Weed Technology

www.cambridge.org/wet

Research Article

Cite this article: Peppers JM, McElroy JS, Askew SD (2024) Plant growth regulators differentially suppress goosegrass and smooth crabgrass in creeping bentgrass turf. Weed Technol. **38**(e44), 1–6. doi: 10.1017/wet.2024.32

Received: 4 March 2024
Revised: 24 April 2024
Accepted: 7 May 2024

Associate Editor:
Prashant Jha, Louisiana State University

Nomenclature:
Fenoxaprop-p; flurprimidol; paclobutrazol; prohexadione-calcium; trinexapac ethyl; goosegrass, *Eleusine indica* L. Gaertn.; smooth crabgrass, *Digitaria ischaemum* Schreb.; creeping bentgrass, *Agrostis stolonifera* L.

Keywords:
Turfgrass; putting greens

Corresponding author:
Shawn Askew; Email: saskew@vt.edu

Plant growth regulators differentially suppress goosegrass and smooth crabgrass in creeping bentgrass turf

John M. Peppers[1], J. Scott McElroy[2] and Shawn D. Askew[3]

[1]Graduate Research Assistant, School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA; [2]Professor, Department of Crop Soil and Environmental Sciences, Auburn University, Auburn, AL, USA and [3]Professor, School of Plant and Environmental Sciences, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA

Abstract

Goosegrass and smooth crabgrass in creeping bentgrass turf are difficult to control due to a lack of selective herbicides. Based on preliminary field observations, we hypothesized that paclobutrazol and flurprimidol would reduce the overall competitiveness of goosegrass and smooth crabgrass in creeping bentgrass. Greenhouse and field studies were designed to evaluate the effect of several plant growth regulators (PGRs) on goosegrass and smooth crabgrass competitive indices. In greenhouse studies, flurprimidol, paclobutrazol, trinexapac-ethyl, and prohexadione-calcium were applied either preemergence only or preemergence plus two biweekly postemergence applications to goosegrass and smooth crabgrass plants to simulate the first 1.5 mo of typical PGR programs used on golf courses. Two weeks after the final postemergence treatment, aboveground biomass and root biomass were recorded. Programmatic flurprimidol and paclobutrazol applications reduced smooth crabgrass aboveground biomass by 67% and 69%, respectively, and more than trinexapac ethyl or prohexadione-calcium. When averaged across application programs, flurprimidol and paclobutrazol reduced smooth crabgrass root biomass by 74% and goosegrass biomass by 73% to 80%. Field studies were established to further evaluate the influence of PGRs on smooth crabgrass coverage in creeping bentgrass turf. Treatments consisting of flurprimidol, trinexapac-ethyl, flurprimidol plus trinexapac-ethyl, paclobutrazol, and fenoxaprop-p were applied every 3 wk from April to August. Weed coverage data were collected throughout the growing season, and final smooth crabgrass control data were collected at the end of the season. In general, flurprimidol-containing treatments more effectively reduced smooth crabgrass coverage throughout the growing season than trinexapac ethyl. After the studies, regimens that contained flurprimidol controlled smooth crabgrass by 68% to 73%, greater than any other PGR program evaluated. Results from these studies indicate that flurprimidol may be used to effectively control smooth crabgrass or goosegrass in creeping bentgrass turf. These are the first reported data regarding the use of flurprimidol for smooth crabgrass or goosegrass control in turf.

