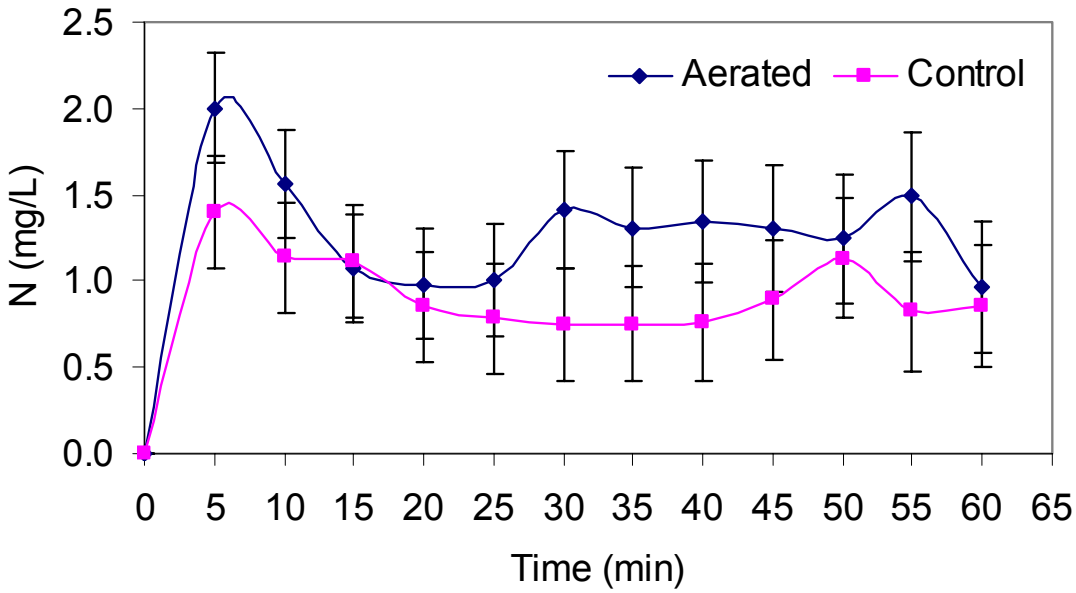
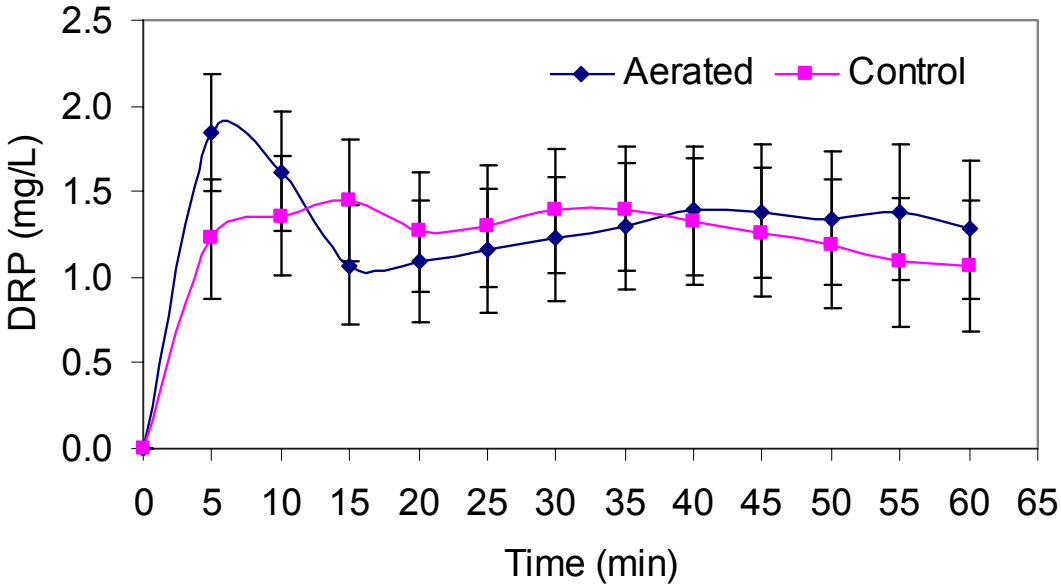

2.5
2.0
1.5
1.0
0.5
0.0
N (mg/L)
Aerated
Control
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Time (min)

Figure 2.3.


