Mowing Operations Influence Creeping Bentgrass Putting Green Ball Roll following Plant Growth Regulator Applications

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Abstract. Plant growth regulators (PGRs) are commonly used to enhance putting green quality and ball roll distances but their effects with various mowing operations have not been reported. Three experiments were conducted and repeated at Clemson University, Clemson, SC, on an 'L-93' creeping bentgrass putting green to evaluate the effects of mowing operations and PGRs on diurnal ball roll distances. The PGRs tested included ethephon at (a.i.) 3.8 kg·ha⁻¹, flurprimidol at (a.i.) 0.28 kg·ha⁻¹, paclobutrazol at (a.i.) 0.28 kg·ha⁻¹, and trinexapac-ethyl at (a.i.) 0.05 kg·ha⁻¹. Mowing operations tested included rolling vs. mowing, morning mowing vs. morning plus afternoon mowing, and single vs. double morning mowing, all with and without PGRs. PGR by mowing operation interactions did not occur in any experiments. Ball roll distances decreased from 12:00 HR to evening observations in all experiments. In Experiment 1, rolling the green without mowing reduced ball roll distance 4% (5 cm) compared to mowing. Turf rolled without mowing in the morning and treated with flurprimidol, paclobutrazol, and trinexapac-ethyl produced similar ball roll at 12:00, 15:00, and 18:00 HR to mowed untreated turf. In Experiment 2, all plots were mowed at 08:00 HR and half of each plot was removed at 12:30 HR. The second mowing at 12:30 HR enhanced ball roll distances 6% (8 cm) over the day. Turf mowed only at 08:00 and treated with paclobutrazol and trinexapac-ethyl had greater or equal ball roll distances at 12:30, 15:30, and 18:30 HR to untreated turf that had a second mowing at 12:30 HR. Turf receiving ethephon and 08:00 HR mowing had 4% to 12% (4 to 17 cm) shorter ball roll distances throughout the day compared to untreated turf mowed at 8:00 and 08:00+12:30 HR, respectively. In the third experiment, mowing twice in the morning increased ball roll 3% (4 cm) compared to mowing once. Trinexapac-ethyl and paclobutrazol treated turf mowed once in the morning had greater or equal ball roll distances throughout the day to untreated turf mowed twice in the morning. Overall, PGR use may provide putting green ball roll distances similar to or greater than untreated turf despite additional mowing; however, ethephon reduced ball roll distances regardless of mowing operations. Chemical names used: [4-(cyclopropyl-[α]-hydroxymethylene)-3,5-dioxo-cyclohexane carboxylic acid ethyl ester] (trinexapac-ethyl); {α-(1-methylethyl)-α-[4-(trifluoro-methoxy)phenyl] 5-pyrimidine-methanol} (flurprimidol); (+/-)-(R*,R*)-β-[4-chlorophenyl] methyl]-α-(1, 1-dimethyl)-1H-1,2,4,-triazole-1-ethanol (paclobutrazol); [(2-chloroethyl)phosphonic acid] (ethephon).

One of the most challenging aspects of golf course management is putting green culture. Successfully maintaining turfgrasses at 3.2 mm or lower is highly dependent on sound agronomic practices. However, turf managers often have to compromise on these fundamental cultural practices in order to achieve desired putting green quality and ball roll distances. Practices implemented in order to promote putting green ball roll include lowering mowing heights, double cutting, and rolling greens (McCarty, 2005). Maintaining turfgrasses

under conditions beyond their physiological capacities, such as from these methods, may have deleterious effects on root growth, turf vigor, and recuperative capabilities from

disease, traffic, heat, and other environmental stresses (Beard, 1973).

Incorporating plant growth regulators (PGRs) into putting green maintenance may provide consistent and acceptable ball roll without deleterious effects on plant health. Reducing turfgrass leaf growth with PGRs has become a common practice for intensive turfgrass management and may provide smoother putting surfaces by promoting lateral growth instead of undesirable top growth (Murphy et al., 2005; Watschke et al., 1992). Reducing diurnal growth fluctuations may further provide consistent putting surfaces and may be a safer approach in producing quality putting green conditions on a long-term basis.