Introduction

Goosegrass and smooth crabgrass are problematic weeds in creeping bentgrass putting greens due to a lack of selective herbicide options. Currently, only five preemergence herbicides are labeled for control of goosegrass and smooth crabgrass in creeping bentgrass putting greens. These include bensulide, dithiopyr, siduron, methiozolin, and oxadiazon. Although bensulide is generally safe for creeping bentgrass turfgrass (Callahan and McDonald 1992) and effectively controls smooth crabgrass (Bingham and Schmidt 1967), it marginally controls goosegrass (Johnson 1982). Oxadiazon is commonly used for goosegrass and smooth crabgrass control in creeping bentgrass putting greens when applied with bensulide. Potential for creeping bentgrass injury (Johnson 1987) and incidents of goosegrass resistance to oxadiazon (McElroy et al. 2017) have driven many turfgrass managers to seek alternative methods for goosegrass and smooth crabgrass control in creeping bentgrass putting greens. Although some studies indicate that dithiopyr can be safely applied to creeping bentgrass putting greens (Dernoeden et al. 1993; Johnson 1994), it is rarely used by turfgrass managers due to restrictions on most product labels and the potential for stress-associated creeping bentgrass injury (Bhowmik and Bingham 1990; Hart et al. 2004). Brewer and Askew (2021) found that siduron selectively controls smooth crabgrass when applied biweekly at 5.6 kg ai ha^{-1}. However, siduron registration was not renewed during a recent review by the U.S. Environmental Protection Agency (US EPA 2018).

Methiozolin is a newly registered herbicide that is labeled for goosegrass and smooth crabgrass control in creeping bentgrass putting greens (Anonymous 2021). Creeping bentgrass putting green safety has been well documented with methiozolin (Askew 2017; Askew and McNulty 2014; Hoisington et al. 2014; McCullough et al. 2013), and methiozolin selectively controls goosegrass and smooth crabgrass when applied frequently preemergence (Peppers et al. 2024). However, methiozolin may be cost prohibitive for some turfgrass managers. In addition to recent studies of methiozolin (Peppers et al. 2024), other herbicides such as fenoxaprop-p ethyl and topramezone have successfully controlled smooth crabgrass or goosegrass when applied frequently at low doses on creeping bentgrass putting greens (Brewer and Askew 2021). This frequent treatment schedule for low doses of selected herbicides is similar to how plant growth regulators (PGRs) are used on golf greens.

PGRs are regularly used to suppress turfgrass growth, increase turfgrass green color, enhance abiotic stress tolerance, increase turfgrass stand density, and reduce plant water usage (Baldwin et al. 2009; Beam and Askew 2005; King et al. 1997; McCarty et al. 2011; McCullough et al. 2005). Paclobutrazol, ethephon, and flurprimidol are also regularly used to selectively suppress annual bluegrass (*Poa annua* L.) (Askew 2017; Peppers et al. 2021; Reicher et al. 2020) or to control it (Johnson and Murphy 1995; Reicher et al. 2015) in turf. These PGRs reduce the competitive advantage of annual bluegrass relative to creeping bentgrass (Johnson and Murphy 1996). Lowe and Whitwell (1999) evaluated goosegrass and large crabgrass (*Digitaria sanguinalis* L.) suppression via several PGRs applied postemergence, including trinexapac-ethyl, flurprimidol and paclobutrazol. No PGR evaluated reduced goosegrass or large crabgrass height greater than bermudagrass in this study. However, no peer-reviewed literature has evaluated these PGRs applied preemergence on goosegrass or smooth crabgrass.

In a long-term preliminary PGR study, Dernoeden (1982) observed that plots of Kentucky bluegrass (*Poa pratensis* L.) turfgrass treated with two yearly applications of flurprimidol had significantly less smooth crabgrass coverage than nontreated and mefluidide-treated plots. Although this observation was not further investigated by Dernoeden in any subsequent peer-reviewed literature, these results suggest that flurprimidol may have herbicidal activity on smooth crabgrass. In a preliminary study, Sawyer et al. (1983) observed a reduction in crabgrass (*Digitaria* spp.) establishment following applications of paclobutrazol and flurprimidol. No peer-reviewed literature was subsequently published further investigating the potential for smooth crabgrass control in turfgrass with paclobutrazol or flurprimidol. However, many subsequent studies have demonstrated the preemergence efficacy of paclobutrazol and flurprimidol on plant germination. Several researchers have found that flurprimidol reduces creeping bentgrass and annual bluegrass germination when applied preemergence (Gaussoin and Branham 1987; Haley and Fermanian 1989). Paclobutrazol inhibits the seed germination of many species of vegetables and other horticultural crops (Koukourikou-Petridou 1996; Mage and Powell 1990; Pressman and Shaked 1988).

