Nitrogen and Trinexapac-ethyl Applications for Managing ‘Diamond’ Zoysiagrass Putting Greens in the Transition Zone, U.S.

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Abstract. As a result of the increasing popularity of fine-leaved zoysiagrasses on golf courses, a 2-year field study was conducted to assess ‘Diamond’ zoysiagrass [*Zoysia matrella* (L.) Merr.] putting green performance at The Cliff’s Communities Turfgrass Research Facility in Marietta, SC. Factors included four nitrogen (N) fertility rates and two trinexapac-ethyl (TE) regimes. Foliar applications of 0, 4.9, 9.8, and 14.7 kg-ha⁻¹ N were made once weekly for 7 and 15 weeks in 2009 and 2010, respectively. Trinexapac-ethyl was tank-mixed and applied weekly for 7 weeks during July to August at 0 or 0.017 kg a.i./ha totaling 0.120 kg a.i./ha for both growing seasons. Putting green performance was measured by assessing turf quality (TQ), ball roll distance (BRD), surface firmness (SF), leaf tissue nutrient concentrations, and thatch accumulation. Turfgrasses receiving 4.9 kg N/ha weekly exhibited acceptable TQ and greater SF and BRD than plots receiving 14.7 kg N/ha weekly on all rating dates in 2010 before seasonal dormancy. Trinexapac-ethyl reduced clipping yield by 15% to 43% and influenced BRD, SF, and tissue nutrient concentration across the 2-year study. Surface firmness decreased as total N input increased during the 2010 growing season and is presumably the result of an increase in leaf tissue causing a cushioned putting surface. Linear regression of thatch accumulation and SF were analyzed and found to be significant at four rating dates in 2010 indicating that as thatch organic matter increased, SF decreased. Nitrogen input for ‘Diamond’ zoysiagrass putting greens grown in the transition zone should begin at 73.5 kg-ha⁻¹/year with supplemental N applications applied as needed.

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Golf course managers in the transition zone of the United States commonly establish and manage creeping bentgrass (*Agrostis stolonifera* L.) as putting greens. However, several turfgrass species have been introduced as alternatives to cool-season putting surfaces and include: ultradwarf bermudagrasses [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burt-Davy], seashore paspalum (*Paspalum vaginatum* Swartz), and fine-leaved zoysiagrass cultivars (*Z. matrella*). *Zoysia matrella* (L.) Merr. ‘Diamond’ is a highly rhizomatous and stoloniferous vegetatively

propagated selection from Texas A&M University that has gained popularity as a result of its shade, salt and wear tolerance, slow growth rate, fine texture, winter-hardiness, and lime green color during the summer (McCarty, 2011; Qian et al., 2000; Qian and Engelke, 1999). Sladek et al. (2009) demonstrated that ‘Diamond’ zoysiagrass exhibited excellent TQ under 50% shade, outperforming other zoysiagrass varieties. The shade tolerance of ‘Diamond’ could increase its desirability for putting greens when excessive shade limits the use of ultradwarf bermudagrasses (Menchyk et al., 2012). A disadvantage of using ‘Diamond’ zoysiagrass on putting greens is its slow establishment, recovery, and growth rate. Patton et al. (2007) demonstrated that ‘Diamond’ zoysiagrass had the slowest establishment rate of *Z. matrella* varieties as a result of the difference in partitioning of dry matter to stems instead of leaves. However, Stiglbauer et al. (2009) confirmed that ‘Diamond’ zoysiagrass can be established from sprigs in one growing season and meet putting green expectations by using sprigging rates greater than 91 m⁻³·ha⁻¹ and total N input between 200 and 350 kg/ha/year in the transition zone.