Routine mowing and PGR applications help reduce uneven leaf growth, thus, promoting uniform surfaces for putting green ball roll. Gibberellic acid (GA) inhibitors are more frequently used on putting greens than cell division inhibitors because of less likelihood for leaf burn and turfgrass injury (Murphy et al., 2005). Fagerness et al. (2000) evaluated monthly applications of two GA inhibitors, trinexapac-ethyl and paclobutrazol, on 'Penncross' creeping bentgrass ball roll when maintained at 3.2, 4, and 4.8 mm mowing heights. Plant growth regulators did not improve ball roll measurements through one month after application; however, ball roll increased from reducing mowing heights. In another experiment, PGRs enhanced ball roll on several observations throughout the same day. It was concluded long term ball roll improvements were more consistent from reducing mowing height, while PGRs may be beneficial over the course of a given day.

Effects of ball roll distance for the PGR flurprimidol, a popular GA inhibitor for creeping bentgrass, have not been reported. Another PGR commonly used on bentgrass greens is ethephon. Ethephon is a PGR that decomposes to release ethylene which effectively suppresses *Poa annua* L. seedheads in creeping bentgrass putting greens (Gelertner and Stowell, 2001; Kane and Miller, 2003). The effects of ethephon on putting green ball roll in monostand creeping bentgrass turf have not been reported.

For golf courses to maintain quality putting green surfaces and acceptable ball roll distances, daily mowing is a fundamental part of routine maintenance (McCarty, 2005). It is believed, however, that other mowing operations commonly implemented to enhance

Table 1. Main effects of mowing operations and plant growth regulators (PGRs) on an 'L-93' creeping bentgrass putting green.

Experiment	Mowing operation ²
1 ¹	Morning mowing vs. rolling ³
2	Mowing at 8:00 vs. 8:00+12:30
3	Morning single vs. double mowing
PGR ⁴	Rate (a.i., kg·ha ⁻¹)
Untreated	---
Ethephon (2L)	3.80
Flurprimidol (50WP)	0.28
Paclobutrazol (2SC)	0.28
Trinexapac-ethyl (1EC)	0.05

¹Mowing height was 3.2 mm with a walk-behind reel-type mower.

²Turf was mowed about 24 h before experiment initiation at 3.2 mm.

³Rolling operations were performed with the walk-behind mower without reels engaged.

⁴Plant growth regulators were applied 2 d before the first experiment.

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putting green ball roll may not be necessary following plant growth regulator use. Three experiments were conducted to investigate effects of mowing vs. rolling, morning vs. afternoon mowing, and single vs. double morning mowing on ball roll distances of an 'L-93' creeping bentgrass putting green following plant growth regulator use.

Materials and Methods

Three experiments were conducted and repeated at the Turfgrass Service Center, Clemson, S.C., in 2004 on an experimental 'L-93' creeping bentgrass putting green established in August 2002. The first round of experiments (Study 1) was conducted 15 through 19 May 2004. Experiments were repeated 28 May through 1 June 2004 (Study 2) on plots located adjacent to turf used for the initial experiments. The green was constructed approximately to United States Golf Association specifications with a medium/fine textured sand soil (USGA Green Section Staff, 1993). Turf was maintained at a 3.2 mm mowing height and irrigated as needed to prevent plant wilt. Aerifications were performed on the green 23 Sept. 2003 and 8 Mar. 2004 with 1.3 cm hollow tines. Beginning in March 2004, bentgrass was fertilized with N at 6 kg·ha⁻¹·week⁻¹, with a greens-grade granular fertilizer (Anderson's, Maumee, OH; 18N-1P-15K).

The experimental design was a split-block with three replications of 1.5 × 1.8-m plots. Five plots were arranged per block (four PGRs plus a control) receiving two mowing operations (Table 1) which were randomly assigned in each experiment to half of every block. Mowing operations were performed by making one pass with a walk-behind greensmower (Toro, Bloomington, MN). Turf was mowed again after each experiment to reduce influences for the next scheduled experiment. Before experiment initiation, mowing treatments were randomly assigned for each day and turf had not received prior PGR treatments. Plant growth regulators, including ethephon, flurprimidol, paclobutrazol, and trinexapac-ethyl (Table 1), were applied to separate plots 15 and 28 May 2004 in Studies 1 and 2, respectively. Applications were made with a CO₂-sprayer calibrated to deliver 1800 L·ha⁻¹. Turf treated with paclobutrazol and flurprimidol were immediately irrigated to about 1 cm depth after applications.