Based on existing literature, we hypothesized that programmatic applications of flurprimidol or paclobutrazol would reduce smooth crabgrass and goosegrass coverage on creeping bentgrass putting greens, likely through residual effects on germinating seedlings or postemergence suppression of weedy grasses to favor improved turfgrass density. Therefore, studies were designed to evaluate four PGRs commonly used in creeping bentgrass putting greens for their effects on goosegrass and smooth crabgrass growth when applied prior to weed emergence and when multiple treatments are extended through the summer season.

Materials and Methods

Goosegrass and Smooth Crabgrass Greenhouse Response to Preemergence-Applied PGRs

Four greenhouse studies were conducted between winter 2021 and spring 2022 to evaluate smooth crabgrass and goosegrass foliar growth and root development in response to four PGRs applied either once preemergence or thrice biweekly. Two studies evaluated smooth crabgrass, whereas the other two evaluated goosegrass. All studies were repeated in time and space. Trials were arranged as randomized complete block designs with six replications and nine treatments that included an embedded four-by-two factorial arrangement with four levels of PGR treatment and two levels of application program compared to a nontreated control. The four levels of PGR treatment were flurprimidol (Cutless® MEC; SePro Corp, Carmel IN) applied at 280 g ai ha^{-1}, paclobutrazol (Trimmit® 2SC; Syngenta Crop Protection LLC, Greensboro, NC) applied at 280 g ai ha^{-1}, trinexapac-ethyl (PrimoMaxx®; Syngenta) applied at 53 g ai ha^{-1}, and prohexadione-calcium (Anuew™; Nufarm Americas Inc., Morrisville, NC) applied at 154 g ai ha^{-1}. The two levels of the application program included a single application made 1 h following seeding and a single application made 1 h after seeding followed by two additional biweekly applications to simulate a PGR reapplication schedule typically employed by golf course superintendents.

Approximately 50 goosegrass seeds and approximately 100 smooth crabgrass seeds were seeded into 4.4- by 7.6- by 12.7-cm pots containing a 2:1 ratio of sand to native soil mixture. The native soil admixture was a Groseclose-Urban land complex loam (clayey, mixed, mesic Typic Hapludults), pH 6.0, with 3.1% organic matter. All plants were fertilized with approximately 25 kg N ha^{-1} approximately 1 wk after germination to maintain proper plant growth. Irrigation was supplied twice daily to prevent plant wilt. Supplemental lighting of 750 μmol s^{-1} photosynthetically active radiation via sodium halide lights was set to a 14-h daylength throughout the studies. Greenhouse day/night temperatures were maintained at 29/24 C. All treatments were applied with a CO_2-pressurized backpack sprayer calibrated to deliver 374 L ha^{-1} at 331 kPa via TeeJet TTI11004 nozzles (Spraying Systems Co., Wheaton, IL). Following application, all pots were allowed to dry for 2 h before applying approximately 3 mm of overhead irrigation. Two weeks following the final application, aboveground biomass and root biomass were measured. Aboveground biomass was collected and dried at 50 C for 72 h prior to weighing. Root biomass was removed from each pot, washed clean of all debris, then dried at 50 C for 72 h, and weighed. The dried roots were then ashed in a muffle furnace at 500 C for approximately 8 h. The weight of the resulting matter was then weighed and subtracted from the measured root dry weight. Data were subjected to ANOVA with SAS software (v. 9.4; SAS Institute, Cary, NC) with sums of squares partitioned to reflect the four by two factorial treatment design and trial effects as previously described. Appropriate means were separated with Fisher's protected LSD test at $\alpha = 0.05$.