2.5
2.0
1.5
1.0
0.5
0.0
DRP (mg/L)
Aerated
Control
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Time (min)

CHAPTER III

DEVELOPMENT OF A PRECISION SENSING SPRAYER FOR THE APPLICATION OF FERTILIZER TO TURFGRASS

Development of a Precision Sensing Sprayer for the Application of Fertilizer to Turfgrass

J. Q. Moss, G. E. Bell*, J. B. Solie, M. L. Stone, D. L. Martin, and M. E. Payton

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ABSTRACT

Normalized difference vegetation index (NDVI) may be very useful for turfgrass managers to measure turf quality and obtain an indirect measurement of turf N status. The objective of this research was to develop a Nitrogen Fertilization Optimization Algorithm (NFOA) for use in a turfgrass variable rate N applicator on bermudagrass (*Cynodon* spp.) fairways and creeping bentgrass (*Agrostis stolonifera* L.) greens in Oklahoma. Plots (0.9 X 1.5 m) were established during 2004 in Stillwater, OK on a sand based 'Crenshaw' creeping bentgrass green and a Norge silt loam (fine-silty, mixed, active, thermic Udic Paleustolls) common bermudagrass (*C. dactylon* [L.] Pers.) fairway in a randomized complete block design with 10 replications. Treatments consisted of plots fertilized with 0, 12.2, 24.4, 36.6, 48.8, and 61 kg N ha^{-1}. Handheld *GreenSeeker*^{TM} sensors (NTech Industries Inc, Ukiah, CA) were used to obtain NDVI readings twice during each month of August and September. Multiple regression analysis ($NDVI_{14} = a + b_1R_{14} + b_2NDVI_0$) was performed where $NDVI_{14}$ = NDVI of turf 14 d following fertilization (Target NDVI), a = intercept, b_1 = regression coefficient for N application rate, R_{14} = N application rate in kg N ha^{-1}, b_2 = regression coefficient for NDVI prior to fertilization, and $NDVI_0$ = NDVI prior to fertilization (Current NDVI). Coefficients of determination for predicting N application rate for creeping bentgrass and common bermudagrass averaged r^2 = 0.78 and r^2 = 0.76, respectively and were highly significant (P <0.0001), positive relationships.

Golf course turf is intensively managed in order to provide acceptable playing conditions. There are currently over 16,000 golf courses in operation in the United States (National Golf Foundation, 2005). A typical Oklahoma golf course consists of bermudagrass (*Cynodon* spp.) tees, fairways, and roughs and creeping bentgrass (*Agrostis stolonifera* L.) greens. Golf course superintendents may apply as much as 49 kg N ha^{-1} mo^{-1} to the bermudagrass fairway during the growing season. Nitrogen is applied in either a granular form using a broadcast fertilizer spreader or in a liquid formulation using a spray rig. Golf course managers typically apply fertilizers containing P and K as recommended by soil test results, but the application of N is often based on a monthly rate of no more than 49 kg N ha^{-1} mo^{-1} during the growing season and no more than 245 kg N ha^{-1} yr^{-1}.

Agricultural researchers recently learned that significant differences in soil test results can occur at distances less than 1 meter (Raun et al., 1998), and Solie et al. (1999) suggested that soil, plant and indirect measurements should be made at the meter or submeter level. Raun et al. (2002) conducted a study to determine the validity of using optically sensed in-season estimates of grain yield (INSEY) and a response index in winter wheat (*Triticum aestivum* L.) at the 1 m^2 level. Nitrogen use efficiency was improved by >15% when N fertilization was based on optically sensed INSEY determined for each 1 m^2 and a response index compared to traditional practices at a single N rate. Also, Raun et al. (2002) determined that variable rate N application at the 1 m^2 spatial resolution could result in an increased profit of \$30 ha^{-1} when compared with traditional

single rate N applications. The use of optical sensors may help golf course managers increase or maintain adequate turfgrass quality while reducing the total amount of N fertilizer applied. Turfgrass managers are not concerned with increasing yield, but are concerned with improving or maintaining adequate turfgrass quality for their particular playing conditions.

Bell et al. (2002b) conducted a study to evaluate the use of vehicle-mounted optical sensing (VMOS) for mapping large turf areas of creeping bentgrass. The VMOS was mounted on a cart and manually pushed across the turf. Results indicated that VMOS measurements that were constructed into maps using normalized difference vegetative index (NDVI) were correlated with turf response to N fertilizer and turf cover during construction or grow in. Normalized difference vegetative index relies on the spectral contrast between the near-infrared and red regions of the spectrum to measure plant status. Normalized difference vegetative index can be defined as the difference between the reflectances in the near infrared region and red regions to the spectrum normalized to the sum of these reflectances (Tucker, 1979). These maps could possibly be used to identify areas of poor fertility and/or the amount of fertilizer needed. Bell et al. (2002a) conducted a study that used VMOS of plant reflectance to evaluate turfgrass quality of tall fescue (*Festuca arundinacea* Schreb.) and creeping bentgrass. The VMOS was mounted on a utility tractor and driven at speeds between 5 to 8 km hr^{-1}. Data collection was slower with VMOS than by human evaluators because vehicle speed had to be slow for data collection but the researchers concluded that turfgrass color ratings could be