Turfgrass visual quality was rated on a 1 to 9 scale with 1 = dead turf and 9 = ideal, dark green turf. Ratings below 7 were considered unacceptable. Six ball roll measurements (three rolls in opposite directions) were made with a 38 cm stimpmeter on 17, 18, and 19 May 2004 for the first round of experiments and again on 30 and 31 May and 1 June 2004 for the second round of experiments. The stimpmeter was raised off of the ground until gravity caused the golf ball to roll off the cleft located on the opposite end. Ball roll distances were obtained with tape measurers running parallel with the plots. The six rolls were pooled per treatment (PGR and mowing combination) and subjected to an analysis of variance with SAS General

Table 2. Pooled ball roll distance for 'L-93' creeping bentgrass rolled and mowed with and without plant growth regulator (PGR) applications in combined field studies. Different letters indicate a significant difference at the 0.05 probability level.

		Ball roll ^z (time of day, HR)			
Mowing operation ^y	PGR ^y	09:00	12:00	15:00	18:00
				(cm)	
Rolled	---	128	131	125	125
	Ethephon	120	125	118	115
	Flurprimidol	130	135	129	128
	Paclobutrazol	136	135	132	131
	Trinexapac-ethyl	132	137	127	130
Mowed	-	131	134	128	126
	Ethephon	129	131	123	122
	Flurprimidol	137	138	135	133
	Paclobutrazol	140	142	136	134
	Trinexapac-ethyl	140	144	135	134
LSD _{0.05}		5	6	8	4
Main effects	Mean	P value			
09:00	132 b				
12:00	135 a				
15:00	129 c				
18:00	128 c				
Linear		0.0001			
Quadratic		0.0001			
Mowing operation		0.0001			
Rolled	129 b				
Mowed	134 a				
Plant growth regulator		0.0001			
Untreated	129 c				
Ethephon	123 d				
Flurprimidol	133 b				
Paclobutrazol	136 a				
Trinexapac-ethyl	135 a				

^zBall roll measurements were made with a 38 cm stimpmeter.

^yTurf was mowed at 3.2 mm about 24 hours before mowing operations were performed. PGRs were applied 2 d before in both studies.

Table 3. Pooled ball roll distance for 'L-93' creeping bentgrass treated with four plant growth regulators (PGRs) and mowed at 08:00 HR with and without a second mowing at 12:30 in combined field studies. Different letters indicate a significant difference at the 0.05 probability level.

			Ball roll ^z (time of day, HR)		
Morning mowing ^y	PGR ^y		12:30	15:30	18:30
			(cm)		
08:00	---		136	132	127
	Ethephon		130	128	118
	Flurprimidol		136	134	130
	Paclobutrazol		147	138	137
	Trinexapac-ethyl		144	138	137
08:00 + 12:30	---		146	139	135
	Ethephon		140	131	129
	Flurprimidol		149	144	140
	Paclobutrazol		154	146	142
	Trinexapac-ethyl		150	146	142
LSD _{0.05}			6	4	6
Main effects	Mean	P value			
Time of day		0.0001			
12:30	143 a				
15:30	138 b				
18:30	134 c				
Linear		0.0001			
Quadratic		NS			
Mowing Time		0.0001			
08:00	134 b				
08:00 + 12:30	142 a				
PGR		0.0001			
Untreated	136 c				
Ethephon	129 d				
Flurprimidol	139 b				
Paclobutrazol	144 a				
Trinexapac-ethyl	143 a				

^zBall roll measurements were made using a 38 cm stimpmeter.

^yTurf was mowed at 3.2 mm. Plant growth regulators were applied 3 and 4 d before in Studies 1 and 2, respectively.

Table 4. Pooled ball roll distance for 'L-93' creeping bentgrass treated with four plant growth regulators (PGRs), mowed once or twice at 08:00 HR in combined field experiments. Different letters indicate a significant difference at the 0.05 probability level.