Field Evaluation of Smooth Crabgrass and Creeping Bentgrass as Affected by PGRs

Three field studies were conducted between 2022 and 2023 in Blacksburg, VA (37.22°N, 80.41°W), to evaluate smooth crabgrass control in creeping bentgrass using PGRs. Two trials were conducted at the Virginia Tech Turfgrass Research Center

(TRC) and one at the Glade Road Research Facility (GRRF). The two trials at the TRC were conducted on an 'L93' creeping bentgrass putting green maintained at 3.2 mm in 2022 (TRC1) and 2023 (TRC2). The trial conducted at GRRF was conducted in 2023 on an L93 creeping bentgrass fairway maintained at 12.7 mm. All trials were arranged as randomized complete block designs with six treatments and four replications. The treatments evaluated were flurprimidol (140 g ai ha^{-1}, Cutless MEC®; SePro Corporation, Rocky Mount, NC), trinexapac-ethyl (52.6 g ai ha^{-1}, Primo Maxx®; Syngenta Crop Protection LLC), flurprimidol plus trinexapac-ethyl (Legacy®; SePro Corporation), paclobutrazol (175 g ai ha^{-1}, Trimmit 2SC®; Syngenta Crop Protection LLC), fenoxaprop-p (17.5 g ai ha^{-1}, Acclaim Extra®; Bayer Environmental Science), and a nontreated control plot. Flurprimidol and paclobutrazol application rates were less than the rates used in the greenhouse study to reduce turfgrass injury potential throughout the growing season. Herbicides were applied via CO_2-pressurized sprayer calibrated to deliver 375 L ha^{-1} at 330 kPa. All treatments were applied every 3 wk, beginning prior to weed emergence (approximately April 15), throughout the growing season, for seven total applications per season. All treated plots received approximately 4 mm of irrigation approximately 2 h following application to wash flurprimidol and paclobutrazol treatments to the root system while also allowing for foliar absorption of trinexapac-ethyl and fenoxaprop-p. Smooth crabgrass coverage and creeping bentgrass injury were visually evaluated throughout the growing season as a percentage in which 0% equals no weed presence or turfgrass injury and 100% equals complete weed coverage or complete turfgrass death. At the conclusion of the studies (approximately August 30), smooth crabgrass coverage was assessed via line-intersect grids with 196 assessments per plot. Final assessments of weed control were extrapolated from the line-intersect counts by comparing weed coverage in the nontreated control in each replication versus the coverage in each treated plot. To control for variance structure in repeated measures over time, smooth crabgrass coverage data were transformed to the daily area under the progress curve (AUPC) (Askew et al. 2013). The area under the resulting curves was calculated using Equation 1:

$$\mathrm{AUPC} = \sum^{ni-1}\{[(y_i + y_{i+1})/2] * [t_{i+1} - ti]\} \quad [1]$$

where y_i is response variable y at the ith observation, t_i is days after initial application at the ith observation, and n is the number of observations. The resulting AUPC was then converted to AUPC d^{-1} by dividing AUPC by the total number of days spanned by assessments. Similarly, creeping bentgrass injury data were expressed as the number of days over an injury threshold of 20% (DOT_{20}). These injury DOT_{20} values were calculated assuming linear trends in changes to creeping bentgrass injury between assessment dates. All data were subjected to ANOVA with SAS software (v. 9.4) to test for significance between trial locations and treatments with appropriate means separated using Fisher's protected LSD at $\alpha = 0.05$. The nontreated control plot data were excluded from the analysis for the end-of-season smooth crabgrass control data.