reliably predicted using the VMOS system. Trenholm et al. (1999) conducted a study that used a multispectral radiometer to evaluate turf quality, turf density, percentage of shoot tissue injury, and shoot growth of seashore paspalum (*Paspalum vaginatum* Swartz) and hybrid bermudagrass (*Cynodon dactylon* [L.] Pers. x *C. transvaalensis* Burtt-Davy) that were exposed to simulated wear treatments. The researchers concluded that spectral radiometry was reliable for distinguishing between wear-treated and untreated plots. Bell et al. (2004) provided some evidence that NDVI may be useful for determining turf chlorophyll content, which is highly correlated to turf N content. Therefore, NDVI may be very useful for turfgrass managers to measure turf quality and obtain an indirect measurement of turf N status. The objective of this research was to develop a Nitrogen Fertilization Optimization Algorithm (NFOA) for use in a turfgrass variable rate N applicator on bermudagrass fairways and creeping bentgrass greens in Oklahoma.

MATERIALS AND METHODS

Plots (0.9 X 1.5 m) were established at the Oklahoma State University Turfgrass Research Center in Stillwater, OK on a sand based 'Penncross' creeping bentgrass green and a Norge silt loam (fine-silty, mixed, active, thermic Udic Paleustolls) common bermudagrass fairway in a randomized complete block design with 10 replications. The creeping bentgrass site was maintained as a putting green surface mowed at 3.8 mm. The common bermudagrass site was maintained as a golf course fairway mowed at 12.7 mm. Both the creeping bentgrass and common bermudagrass sites were maintained under well-irrigated conditions during the course of the experiment. Soil samples were taken before the study began. The creeping bentgrass site had a pH of 6.8 and a total of 146 kg N ha^{-1} was applied during the 12 months prior to the study. The common bermudagrass site had a pH of 7.0 and a total of 123 kg N ha^{-1} was applied during the 12 months prior to the study. Treatments consisted of plots fertilized with 0, 12.2, 24.4, 36.6, 48.8, and 61 kg N ha^{-1}. The experiment was performed once during August 2004 and repeated during September 2004. Handheld *GreenSeeker*^{TM} sensors (NTech Industries Inc, Ukiah, CA) were used to obtain NDVI readings twice during each month. Normalized difference vegetative index is calculated using the following equation: $NDVI = (NIR_{reflected} - Red_{reflected}) / (NIR_{reflected} + Red_{reflected})$ where, $NIR_{reflected}$ = magnitude of reflected near infrared light and $Red_{reflected}$ = magnitude of reflected red light (Red = 650 ± 10 nm; NIR = 770 ± 10 nm). The NDVI values for each plot were recorded before the experiment and the plots were blocked from lowest NDVI values to highest NDVI

values. After determining the blocking areas, the fertilizer treatments were randomly assigned to each block. Each treatment was applied using 18% N, 6% P_2O_5, and 15% K_2O (2.34% ammoniacal N, 5.72% urea N, 5.85% other water soluble N from methylene ureas, and 4.09% water insoluble N) fertilizer. NDVI readings for each plot were recorded again at 14 d following treatment. Multiple regression analysis ($NDVI_{14} = a + b_1R_{14} + b_2NDVI_0$) was performed with SAS version 8 (SAS Inst., Cary, NC) where $NDVI_{14}$ = NDVI of turf 14 d following fertilization (Target NDVI), a = intercept, b_1 = regression coefficient for N application rate, R_{14} = N application rate in kg N ha^{-1}, b_2 = regression coefficient for NDVI prior to fertilization, and $NDVI_0$ = NDVI prior to fertilization (Current NDVI).

The regression equations for creeping bentgrass and bermudagrass for August 2004 were used to predict September 2004 NDVI and these predicted values were then tested for significant differences against the measured September 2004 NDVI values.

RESULTS AND DISCUSSION

The ultimate goal of this research was to develop a NFOA for use in a variable rate nitrogen applicator for turf. Therefore, the regression equation was rearranged to solve for N application rate. Target NDVI was determined by taking the average NDVI *GreenSeeker*^{TM} sensor reading from the 48.8 kg N ha^{-1} (non N limiting) plots.

Multiple regression analysis for August 2004 creeping bentgrass nitrogen application rate resulted in the following equation (r^2 = 0.66, P < 0.0001):

N application rate$_{\text{creeping bentgrass}}$ = [(0.804 – 0.227) – 0.693 (Current NDVI)] / 0.499.