Morning mowing ^y	PGR ^y	Ball roll ^z (time of day, HR)		
		08:00	12:00	16:00
Once	---	139	137	128
	Ethephon	136	130	123
	Flurprimidol	143	141	133
	Paclobutrazol	146	143	137
	Trinexapac-ethyl	150	146	136
Twice	---	141	141	136
	Ethephon	139	135	127
	Flurprimidol	150	142	138
	Paclobutrazol	151	147	143
	Trinexapac-ethyl	151	145	139
LSD _{0.05}		6	5	5
Main effects	Mean	P value		
Time of day		0.0001		
08:00	145 a			
12:00	141 b			
16:00	134 c			
Linear		0.0001		
Quadratic		0.0111		
Morning mowing		0.0001		
Once	138 b			
Twice	142 a			
PGR		0.0001		
Untreated	137 c			
Ethephon	132 d			
Flurprimidol	141 b			
Paclobutrazol	144 a			
Trinexapac-ethyl	144 a			

^zBall roll measurements were made with a 38 cm stimp meter.

^yTurf was mowed at 3.2 mm. Plant growth regulators were applied 4 and 3 d before in Studies 1 and 2, respectively.

Table 5. Visual quality for 'L-93' creeping bentgrass, 5 d after plant growth regulator (PGR) applications. Different letters indicate a significant difference at the 0.05 probability level.

PGR ^z	Visual quality ^y 1–9
Untreated	7.0 a
Ethephon	5.7 b
Flurprimidol	7.0 a
Paclobutrazol	7.0 a
Trinexapac-ethyl	7.0 a

^zPlant growth regulators were applied 5 d before.

^yVisual quality was rated on a 1 to 9 scale with 1 = dead turf and 9 = uniform, dark green turf. Ratings below 7 were considered unacceptable.

Linear Model procedure (SAS Institute, Cary, N.C.). Mean separations were based on Fishers protected LSD test at the 0.05 probability level. Orthogonal polynomial contrasts examined linear and quadratic relationships between ball roll and times of day. Study × treatment interactions did not occur; therefore, Studies 1 and 2 were combined for the three experiments.

Results and Discussion

Experiment 1. Time of day (TOD) × mowing, TOD × PGR, PGR × mowing, and TOD × PGR × mowing had no interactions for ball roll distances. Mowing and PGR use did not mask diurnal leaf growth effects; however, both practices had highly significant ($P < 0.0001$) effects on ball roll distances. Ball roll distances decreased 5% (7 cm) from 12:00 to 18:00 HR (Table 2). Although dew was removed an hour before (08:00 HR), soil and bentgrass leaves

likely had higher moisture at 09:00 relative to 12:00 HR, due to sunlight intensities drying the leaf tissue in the afternoon and providing a better surface for ball roll.

Rolling the green in the morning reduced ball roll distance 4% (5 cm) over the day compared to mowing. Main effects of flurprimidol, paclobutrazol, and trinexapac-ethyl enhanced ball roll distances 3% to 5% (4 to 7 cm) compared to untreated turf while ethephon reduced ball roll distances 5% (6 cm). Rolling the putting green in the morning having mowed 24 h beforehand, with suppressed leaf growth from paclobutrazol and trinexapac-ethyl, produced 3% and 4% (4 and 5 cm) longer ball roll distances at 18:00 HR compared to untreated turf that was mowed. Reducing mowing frequencies may be advantageous on creeping bentgrass putting greens, especially during summer stress. These results suggest putting green quality and ball roll distances can still be maintained by rolling the turf in the morning instead of mowing after applying these PGRs. Ethephon appears to reduce ball roll distances on creeping bentgrass putting greens free of *Poa annua*.