Results and Discussion

Goosegrass and Smooth Crabgrass Response to PRE-Applied PGRs in a Controlled Environment

The trial-by-treatment interaction on smooth crabgrass aboveground biomass was insignificant ($P = 0.654$), therefore, aboveground biomass data were pooled over the two greenhouse trials. The PGR main effect, the application program main effects, and PGR by application program interaction, were significant ($P = <0.0001$, 0.025, and 0.036, respectively). Single preemergence applications of flurprimidol, paclobutrazol, and trinexapac-ethyl reduced smooth crabgrass aboveground biomass by 34%, 37%, and 17% respectively, relative to the nontreated control (Table 1). Single preemergence prohexadione-calcium applications did not reduce smooth crabgrass aboveground biomass compared with the other PGR treatments. Turfgrass response to prohexadione-calcium varies depending on species when the product is applied to actively growing foliage (Beam and Askew 2005), but plant response to preemergence treatments has not been reported. For all PGR treatments except trinexapac-ethyl, two additional biweekly applications reduced smooth crabgrass biomass compared to single preemergence applications. Three biweekly applications of flurprimidol and paclobutrazol reduced smooth crabgrass aboveground biomass by 67% and 69%, respectively, relative to the nontreated control, and more than trinexapac-ethyl and prohexadione-calcium. Three biweekly applications of trinexapac-ethyl and prohexadione-calcium reduced smooth crabgrass aboveground biomass compared to the nontreated control similarly (21% and 33%, respectively). Trinexapac-ethyl was the only PGR for which additional applications did not further decrease smooth crabgrass aboveground biomass.

The main effect of PGR was significant for smooth crabgrass root biomass ($P = 0.0002$), and this was not influenced by the interacting effects of the trial ($P = 0.185$) or application program ($P = 0.381$). Multiple PGR applications did not reduce root biomass compared to single preemergence applications. This lack of application program effect was expected from trinexapac ethyl and prohexadione-calcium since they had minimal impact on foliar biomass and did not reduce root biomass more than 15% (Table 1). The lack of a differential effect on root biomass from flurprimidol and paclobutrazol was surprising because these products applied sequentially reduced foliar biomass to approximately half that of plants treated only once (Table 1). Apparently, flurprimidol and paclobutrazol are highly effective at reducing root biomass regardless of the number of treatments, as they reduced smooth crabgrass root biomass by 74% on average compared to the nontreated control (Table 1).

The effect of the trial on goosegrass aboveground biomass was also insignificant ($P = 0.681$). Therefore, data are pooled over trials. The main effects of PGR and application program on goosegrass aboveground biomass were significant ($P = 0.008$ and $P = 0.029$, respectively), with no significant interaction ($P = 0.191$). Like smooth crabgrass, trinexapac-ethyl and prohexadione-calcium had limited effect on goosegrass growth regardless of application program. When averaged over both application programs, flurprimidol and paclobutrazol reduced goosegrass aboveground biomass by 66% and 59%, respectively, relative to the nontreated control (Table 1). Trinexapac-ethyl and prohexadione-calcium reduced goosegrass aboveground biomass by 24% and 19%, respectively, relative to the nontreated control. Single and sequential PGR applications reduced goosegrass aboveground biomass by 28% and 56%, respectively, relative to the nontreated control, and were significantly different (data not shown).

The main effect of PGR was the only significant effect on goosegrass root biomass reduction ($P = 0.029$). When averaged across application programs, flurprimidol and paclobutrazol reduced goosegrass root biomass by 80% and 73%, respectively (Table 1). Conversely, trinexapac-ethyl and prohexadione-calcium only reduced goosegrass root biomass by 27% and 24%, respectively.

Table 1. Influence of plant growth regulator and either a single PRE application or three biweekly applications (PRE + POST) on smooth crabgrass and goosegrass aboveground and root biomass percent reduction relative to the nontreated control in a greenhouse study.[a–c]

	Biomass reduction				
	Smooth crabgrass			Goosegrass	
	Aboveground				
	PRE	PRE + POST	Root	Aboveground	Root
PGR[d]			%		
Flurprimidol	34 a**	67 a**	74 a	66 a	80 a
Paclobutrazol	37 a**	69 a**	74 a	59 a	73 a
Prohexadione-calcium	−12 b**	33 b**	3 b	19 b	24 b
Trinexapac ethyl	17 b	21 b	15 b	24 b	27 b