Multiple regression analysis for the August 2004 common bermudagrass nitrogen application rate resulted in the following equation (r^2 = 0.75, P < 0.0001):

N application rate$_{\text{bermudagrass}}$ = [(0.725 – 0.014) – 0.966 (Current NDVI)] / 0.275.

Multiple regression analysis for the September 2004 creeping bentgrass nitrogen application rate resulted in the following equation (r^2 = 0.90, P < 0.0001):

N application rate$_{\text{creeping bentgrass}}$ = [(0.807 – 0.363) – 0.484 (Current NDVI)] / 0.148.

Multiple regression analysis for the September 2004 common bermudagrass nitrogen application rate resulted in the following equation (r^2 = 0.76, P < 0.0001):

N application rate$_{\text{bermudagrass}}$ = [(0.738 – 0.181) – 0.680 (Current NDVI)] / 0.182.

There was a significant date x treatment interaction, therefore the data for each month are presented separately. For both creeping bentgrass and bermudagrass, there was a significant N response among treatments (Table 3.1). The August 2004 equation was not a good predictor of measured September 2004 NDVI values for creeping bentgrass or bermudagrass (Table 3.2). This could be due to the warmer average daytime and nighttime temperatures experienced during September 2004 compared to August 2004. The average high and low temperature at the site during August 2004 was 28.6 and 12.4 C respectively whereas the average high and low temperature at the site during September 2004 was 31.7 and 18.3 C respectively.

Conclusions

The results indicate that under well-irrigated conditions, monthly NDVI readings from the *GreenSeeker*™ sensors may be very useful for estimating N application rate required to maintain creeping bentgrass greens and bermudagrass fairways. These sensors could be mounted on a utility spray vehicle and used on-the-go as a variable rate N applicator to maintain healthy turf by applying prescribed rates in areas as small as 0.6 m^2. Target NDVI readings could be obtained monthly by maintaining a non N limiting plot of turf. Under similar management practices as described in this study, the preliminary NFOA would be as follows:

1. Determine the target NDVI (average NDVI from non N limiting plot of turf) using a handheld *GreenSeeker*™ sensor,
2. Use the appropriate monthly N application rate regression

equation for creeping bentgrass or bermudagrass.

Currently, a turfgrass manager would need a study area, a handheld *GreenSeeker*™ sensor, and would need to conduct this experiment on a monthly basis to determine the appropriate monthly N application rate regression equation. Further research is needed to determine if the NFOA and the turfgrass variable rate N applicator will provide similar turf visual and functional quality when compared to a single-rate broadcast N application.

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Table 3.1. Average normalized difference vegetative index (NDVI) values as influenced by N rate on creeping bentgrass and common bermudagrass during August and September, 2004.

N rate	Creeping bentgrass		Bermudagrass	
	Aug 2004	Sep 2004	Aug 2004	Sep 2004
kg N ha^{-1}	NDVI			
0.0	0.767c†	0.752e	0.677e	0.629d
12.2	0.800b	0.775d	0.692de	0.662c
24.4	0.800b	0.793c	0.698cd	0.693b
36.6	0.824a	0.806b	0.716c	0.699b
48.8	0.825a	0.828a	0.742b	0.734a
61.0	0.830a	0.832a	0.772a	0.739a

†Means within columns followed by the same letter are not significantly different at the 5% level.

Table 3.2. Measured versus predicted normalized difference vegetative index (NDVI) values for creeping bentgrass and common bermudagrass†.

Parameter	Creeping bentgrass	Bermudagrass
	NDVI	
	0.0 kg N ha^{-1}	
Measured	0.726	0.635
Predicted	0.757*	0.664*
Difference, %‡	-4.270	-4.567
	12.2 kg N ha^{-1}	
Measured	0.754	0.658
Predicted	0.883*	0.735*
Difference, %	-17.109	-11.702
	24.4 kg N ha^{-1}	
Measured	0.771	0.692
Predicted	1.009*	0.808*
Difference, %	-30.869	-16.763
	36.6 kg N ha^{-1}	
Measured	0.790	0.696
Predicted	1.135*	0.880*
Difference, %	-43.671	-26.437
	48.8 kg N ha^{-1}	
Measured	0.807	0.730
Predicted	1.261*	0.951*
Difference, %	-56.258	-30.274
	61.0 kg N ha^{-1}	
Measured	0.812	0.735
Predicted	1.386*	1.023*
Difference, %	-70.690	-39.184

* Significant at the 5% level.