TE is a commonly used plant growth regulator (PGR) for managed turf that inhibits cell elongation by inhibiting GA₂₀ to GA₁ production late in the mevalonic acid pathway (Baldwin, 2008; Fagerness et al., 2000; McCullough et al., 2007). Research has shown that PGR use enhances turfgrass quality and playability, increases ball roll, reduces mowing frequency, decreases weed pressure, improves disease resistance, reduces encroachment of other turf species, and enhances turfgrass establishment (Baldwin, 2008; Fagerness et al., 2000; McCullough et al., 2007). McCullough et al. (2007) reported that TE increased BRD on creeping bentgrass and ultradwarf bermudagrass by 25 cm over untreated turf. Shade-stressed ‘Diamond’ zoysiagrass benefited from TE use by improving carbohydrate reserves, increasing canopy photosynthesis, and enhancing TQ through a more robust root system (Qian and Engelke, 1999). Applications of TE also caused reduced vertical growth resulting in lowered clipping yields and higher levels of nonstructural carbohydrates leading to a potential increase in shade tolerance in ‘Diamond’ zoysiagrass (Qian and Engelke, 1999). Atkinson et al. (2012) demonstrated that ‘Diamond’ can be maintained with 0.013 kg a.i./ha/week TE in 60% reduced light environments over a 2-year field study. Trinexapac-ethyl applications on ‘TifEagle’ bermudagrass increased root length density, provided excellent TQ, reduced vertical growth, and did not reduce lateral regrowth and increased BRD compared with control treatments (McCarty et al., 2011).

Putting surfaces require intensive cultural management to meet quality and playability demands (Hartwiger et al., 2001; Hollingsworth et al., 2005; McCarty et al., 2007; McCullough et al., 2007; Salaiz et al., 1995). A common problem in putting green management is the accumulation of root zone organic matter and

thatch, which typically contains high lignin contents and is resistant to decay (Beard, 1973, 2002; McCarty, 2011; Turgeon, 2012). Thatch develops when the accumulation rate of organic matter from the actively growing turfgrass exceeds the rate of decomposition and can lead to problems including increased disease and insect pressure, localized dry spot, scalping, and decreased heat, cold, and drought hardness (Beard, 1973, 2002; McCarty, 2011). An accumulation of thatch negatively reduces golf course performance characteristics (i.e., BRD, SF, TQ) resulting in inconsistent and poor-quality putting surfaces. Ball roll distance is important when measuring putting green performance and can be influenced by turfgrass selection, mowing and cultivation practices, fertility and PGR application, water management, and surface rolling (McCarty, 2011). Application of N will increase turf shoot growth by producing wider and more succulent leaf blades leading to a slower putting surface (Beard, 1973). Cultural practices including excessively low mowing heights, reduced N fertilization, and irrigation can increase the BRD on putting surfaces but often conflict with sound agronomic principles (Hartwiger et al., 2001). Prolonged management of BRD by lowered height of cut (HOC) alone is unsustainable and will result in undesirable putting green performance and increased turfgrass stress. Surface firmness is also commonly factored into putting green performance. Linde et al. (2011) found a strong inverse relationship between Clegg Impact Soil Tester and TruFirm firmness values, confirming that they are both useful tools to measure SF. TruFirm is a relatively new tool that has been used by the United States Golf Association (USGA) since 2005 to measure surface firmness of putting greens and bunkers (USGA Green Section Staff, 2009). Soil volumetric water content could play an important role in SF; however, Linde et al. (2011) hypothesized that variability in SF is also the result of turfgrass species, soil texture, bulk density, thatch accumulation, and management practices.

There is a growing interest in using 'Diamond' zoysiagrass for golf course putting greens in the transition zone. However, minimal research examining the performance and management of 'Diamond' zoysiagrass putting green scenarios is available. Therefore, the primary objectives of this study was to evaluate the influence of three N input levels and TE application on 'Diamond' zoysiagrass putting green performance as measured by TQ, BRD, SF, and thatch accumulation. Second, as a result of the importance of maintaining turfgrass health and proper nutrition when managing putting greens, the treatment effects on clipping yield, N, phosphorus (P), and potassium (K) leaf tissue nutrient contents were also measured. Lastly, as a result of TruFirm being a relatively new management tool, there is a lack of research examining how management practices influence putting green surface firmness; therefore,

this research begins to address that gap in the literature.