[a]Abbreviations: PGR, plant growth regulator; POST, postemergence; PRE, preemergence.
[b]Different letters following means indicate significant differences between means within a given column. A negative value indicates an increase relative to the nontreated, whereas positive values indicate a decrease relative to the non-treated.
[c]Letters followed by asterisks (**) indicate significant differences between application programs within a given PGR treatment.
[d]Flurprimidol, paclobutrazol, prohexadione-calcium, and trinexapac-ethyl treatments were applied at 280, 280, 154, and 53 g ai ha^{-1}, respectively. Approximately 3 mm of irrigation was applied 2 h after application to ensure root uptake of flurprimidol and paclobutrazol.

Results from this study indicate that flurprimidol and paclobutrazol reduce smooth crabgrass and goosegrass aboveground and root biomass more than trinexapac-ethyl and prohexadione-calcium. Previous research indicates that trinexapac-ethyl will not affect or increase the rooting of other grass species (McCarty et al. 2011; McCullough et al. 2005). Prohexadione-calcium is similar to trinexapac-ethyl in that both are late-stage gibberellin inhibitors in the same chemical family (Beam and Askew 2005; Nakayama et al. 1992). Previous research also indicates limited influence of trinexapac-ethyl and prohexadione-calcium specifically on goosegrass and crabgrass species. Henry et al. (2020) observed low growth regulation (14% to 30%) of goosegrass and moderate regulation (40% to 49%) of large crabgrass (*Digitaria sanguinalis* L.) with trinexapac-ethyl and prohexadione-calcium. Additionally, preliminary research indicates that trinexapac-ethyl can even increase goosegrass growth in creeping bentgrass turfgrass systems (Diehl and Elmore 2024). Conversely, paclobutrazol and flurprimidol can decrease the root biomass of creeping bentgrass (Fagerness and Yelverton 2001; Hanson and Branham 1987). Although flurprimidol and paclobutrazol reduced weed root biomass by a significant amount in this study, the reduction was not comparable to that of typical preemergence herbicides such as dinitroanilines (Bhowmik and Bingham 1990; Johnson 1996). In these studies, however, flurprimidol and paclobutrazol reduced smooth crabgrass and goosegrass root biomass more than previously reported creeping bentgrass root reduction from flurprimidol and paclobutrazol (approximately 20% reduction; Fagerness and Yelverton 2001). Additionally, flurprimidol and paclobutrazol reduced weed aboveground biomass by approximately 65%, whereas paclobutrazol reduced creeping bentgrass aboveground growth by approximately 50% in a previous study by Kreuser et al. (2018). Results from our studies corroborate the limited goosegrass and smooth crabgrass growth regulation observed following trinexapac ethyl or prohexadione-calcium treatment in previous literature, but this study is the first to present data comparing root and foliar growth of goosegrass and smooth crabgrass in response to flurprimidol and paclobutrazol. These data indicated that flurprimidol or paclobutrazol may reduce the competitiveness of smooth crabgrass and goosegrass in creeping bentgrass, which suggested that further field evaluations were warranted.

Field Evaluation of Smooth Crabgrass and Creeping Bentgrass as Affected by PGRs

The trial-by-treatment interaction was significant for smooth crabgrass AUPC d^{-1} ($P < 0.0001$); therefore, the three trials are presented separately. An increase in smooth crabgrass cover at TRC1 likely reduced treatment performance and contributed to the trial interaction. For example, trinexapac ethyl smooth crabgrass AUPC d^{-1} was equivalent to nontreated turfgrass at TRC1 but differed at the other two locations. Flurprimidol + trinexapac also performed inconsistently across locations because it decreased smooth crabgrass AUPC d^{-1} compared to trinexapac ethyl at TRC1 and GRRF, but not at TRC2 (Table 2). TRC2 received more frequent applications of preventative fungicides and was maintained with approximately 60% greater nitrogen fertility (data not shown). Trinexapac-ethyl is commonly applied to improve creeping bentgrass quality (Fagerness et al. 2002; King et al. 1997; Kreuser and Soldat 2011) and may have increased the ability of creeping bentgrass to compete against smooth crabgrass at TRC2. Trinexapac-ethyl suppressed smooth crabgrass early in the growing season similar to other treatments at this location resulting in lower AUPC d^{-1} at TRC2 relative to other trial locations. Despite these differences, the mean rank at TRC2 and GRRF were similar for all treatments and both fenoxaprop-p and flurprimidol consistently yielded the lowest smooth crabgrass AUPC d^{-1} at all sites.