† The regression equations for creeping bentgrass and bermudagrass for August 2004 were used to predict September 2004 NDVI and these predicted values were then tested for significant differences against the measured September 2004 NDVI values.

‡ Percentage difference between measured and predicted NDVI values [((measured-predicted)/measured) x 100].

CHAPTER IV

OPTICAL SENSING OF A CREEPING BENTGRASS PUTTING GREEN

Optical Sensing of a Creeping Bentgrass Putting Green

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ABSTRACT

Indirect measurement of tissue N through optical sensing may provide turfgrass managers with non-destructive, inexpensive, and relatively simple real time measurements of turfgrass tissue N status. The objective of this study was to determine the effect of N rate on creeping bentgrass (*Agrostis stolonifera* L.) tissue N, chlorophyll concentration, and color using the *GreenSeeker*^{TM} (NTech Industries, Ukiah, CA) handheld optical sensor. Plots (0.9 X 1.5 m) were established at the Oklahoma State University Turfgrass Research Center in Stillwater, OK on a sand based 'Crenshaw' creeping bentgrass green in a randomized complete block design with 4 replications. Treatments consisted of plots fertilized with 0, 6.1, 12.2, 24.4, 36.6, and 48.8 kg N ha^{-1}. Handheld *GreenSeeker*^{TM} sensors were used to obtain normalized difference vegetative index (NDVI) and green normalized difference vegetative index (GNDVI) readings. These values were regressed with tissue N, chlorophyll content, and visual color ratings. Linear regression of NDVI and GNDVI with tissue N from all data combined were highly significant ($P < 0.0001$), positive relationships. The strength of these relationships were $r^2 = 0.46$ for NDVI (n=576) and $r^2 = 0.26$ for GNDVI (n=288). Normalized difference vegetative index was a better indicator of creeping bentgrass tissue N and visual color than GNDVI. Normalized difference vegetative index may prove to be a useful tool for the potential of creating a variable rate N fertilizer applicator for turfgrass. The results of this study suggest that the *GreenSeeker*^{TM} sensor is an effective tool to measure turfgrass NDVI and that these NDVI readings are valuable for estimating turfgrass tissue N.

Further research is required to determine if the *GreenSeeker*™ sensor can be used on-the-go with a variable rate turfgrass N fertilizer applicator.

Creeping bentgrass golf course greens are intensively managed to provide acceptable playing conditions. Nitrogen is an essential plant element that is required for growth and is the major nutrient that affects turfgrass growth rate and color response. Turfgrass tissue N can be directly measured, but the process is destructive, expensive, and labor intensive (Raun et al., 1998). Indirect measurement of tissue N through optical sensing may provide turfgrass managers with non-destructive, inexpensive, and relatively simple real time measurements of turfgrass tissue N status.

Normalized difference vegetative index (NDVI) is calculated using the following equation: $NDVI = (NIR_{reflected} – Red_{reflected}) / (NIR_{reflected} + Red_{reflected})$ where, $NIR_{reflected}$ = magnitude of reflected near infrared light and $Red_{reflected}$ = magnitude of reflected red light (Red = 650 ± 10 nm; NIR = 770 ± 10 nm). Green normalized difference vegetative index (GNDVI) can be calculated using the following equation: $GNDVI = (NIR_{reflected} – Green_{reflected}) / (NIR_{reflected} + Green_{reflected})$ where, $NIR_{reflected}$ = magnitude of reflected near infrared light and $Green_{reflected}$ = magnitude of reflected green light (Green = 550 ± 10 nm). Plant NDVI readings are affected by factors including leaf color, chlorophyll, plant biomass, plant nitrogen content, plant disease, insect damage, and drought stress (Bell et al., 2002a). Recent research has shown that NDVI may be a useful tool for turfgrass managers to indirectly measure turf quality and turf N status (Trenholm et al., 1999, Bell et al., 2002a and 2002b). Bell et al. (2004) used a spectroradiometer connected to an enclosed sheet metal hood to measure plant reflectance on ‘Midfield’ bermudagrass (*Cynodon dactylon* L.

Pers. x *C. transvaalensis* Burtt-Davy) and 'SR1020' creeping bentgrass. The hood was fitted with an artificial light source and optically measured a 41 cm in diameter area of turf. Normalized difference vegetative index was calculated and tissue clippings were collected and analyzed for tissue N and chlorophyll concentration. The researchers found that the coefficients of determination for NDVI regressed with tissue N and chlorophyll concentration averaged $r^2 = 0.76$ and $r^2 = 0.70$ respectively. These results indicate that NDVI may be an effective tool for indirectly estimating turfgrass N status.