Materials and Methods

Research was conducted from 28 July to 10 Sept. 2009 and 20 May to 25 Aug. 2010 at The Cliffs Communities Turfgrass Research Facility in Marietta, SC. 'Diamond' zoysiagrass plots measuring 0.91 m × 3.7 m were constructed according to USGA putting green specifications with an 85:15 (sand:peat) root zone overlying subsurface drainage (USGA Green Section Staff, 1993). For the duration of the growing season, the plots were mowed daily with a reel mower (Greenmaster; The Toro Company, Bloomington, IL) at 3.2 mm. During seasonal dormancy, the plots were not mowed, covered, overseeded, or painted. Granular applications of P (0N-20P-0K; Howard Fertilizer & Chemical Co., Orlando, FL) and K (0N-0P-41.5K; Harrell's LLC, Lakeland, FL) were made in July of both years at 24.4 and 48.8 kg·ha⁻¹, respectively. In 2009, seven foliar applications of 0, 4.9, 9.8, 14.7 kg N/ha ammonium nitrate were performed weekly supplying 0, 34.3, 68.6, and 102.9 kg N/ha/year for each N treatment, respectively, after the putting green was fully established. Putting green TQ and performance characteristics were recorded and analyzed during spring green-up in 2010 as a means to assess carryover effects from 2009 treatments, which were not significant. Thus, foliar N treatments began earlier in 2010 to simulate typical fertility programs of warm-season turfgrass putting surfaces in the transition zone and 15 N applications were made at the same weekly rates previously stated totaling 0, 73.5, 147, and 220.5 kg N/ha for each treatment, respectively, in 2010. Trinexapac-ethyl applied in 2009 and 2010 totaled 0.120 kg a.i./ha starting in July and ending in August. All N and TE treatments were tank-mixed and applied with a CO₂-pressurized backpack

sprayer fitted with TeeJet (Wheaton, IL) 8004VS nozzles delivering 561 L·ha⁻¹.

Weekly visual readings of TQ were performed by examining color, texture, density, and playability on a scale of 1 to 9 where 1 = dead turf, 9 = perfect turf, and greater than 6 were considered acceptable for golf course putting greens. Putting green SF was measured monthly using USGA's TruFirm, which simulates and measures the depth of golf ball impact (USGA Green Section Staff, 2009). Four SF measurements were taken at random in each plot and averaged. Thatch

Table 1. Clipping yield^a of 'Diamond' zoysiagrass as influenced by N and TE rate during 2009 and 2010.

	2009		2010	
	Aug.	Sept.	July	Aug.
Main effects	(g·m ⁻²)			
Nitrogen rate (N)				
0	5.9	1.3	2.6	1.0
4.9	5.8	1.4	3.8	2.1
9.8	5.5	1.6	5.1	3.1
14.7	5.7	1.6	6.6	4.1
LSD _{0.05}	NS	NS	0.8	0.4
TE rate (TE)				
0	6.4	1.8	4.9	3.3
0.017 kg a.i./ha	5.0	1.2	4.2	1.9
ANOVA				
Source of variation				
N	NS	NS	***	***
TE	***	**	*	***
N*TE	NS	NS	NS	***

^aClipping yield was determined by mowing a 48.3-cm strip the entire length of the plot at a height of cut of 3.2 mm. Alleys were mowed at the top and bottom of each plot to reduce variation from starting and stopping the mower for each harvest. Clippings were collected into brown paper bags with a brush and kept at 72 °C until mass could be determined.

TE = trinexapac-ethyl; LSD = least significant difference; ANOVA = analysis of variance.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 2. Nitrogen, phosphorus, and potassium concentration of 'Diamond' zoysiagrass leaf tissue as influenced by N and TE rate during 2009 and 2010.