Experiment 2. Time of day (TOD) × mowing, TOD × PGR, PGR × mowing, and TOD × PGR × mowing interactions did not occur. Ball roll distances linearly decreased from 12:30 to 18:30 HR (Table 3) due to diurnal leaf growth. Mowing and PGR use did not mask the influence of daily leaf growth on ball roll distances; however, both practices had highly significant ($P < 0.0001$) effects on overall ball roll. Mowing the putting green at 08:00 HR and again at 12:30 HR enhanced ball roll distances

6% (8 cm) from 12:30 to 18:30 HR compared to turf mowed only at 08:00 HR (Table 3). Flurprimidol, paclobutrazol, and trinexapac-ethyl enhanced ball roll distances 2% to 6% (3 to 8 cm) compared to untreated plots while ethephon reduced ball roll distances 5% (7 cm). Compared to bentgrass mowed at 08:00 HR and again at 12:30 HR, turf mowed only at 08:00 HR and treated with trinexapac-ethyl or paclobutrazol had similar ball roll distances at 12:30, 15:30, and 18:30 HR. Bentgrass leaf growth suppression following trinexapac-ethyl and paclobutrazol applications may promote putting green ball roll distances comparable to untreated turf receiving subsequent afternoon mowing. It was also noted that bentgrass treated with flurprimidol, paclobutrazol, and trinexapac-ethyl with an additional mowing at 12:30 HR averaged 9% to 12% (12 to 15 cm) longer ball roll distances compared to untreated turf mowed only at 08:00 HR. Conversely, turf receiving ethephon and 08:00 HR mowing had ball roll distances reduced 4% to 12% (4 to 17 cm) throughout the day compared to untreated turf mowed at 8:00 and 8:00+12:30 HR, respectively. Ethephon applications appear to have negative effects on ball roll distances with and without afternoon mowing for a monostand creeping bentgrass turf.

Experiment 3. Time of day (TOD) × mowing, TOD × PGR, PGR × mowing, and TOD × PGR × mowing interactions did not occur. Ball roll distances quadratically decreased from 08:00 to 16:00 HR (Table 4) by 11 cm due to diurnal leaf growth. Mowing twice in the morning increased ball roll 3% (4 cm) compared to mowing once. Main effects of flurprimidol, paclobutrazol, and trinexapac-ethyl enhanced ball roll distances 3% to 5% (4 to 7 cm) while ethephon reduced ball roll distances 4% (5 cm). Compared to untreated turf mowed twice in the morning, bentgrass mowed once and treated with trinexapac-ethyl had 6% (9 cm) longer ball roll distances at 08:00 HR. Trinexapac-ethyl and paclobutrazol treated turf mowed once in the morning had greater or equal ball roll distances throughout the day compared to untreated turf mowed twice in the morning. Bentgrass treated with flurprimidol, paclobutrazol, and trinexapac-ethyl averaged 6% to 9% (9 to 12 cm) greater ball roll distances when mowed twice at 08:00 HR compared to untreated turf mowed only once at 08:00 HR. Ethephon treated turf mowed twice in the morning had ball roll distances equivalent to untreated bentgrass mowed once in the morning.

Visual quality. Ethephon treated turf had unacceptable visual quality five days after treatments (Table 5). Although ethephon is an effective PGR for *Poa annua* suppression on creeping bentgrass putting greens, it appears that this PGR has deleterious effects on visual quality and ball roll distances on monostand putting greens. Flurprimidol, paclobutrazol, and trinexapac-ethyl applications produced visual quality similar to untreated turf.

Conclusions

Routine mowing and PGR applications help minimize uneven leaf growth, thus, promoting uniform surfaces for putting green

ball roll. Inhibiting turfgrass leaf growth with PGRs may not arrest daily leaf growth fluctuations; however, diurnal growth fluctuations are significantly reduced to enhance ball roll distances relative to untreated turf. It appears that putting green ball roll distances may also be enhanced greater or equivalent to supplemental and subsequent mowing operations following flurprimidol, paclobutrazol, and trinexapac-ethyl use. Ethephon, however, does not appear to be a suitable PGR for promoting ball roll on a monostand (100% weed free) creeping bentgrass putting green. Turf managers may be able to reduce putting green mowing frequencies without compromising ball roll distances following applications of gibberellic acid (GA) inhibitors. Furthermore, supplemental and subsequent mowing with GA inhibitors provided the greatest ball roll distance enhancements relative to routine daily mowing of untreated turf.

Finally, this experiment was conducted on 'L-93' creeping bentgrass. Cultivars such as Crenshaw, the A series, G series, and other bentgrasses may respond differently to mowing and PGR treatments. Bentgrass ball roll distances may also vary when maintained with various fertility inputs, watering regimens, and mowing heights.

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