Raun et al. (2001) used NDVI measurements in winter wheat (*Triticum aestivum* L.) to effectively predict grain yield. Raun et al. (1998) also showed that significant differences in soil test results can occur at distances less than 1 meter, and Solie et al. (1999) suggested that soil, plant and indirect measurements should be made at the meter or submeter level. Raun et al. (2002) conducted a study to determine the validity of using optically sensed in-season estimates of grain yield (INSEY) and a response index in winter wheat (*Triticum aestivum* L.) at the 1 m^2 level. Nitrogen use efficiency was improved by >15% when N fertilization was based on optically sensed INSEY determined for each 1 m^2 and a response index compared to traditional practices at a single N rate. Also, Raun et al. (2002) determined that variable rate N application at the 1 m^2 spatial resolution could result in an increased profit of \$30 ha^{-1} when compared with traditional single rate N applications. The use of optical sensors may help golf course managers increase or maintain adequate turfgrass quality while reducing the total amount of N fertilizer applied. Turfgrass managers are

not concerned with increasing yield, but are concerned with improving or maintaining adequate turfgrass quality for their particular playing conditions.

Researchers at Oklahoma State University (Stillwater, OK) and NTech Industries (Ukiah, CA) developed the *GreenSeeker*^{TM} handheld optical sensor that can calculate plant NDVI in real time. The sensor uses light emitting diodes to generate red and near infrared light. The light generated is reflected off of the plant and measured by a photodiode located at the front of the sensor head. Because this sensor has its own light source, measurements can be made at any time during the day and NDVI data can be collected much faster than with a spectroradiometer. Once the correct turfgrass species algorithm is developed, the *GreenSeeker*^{TM} sensors could be mounted on a utility spray vehicle and used on-the-go as a variable rate N applicator to maintain healthy turf by applying prescribed rates in areas as small as 0.6 m^2. The objective of this study was to determine the effect of N rate on creeping bentgrass tissue N, chlorophyll concentration, and color using the *GreenSeeker*^{TM} handheld optical sensor.

MATERIALS AND METHODS

Plots (0.9 X 1.5 m) were established at the Oklahoma State University Turfgrass Research Center in Stillwater, OK on a sand based 'Crenshaw' creeping bentgrass green in a randomized complete block design with 4 replications. The plots were maintained as a golf course green mowed at 3.8 mm and were irrigated throughout the course of the study. Treatments consisted of plots fertilized with 0, 6.1, 12.2, 24.4, 36.6, and 48.8 kg N ha^{-1}. Water soluble fertilizer (20% N, 20% P_2O_5, 20% K_2O) was applied to each plot according to N rate with a CO_2 bicycle type research sprayer. The experiment was performed from April 2003 until September 2004. Visual turfgrass color ratings on a scale of 1 to 9 (1 = brown; 5 = yellow; 9 = dark green) were recorded. Immediately following visual ratings, handheld *GreenSeeker*^{TM} sensors were used to obtain NDVI and GNDVI readings. Immediately following the NDVI and GNDVI readings, clippings were collected from each plot with a walk behind reel mower and collection basket. These clippings were used to determine tissue chlorophyll content and tissue N. Tissue N was determined using a dry combustion analyzer (LECO, St. Josephs, MI). Tissue chlorophyll clippings were bagged, put on ice, kept in the dark, and were immediately transported to the laboratory for preparation. Tissue chlorophyll samples contained 30 mg tissue to 10 ml N,N dimethylformamide. Samples were stored in a freezer at -20°C for two days for extraction. After the extraction period, samples were taken out of the freezer and analyzed for total chlorophyll using a spectrophotometer as described by Inskeep and Bloom (1985). Visual color ratings, NDVI readings, and tissue N were

collected on 1 and 14 May, 2 and 17 June, 1 and 15 July, 1 and 15 August, 2 and 22 September, and 3 and 17 October 2003 and 3 and 15 April, 4 and 19 May, 3 and 16 June, 2 and 15 July, 5 and 17 August, and 6 and 17 September 2004. Tissue chlorophyll was collected on 1 May, 2 June, 1 August, 2 September, and 3 October 2003 and 3 April, 4 May, 3 June, 2 July, 5 August, and 6 September 2004. Green normalized difference vegetative index was recorded on 3 and 15 April, 4 and 19 May, 3 and 16 June, 2 and 15 July, 5 and 17 August, and 6 and 17 September 2004.

Linear regression analysis and least significant difference mean separation test were performed using Statistical Analysis Software version 8 (SAS Inst., Cary, NC). Results were tested at the 0.01 significance level for linear regression analysis and at the 0.05 significance level for least significant difference mean separation analysis.