	2009						2010					
	Aug.			Sept.			July			Aug.		
	N	P	K	N	P	K	N	P	K	N	P	K
Main effects	(g·kg ⁻¹)											
Nitrogen rate (N)												
0	31.5	4.3	11.2	24.4	3.6	9.5	16.0	3.5	12.1	16.4	3.1	9.5
4.9	33.5	4.4	10.5	26.6	4.0	9.3	21.6	3.9	13.2	20.1	3.3	10.8
9.8	35.3	4.5	10.3	27.4	4.1	8.6	26.7	4.6	13.9	24.2	3.7	11.8
14.7	36.0	4.6	10.2	26.9	3.8	7.4	34.6	5.0	14.3	28.1	4.1	12.7
LSD _{0.05}	1.2	NS	NS	NS	0.2	0.9	4.7	0.8	0.2	1.4	0.5	0.1
TE rate (TE)												
0	33.8	4.4	10.6	26.8	3.9	9.0	24.2	4.5	13.9	22.2	3.7	12.1
0.017 kg a.i./ha	34.3	4.5	10.5	25.9	3.9	8.4	25.3	4.1	12.8	22.2	3.4	10.3
ANOVA												
Source of variation												
N	***	NS	NS	NS	**	**	***	*	*	***	**	***
TE	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	*	***
N*TE	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

TE = trinexapac-ethyl; P = phosphorus; K = potassium; LSD = least significant difference; ANOVA = analysis of variance.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

was measured monthly by harvesting four samples averaged per plot (adjacent to TruFirm observations) with a 1.90-cm diameter soil sampler to a 9-cm depth and then thatch samples were oven-dried at 72 °C for 48 h. Loss on ignition (LOI) data were determined by excising shoot and root materials from each thatch sample, measuring the depth of thatch, and determining its mass. Thatch samples were ashed in a muffle furnace (Omegalux LMF-A550) at 525 °C for 2 h. The ashed weight was recorded and the total organic material was determined. Ball roll distance was measured weekly in two directions using a Stimpmeter (USGA Green Section Staff, 1981). Clipping yield was determined in August and September of 2009 and July and August of 2010 with a reel mower (Greenmaster; The Toro Company) at 3.2 mm by mowing a 48.3-cm strip the entire length of the plot. Alleys were mowed at the top and bottom of each plot to reduce variation from starting and stopping the mower for each harvest. Clippings were collected into brown paper bags from the mower clipping collection basket and kept at 72 °C in an oven until mass could be determined. Tissue nutrient concentrations were determined monthly at the Clemson University Agricultural Service Laboratory. Tissue N analysis was determined by combustion using a LECO FP528 N combustion analyzer (St. Joseph, MI). Mineral analysis of leaf tissue for P and K was performed by HNO₃/H₂O₂ digestion and then analysis with inductively coupled plasma mass spectrometry (Baldwin, 2008).

The experiment was conducted as a completely randomized design with three replications. Treatments consisted of the factorial combination of four N rates and two TE rates. Data from each year were subjected to analysis of variance to analyze treatment-by-year interactions. Differences in total N fertility applied in 2009 and 2010 and potential variation resulting from a newly established putting green resulted in significant year-by-treatment interactions; therefore, data will be presented by harvest or rating date with all main effects and simple interactions that were significant. Mean separations were performed using Fisher's protected least significant difference test at 5% probability level. Analyses were conducted using JMP 10 (SAS Institute Inc., Cary, NC). Linear regression analysis was conducted to determine the relationship between thatch LOI and SF by SigmaPlot Version 10.0 (Systat Software, London, U.K.) at a 5% probability level.

Results and Discussion

Putting green performance characteristics (BRD, SF) were not influenced by N or TE in 2009 presumably as a result of the short duration of treatment application (7 weeks). As a result of this observation, treatments began earlier in the 2010 growing season, which resulted in differences in putting green characteristics that will be discussed in detail.

Table 3. Turf quality^z of 'Diamond' zoysiagrass as influenced by N rate and TE rate during 2009 and 2010.