It should be noted that all of these sites had smooth crabgrass infestation levels that resulted in nearly complete late-season smooth crabgrass coverage (data not shown). Evidence of high weed pressure lies in the smooth crabgrass coverage AUPC d^{-1}, which was 44% to 59% depending on the site. Considering that the season starts with no smooth crabgrass and considerable time is needed for smooth crabgrass population expansion, these AUPC d^{-1} values would necessitate more than 70% late-season smooth crabgrass coverage at all sites. Although smooth crabgrass AUPC d^{-1} following paclobutrazol treatment was always numerically twice that of flurprimidol or fenoxaprop-p, paclobutrazol plots had statistically equivalent AUPC d^{-1} compared to flurprimidol and fenoxaprop-p at two of the three locations (Table 2).

The trial-by-treatment interaction for end-of-season smooth crabgrass control was insignificant ($P = 0.193$), whereas the treatment main effect was significant ($P < 0.0001$); therefore, all end-of-season smooth crabgrass control data were pooled over sites. Fenoxaprop-p controlled smooth crabgrass by 95%, greater than all other treatments (Table 2). However, fenoxaprop-p was the only treatment that significantly increased creeping bentgrass injury DOT_{20} compared to the nontreated plots (17 d; data not shown). Averaged across all site-years, flurprimidol alone and in conjunction with trinexapac-ethyl controlled smooth crabgrass by 76% and 68%, respectively, more than all other PGR treatments. Although greenhouse studies indicated that paclobutrazol should suppress smooth crabgrass similarly to flurprimidol, late-season smooth crabgrass control by paclobutrazol was 46%, which was less than that of flurprimidol and more that of trinexapac-ethyl (18%). The differential response of late-season smooth crabgrass to paclobutrazol and flurprimidol appears to conflict with season-long AUPC data in which both PGRs collectively controlled

https://doi.org/10.1017/wet.2024.32 Published online by Cambridge University Press

Table 2. Influence of treatment on smooth crabgrass coverage area under the progress curve per day and end-of-season control.[a,b]

	Rate	Coverage AUPCD[c,d]			End-of-season control[e]
		TRC1	TRC2	GRRF	
Treatment[f]	g ai ha^{-1}	%			
Nontreated	–	59 a	45 a	44 a	-
Fenoxaprop-p	17.5	3 d	0 c	6 c	95 a
Flurprimidol	140	12 c	6 c	8 c	73 b
Flurprimidol + trinexapac ethyl	140 + 52.6	22 b	10 bc	8 c	68 b
Paclobutrazol	175	26 b	14 bc	19 bc	46 c
Trinexapac ethyl	52.6	58 a	24 b	30 b	18 d

[a]Abbreviations: AUPCD, area under the progress curve d^{-1}; GRRF, Glade Road Research Facility; TRC1 and TRC2, Virginia Tech Turfgrass Research Center trial 1 and trial 2, respectively.
[b]Letters following means denote significant differences between means within a given column.
[c]AUPCD was calculated by assuming linear changes in smooth crabgrass coverage between rating assessments.
[d]Trials at TRC1 and TRC2 were conducted on ‘L93’ creeping bentgrass putting greens maintained at 3.2 mm. The trial at GRRF was conducted on an L93 creeping bentgrass fairway maintained at 12.7 mm.
[e]End-of-season smooth crabgrass control was derived via line-intersect counts taken at the conclusion of the trial (approximately August 30) and compared with that of the nontreated within a given replication.
[f]Approximately 4 mm of irrigation was applied approximately 2 h following application to allow for root uptake of flurprimidol and paclobutrazol according to label recommendations.