RESULTS AND DISCUSSION

Average NDVI readings ranged from 0.701 to 0.795 and average GNDVI readings ranged from 0.710 to 0.765 depending on N rate (Table 4.1). Average tissue N ranged from 3.25 to 3.96 %, average chlorophyll content ranged from 7.48 to 8.07 mg g^{-1}, and average color ratings ranged from 4.5 to 7.5 depending on N rate (Table 4.1).

The relationships between N application rates and turfgrass responses during the study generally followed expected trends. Normalized difference vegetative index, GNDVI, tissue N, chlorophyll content, and visual color ratings significantly increased with increasing N application rates (Table 4.1). Linear regression of N rate with tissue N (n = 576) and chlorophyll content (n = 264) from all data combined were significant ($P < 0.01$), positive relationships (Table 4.2). The strength of these relationships were $r^2 = 0.07$ for tissue N and $r^2 = 0.03$ for chlorophyll content.

Linear regression of N rate with tissue N and chlorophyll content were significant ($P < 0.01$), positive relationships on each rating date (n = 24). The strength of these relationships ranged from $r^2 = 0.03$ to $r^2 = 0.98$ for tissue N and $r^2 = 0.07$ to $r^2 = 0.92$ for chlorophyll content (Table 4.3). During July and August 2004, the chlorophyll content of the creeping bentgrass was highly variable among plots and during August 2003 and 2004 tissue N was highly variable among plots. This was likely contributed to the fact that these times had the highest average daily temperatures (28 C) throughout the course of the study. These results suggest that creeping bentgrass N uptake and chlorophyll content

vary by month depending upon factors other than N fertilization rate. Linear regression of N rate with visual color ratings (n = 576) from all data combined was a significant ($P < 0.01$), positive relationship (Table 4.2). The strength of this relationship was $r^2 = 0.56$. Linear regression of N rate with visual color ratings was a significant ($P < 0.01$), positive relationship on each rating date (n = 24). The strength of this relationship ranged from $r^2 = 0.31$ to $r^2 = 1.00$.

Turfgrass managers often determine turfgrass nitrogen needs by visual turfgrass color evaluation and growth rate. This method for determining turfgrass N needs can be subjective and may be improved using objective NDVI measurements to estimate turfgrass N status (Bell et al., 2004). Linear regression of NDVI with tissue N (n = 576) and GNDVI with tissue N (n= 288) from all data combined were highly significant ($P < 0.0001$), positive relationships (Table 4.2). The strength of these relationships were $r^2 = 0.46$ for NDVI and $r^2 = 0.26$ for GNDVI. These results suggested that NDVI readings from the *GreenSeeker*™ sensor may be more useful for predicting tissue N than GNDVI readings. Linear regression of N rate with NDVI (n = 576) and N rate with GNDVI (n = 288) from all data combined resulted in highly significant ($P < 0.0001$), positive relationships. The strength of these relationships were $r^2 = 0.19$ for NDVI and $r^2 = 0.19$ for GNDVI. Linear regression of N rate with NDVI (n = 24) and N rate with GNDVI (n = 24) were highly significant ($P < 0.0001$), positive relationships through all rating dates (Table 4.3). The strength of these relationships ranged from $r^2 = 0.49$ to $r^2 = 0.99$ for NDVI and $r^2 = 0.37$ to $r^2 = 0.99$ for GNDVI.

Conclusions

Normalized difference vegetative index was a better indicator of creeping bentgrass tissue N and visual color than GNDVI (Table 4.2). Green normalized difference vegetative index was a better indicator of creeping bentgrass chlorophyll content (Table 4.2). Normalized difference vegetative index and GNDVI may prove to be useful tools for the potential of creating a variable rate N fertilizer applicator for turfgrass. This study supports earlier work by Bell et al. (2004) where the researchers found that NDVI and GNDVI were effective for estimating turfgrass N status and chlorophyll content. This research indicates that creeping bentgrass response to fertilization varies considerably on a month-to-month basis (Table 4.1). Handheld *GreenSeeker*™ sensors that calculate NDVI in real time provide turfgrass managers with a quick and easy method for determining plant NDVI. This study suggest that the *GreenSeeker*™ sensor is an effective tool to measure turfgrass NDVI and that these NDVI readings are valuable for estimating turfgrass tissue N. The *GreenSeeker*™ sensor has been shown to be an effective tool to predict grain yield and make in-season variable rate N applications to winter wheat (Raun et al. 2002). Further research is required to determine if the *GreenSeeker*™ sensor can be used on-the-go with a variable rate turfgrass N fertilizer applicator.