Main effects	2009		2010						
	Sept.	Oct.	May	June	July	Aug.	Sept.	Oct.	Nov.
Nitrogen rate (N)									
0	7.2	7.1	5.0	5.8	5.4	5.0	4.9	4.6	3.9
4.9	7.2	7.3	5.3	6.0	6.3	6.8	7.0	6.6	6.0
9.8	6.5	6.8	4.3	5.3	6.0	7.4	7.6	7.3	6.8
14.7	6.2	6.8	4.0	5.0	6.3	7.6	7.8	7.6	6.8
LSD _{0.05}	0.5	0.4	0.5	0.5	0.5	0.3	0.3	0.4	0.3
TE rate (TE)									
0	6.8	6.9	4.6	5.4	6.0	6.7	6.9	6.4	5.8
0.017 kg a.i./ha	6.7	7.0	4.8	5.7	6.0	6.7	6.8	6.6	5.9

ANOVA

Source of variation									
N	**	*	***	**	**	***	***	***	***
TE	NS	NS	NS	NS	NS	NS	NS	NS	NS
N*TE	NS	NS	NS	NS	NS	NS	NS	NS	NS

^zWeekly visual readings of turf quality were performed by examining color, texture, density, and playability on a scale of 1 to 9 where 1 = dead turf, 9 = perfect turf, and greater than 6 was considered acceptable for golf course putting greens and averaged to obtain monthly means.

TE = trinexapac-ethyl; LSD = least significant difference; ANOVA = analysis of variance.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 4. Ball roll distance^z of 'Diamond' zoysiagrass as influenced by N rate and TE rate during 2009 and 2010.

Main effects	2009		2010						
	Sept.	Oct.	May	June	July	Aug.	Sept.	Oct.	Nov.
Nitrogen rate (N)									
0	236.8	240.6	239.4	239.6	237.0	241.9	263.2	265.1	272.9
4.9	236.3	244.3	239.5	238.6	233.7	229.5	252.2	237.2	240.3
9.8	233.1	243.1	237.8	235.1	229.7	219.3	235.1	232.1	236.6
14.7	230.9	238.9	236.2	237.0	226.6	211.5	227.8	235.7	245.6
LSD _{0.05}	5.3	NS	NS	NS	6.0	4.9	6.5	6.3	6.7
TE rate (TE)									
0	230.2	240.6	236.7	237.0	231.6	223.1	241.6	247.3	253.7
0.017 kg a.i./ha	238.4	242.9	239.8	238.2	231.9	228.0	247.5	237.7	244.1

ANOVA

Source of variation									
N	NS	NS	NS	NS	**	***	***	***	***
TE	***	NS	NS	NS	NS	**	*	***	**
N*TE	NS	*	*	*	NS	NS	*	NS	NS

^zBall roll distance in cm was measured weekly in two directions using a Stimpmeter.

TE = trinexapac-ethyl; LSD = least significant difference; ANOVA = analysis of variance.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 5. Surface firmness^z of 'Diamond' zoysiagrass as influenced by N rate and TE rate during 2009 and 2010.

Main effects	2009		2010						
	Sept.	Oct.	May	June	July	Aug.	Sept.	Oct.	Nov.
Nitrogen rate (N)									
0	1.22	1.20	1.14	1.16	1.12	1.13	1.09	1.08	1.08
4.9	1.23	1.19	1.15	1.16	1.13	1.14	1.16	1.16	1.14
9.8	1.24	1.20	1.16	1.15	1.15	1.19	1.22	1.21	1.22
14.7	1.27	1.23	1.13	1.14	1.14	1.24	1.28	1.27	1.25
LSD _{0.05}	NS	NS	NS	NS	NS	0.04	0.06	0.08	0.05
TE rate (TE)									
Control	1.25	1.21	1.14	1.15	1.13	1.19	1.21	1.17	1.19
0.017 kg a.i./ha	1.23	1.20	1.15	1.16	1.13	1.16	1.17	1.19	1.15

ANOVA

Source of variation									
N	NS	NS	NS	NS	NS	**	***	**	***
TE	NS	NS	NS	NS	NS	NS	NS	NS	*
N*TE	NS	NS	NS	NS	NS	*	NS	NS	*

^zSurface firmness was measured monthly using USGA's TruFirm, which simulates and measures the depth of golf ball impact. Four surface firmness measurements were taken at random in each plot and averaged.

TE = trinexapac-ethyl; LSD = least significant difference; ANOVA = analysis of variance.

NS, *, **, *** Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Trinexapac-ethyl decreased clipping yield at every rating date and reductions ranged from 15% to 43% across 2009 and 2010 rating dates. Clipping yield in 2010 was influenced by N input at both harvest events (Table 1).