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Table 4.1. Average normalized difference vegetative index (NDVI) (*n*=96), green normalized difference vegetative index (GNDVI) (*n*=48), tissue N (*n*=96), tissue chlorophyll (*n*=44), and visual color ratings (*n*=96) from 'Crenshaw' creeping bentgrass from ratings and tissue collections from May 2003 to October 2003 and April 2004 to September 2004.

N rate	NDVI	GNDVI	Tissue N	Chlorophyll	Color
kg N ha^{-1}			%	mg g^{-1}	(1-9)†
0.0	0.701e‡	0.710d	3.25e	7.48cde	4.5f
6.1	0.728d	0.716d	3.43d	7.42e	5.1e
12.2	0.732d	0.728c	3.45d	7.45de	5.5d
24.4	0.746c	0.734c	3.64c	7.74bce	6.2c
36.6	0.767b	0.755b	3.79b	8.07a	6.8b
48.8	0.795a	0.765a	3.96a	7.94ab	7.5a

† Color ratings based on a 1-9 scale where 1 = brown, 5 = yellow, and 9 = dark green.
‡ Means within columns followed by the same letter are not significantly different at the 5% level.

Table 4.2. Coefficients of determination for linear regressions† associated with N rate (*n*=576), normalized difference vegetative index (NDVI) (*n*=576), green normalized difference vegetative index (GNDVI) (*n*=288), tissue N (*n*=576), tissue chlorophyll (*n*=264), and visual color ratings (*n*=576) from 'Crenshaw' creeping bentgrass from ratings and tissue collections from May 2003 to October 2003 and April 2004 to September 2004.

Variable		Creeping bentgrass	
Independent	Dependent	r	r^2
N rate	tissue N	.26	.07
N rate	chlorophyll	.17	.03
N rate	NDVI	.44	.19
N rate	GNDVI	.44	.19
N rate	color	.75	.56
NDVI	tissue N	.68	.46
NDVI	chlorophyll	.57	.33
NDVI	color	.62	.38
GNDVI	tissue N	.51	.26
GNDVI	chlorophyll	.73	.53
GNDVI	color	.49	.24
color	tissue N	.41	.17
color	chlorophyll	.39	.15

† All relationships were positive significant relationships at the 1% level.

Table 4.3. Coefficients of determination† for N rate‡ with: normalized difference vegetative index (NDVI) readings, green normalized difference vegetative index (GNDVI), tissue N, tissue chlorophyll, and visual color ratings by date of sampling§.

	r^2				
Date	NDVI	GNDVI¶	Tissue N	Chlorophyll#	Color††
1 May 2003	0.90	.	0.94	0.30	0.91
14 May 2003	0.88	.	0.11	.	0.91
2 Jun 2003	0.89	.	0.03	0.92	0.95
17 Jun 2003	0.71	.	0.91	.	0.92
1 Jul 2003	0.94	.	0.90	.	0.98
15 Jul 2003	0.92	.	0.75	.	0.97
1 Aug 2003	0.86	.	0.05	0.45	0.95
15 Aug 2003	0.87	.	0.44	.	0.82
2 Sep 2003	0.80	.	0.18	0.54	0.97
22 Sep 2003	0.99	.	0.52	.	0.97
3 Oct 2003	0.92	.	0.97	0.85	0.97
17 Oct 2003	0.83	.	0.63	.	0.97
3 Apr 2004	0.98	0.83	0.90	0.59	1.00
15 Apr 2004	0.98	0.90	0.92	.	0.99
4 May 2004	0.99	0.91	0.71	0.46	0.99
19 May 2004	0.92	0.92	0.98	.	0.91
3 Jun 2004	0.90	0.73	0.77	0.83	0.97
16 Jun 2004	0.94	0.86	0.77	.	0.94
2 Jul 2004	0.85	0.77	0.79	0.09	0.80
15 Jul 2004	0.49	0.37	0.43		0.91
5 Aug 2004	0.63	0.89	0.94	0.07	0.31
17 Aug 2004	0.56	0.58	0.34	.	0.85
6 Sep 2004	0.89	0.99	0.86	0.84	0.98
17 Sep 2004	0.95	0.99	0.92	.	0.95

† All relationships were positive, significant relationships at the 1% level.
‡ N rates were 0.0, 6.1, 12.2, 24.4, 36.6, and 48.8 kg N ha^{-1}.
§ n = 24 for each sampling date (6 N rates x 4 replications).
¶ GNDVI readings were recorded during each month listed in 2004.
# Chlorophyll analysis was performed at the beginning of each month listed with the exception of July 2003.
†† Color ratings based on a 1-9 scale where 1 = brown, 5 = yellow, and 9 = dark green.

VITA

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