As N input increased, leaf tissue N concentration increased correspondingly (Table 2). Trinexapac-ethyl had no effect on N concentration of leaf tissue at any monthly assessment, which contradicts McCullough et al. (2006) who found significant reductions in N content of bermudagrass leaf tissue with increasing TE and higher retention of N in thatch and root tissue. Nitrogen content in thatch and root tissue was not measured in the current study and further research to examine the N uptake and partitioning of zoysiagrass putting greens needs to be conducted. Leaf tissue P concentration increased as N input increased at the July and Aug. 2010 harvests (Table 2). Trinexapac-ethyl caused an 8% reduction in leaf tissue P concentration at the Aug. 2010 rating date. Potassium concentration was influenced by N fertility level and TE at three harvest dates across 2009 and 2010 (Table 2). In 2009, K concentrations decreased with increasing N rate, but the opposite effect was observed in 2010 (Table 2). This observation could be the result of K accumulation in the root zone and plant uptake during the 2010 season. Havlin et al. (2014) documented that as much as 25% to 60% of residual in soils for P and K accumulated from the previous year applications. Reductions in leaf tissue K concentrations were observed at the 2010 July and August rating dates by 8% and 15%, respectively, as a result of TE (Table 2), which agrees with McCullough et al. (2006) who recorded reductions in K concentration of bermudagrass leaf tissue under a TE regime in the greenhouse. Trinexapac-ethyl use could reduce N requirement in 'Diamond' zoysiagrass putting greens by reducing mowing and N loss in clippings as hypothesized by Kreuser and Soldat (2012) for creeping bentgrass. It is possible that 'Diamond' zoysiagrass redirects nutrients away from leaf tissue under TE regimes as observed by McCullough et al. (2006), which could also explain the reduction in P and K leaf tissue.

Over the course of the 2-year study, TQ was influenced by N input (Table 3). Turf quality increased as total N increased during the growing season in 2010, except where higher N rates resulted in scalping events that caused a reduction in TQ observed throughout the late summer of 2009 and spring of 2010 rating dates. There was a decrease in TQ in late fall and early spring as a result of seasonal dormancy with only control plots having TQ values below the acceptable level (less than 6) during the summer growing season of 2010. Turf quality was not influenced by TE throughout the 2-year study and is presumably the result of the rate used. Higher rates of TE could possibly have a profound effect on TQ and long-term putting green health and performance of zoysiagrass putting greens.

Ball roll distance was influenced by N input and TE rate (Table 4). The greatest

BRD was recorded in control treatments not receiving N and decreased as total N input increased. This trend was observed for five rating dates over the 2010 growing season, which is presumably the result of the increase in leaf tissue and growth under higher N inputs causing ball roll resistance. Applications of TE influenced BRD on five rating dates over the 2-year study. Trinexapac-ethyl increased BRD in Sept. 2009 and August and September of 2010 $\times$ 3.6%, 2.2%, and 2.4%, respectively. However, TE decreased BRD in October and November of 2010 $\times$ 4.0% and 3.9%, respectively (Table 4). Applications of TE produce a dense turf canopy that could result in greater resistance to ball roll during the October and Nov. 2010 rating dates. Turfgrasses not receiving TE applications were less dense and offered little ball roll resistance going into winter resulting in greater BRD values. Significant N rate by TE was observed at four rating dates (Table 4); however, no definitive result was found except for the Sept. 2010 rating date where turfgrasses receiving 4.9 kg-ha⁻¹ weekly N and TE exhibited greater BRD than turfgrasses at the same N input without TE applications. A low rate of TE and a 3.2-mm HOC used in this study decreased BRD measurements. Stiglbauer et al. (2009) found that 'Diamond' can be maintained at a 2.5 mm HOC without scalping or affecting winter survival. Increases in BRD resulting from reductions in HOC have been well documented in bentgrass and seashore paspalum (Fagerness et al., 2000; Kopec et al., 2007; Pease et al., 2011) and should be further

investigated in 'Diamond' zoysiagrass putting greens.

Surface firmness was influenced by N rate over 4 months during the 2010 growing season as increasing N input resulted in decreasing SF (Table 5). Turfgrass receiving 4.9 kg-ha⁻¹ weekly N resulted in a firmer putting surface than 14.7 kg-ha⁻¹ N fertilized turfgrasses for four of seven measurements during the 2010 growing season. Surface firmness increased 3.5% in Nov. 2010 for TE-treated turfgrass. Significant main effects and interactions of N input and TE rate were not detected for LOI data (data not shown). However, linear regression of thatch accumulation (LOI data) and SF were analyzed and found to be significant at four rating dates in 2010 including [May ($P = 0.03$, $R^2 = 0.20$), June ($P = 0.01$, $R^2 = 0.12$), July ($P = 0.004$, $R^2 = 0.32$), and October ($P = 0.005$, $R^2 = 0.33$); Fig. 1] indicating that as thatch organic matter increased (LOI), SF (penetration) increased. The lower R^2 values (0.12 to 0.33) for those linear regressions indicate significant variability. Soil moisture readings were not recorded during this study, but SF has been reported to be influenced by moisture, thatch, and organic matter accumulation in the upper soil profile (Linde et al., 2011). To more fully understand the seasonal fluctuations in SF, soil moisture data need to be included in future studies. However, with such newly established USGA specification greens, no localized dry spot signs were observed during the 2-year study and the green was irrigated as needed with proper water drainage without drought stresses.

Fig. 1. Linear regression of thatch LOI (g m⁻²) and surface firmness (cm of penetration) at four rating dates in 2010. Each data point represents actual measurements in May (24 observations, $P = 0.03$), June (46 observations, $P = 0.01$), July (23 observations, $P = 0.004$), and Oct. 2010 (21 observations, $P = 0.005$). Linear regression analysis was conducted to determine the relationship between thatch LOI and SF at the conclusion of the study by SigmaPlot Version 10.0 (Systat Software, London, UK) at the 5% probability level. LOI = loss on ignition; SF = surface firmness.

Thatch management practices such as aeration, vertical mowing, and topdressing need to be evaluated for 'Diamond' zoysiagrass putting greens to determine their effects on putting green performance. Extensive cultivation as tested by Hollingsworth et al. (2005) on ultradwarf bermudagrass would not be recommended as a result of slow growth and recovery of 'Diamond' zoysiagrass documented by Patton (2009). In the future, thatch sampling practices on 'Diamond' zoysiagrass greens and other warm-season putting greens require improvement with greater size of thatch samplers and more consistent ways to separate thatch materials from living materials and roots.

Conclusions

'Diamond' zoysiagrass has potential to be used successfully for putting greens in the transition zone, especially in shady areas and in more northern locations where ultradwarf bermudagrasses are less successful. An N input of 73.5 kg/ha/year (equivalent to 4.9 kg N/ha/week for 15 weeks) during the summer growing season resulted in acceptable TQ and better playability (greater BRD and SF) than 220.5 kg/ha N/year (equivalent to 14.7 kg N/ha/week for 15 weeks) treated plots during all rating dates in 2010 before seasonal dormancy where no differences were observed. Results showed that as total N input approached and surpassed 147 kg N/ha/year (equivalent to 9.8 kg N/ha/week for 15 weeks), putting green performance decreased as a result of increased clipping yield (growth) impeding BRD and softening the putting surface. Yearly N input for 'Diamond' zoysiagrass putting greens should begin at 73.5 kg/ha/year. This N fertility input level is significantly lower than other warm-season turfgrasses used on putting greens and is desirable when fertilizer costs and labor are considered in the transition zone. A balance among acceptable TQ, putting green performance, and long-term plant health needs to be determined to optimize N fertility inputs for 'Diamond' zoysiagrass putting greens because it can be adapted in a broader zone than bermudagrasses based on cold-hardiness. Additional field research needs to be conducted to further refine recommendations for 'Diamond' putting green management under several HOCs, PGR rates

and application intervals, and surface management cultivation techniques.

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