smooth crabgrass equivalently. Responses following the two PGR treatments diverged only at the end of the season. Potentially greater creeping bentgrass suppression with paclobutrazol during periods of heat stress may have limited late-season competition between creeping bentgrass and smooth crabgrass. Although paclobutrazol has been reported to injure creeping bentgrass during summer heat (Baldwin and Brede 2011), visible evidence of creeping bentgrass injury was not apparent in the current study.

These results indicate that flurprimidol-containing treatments will more effectively suppress smooth crabgrass throughout the growing season in creeping bentgrass than other PGR treatments, particularly trinexapac-ethyl. These results are consistent with previous literature in which flurprimidol effectively suppressed grass species when applied preemergence (Gaussoin and Branham 1987; Haley and Fermanian 1989). Although flurprimidol and paclobutrazol share a similar mode of action (Ervin and Zhang 2008), peer-reviewed literature evaluating paclobutrazol on grass germination is lacking. Several published studies have detailed germination inhibition via paclobutrazol but are limited to broadleaf plant species (Koukourikou-Petridou 1996; Mage and Powell 1990; Pasian and Bennett 2001; Pressman and Shaked 1988). Conversely, flurprimidol reduces grass species germination (Gaussoin and Branham 1987; Haley and Fermanian 1989). It is possible that the difference in smooth crabgrass control between paclobutrazol and flurprimidol is a difference in selectivity. However, paclobutrazol and flurprimidol similarly affected smooth crabgrass in the greenhouse. It is more likely that the difference in smooth crabgrass control with paclobutrazol and flurprimidol was due to differential late-season creeping bentgrass suppression between the two growth regulators.

Practical Implications

Results from these studies indicate programmatic flurprimidol use can significantly reduce smooth crabgrass and goosegrass invasion into creeping bentgrass turf. In the U.S. transition zone, trinexapac-ethyl is commonly used on creeping bentgrass turfgrass in the summer months to increase putting green speed, color, and root mass (Fagerness et al. 2002; King et al. 1997; Kreuser and Soldat 2011). Conversely, flurprimidol and paclobutrazol are often avoided due to perceived injury risks to creeping bentgrass in warmer, transition-zone summers as was observed by Baldwin and Brede (2011). However, neither paclobutrazol nor flurprimidol unacceptably injured creeping bentgrass in this research, which is consistent with previous literature (Koski 1997; Petelewicz 2021; Reicher et al. 2015). Many turfgrass managers include early-gibberellin-inhibiting PGRs with trinexapac-ethyl applications to prolong creeping bentgrass growth suppression while maintaining the physiological benefits associated with trinexapac-ethyl applications (Kreuser et al. 2018). Results from these studies indicate that flurprimidol and trinexapac-ethyl applied in conjunction controls smooth crabgrass as effectively as flurprimidol applied alone. Likewise, paclobutrazol increased smooth crabgrass control more than trinexapac ethyl, but not as much as programs that contain flurprimidol. Although goosegrass was not evaluated in the field studies, it responded similarly to that of smooth crabgrass in the greenhouse studies. It can be inferred that flurprimidol may control goosegrass similarly to smooth crabgrass. Preliminary observations by McElroy et al. (2018) indicate that flurprimidol can effectively reduce goosegrass coverage within creeping bentgrass putting greens. These are the first published data regarding using flurprimidol or paclobutrazol for selective control of smooth crabgrass or goosegrass in creeping bentgrass turf.

Acknowledgments. We thank Mr. John Hinson for maintaining research plots in Blacksburg, VA.

Funding. This research received no specific grant from any funding agency, commercial or not-for-profit sectors.

Competing interests. The authors declare they have no competing interests.

References

Anonymous (2021) PoaCure® specimen label. Daejon, South Korea: Moghu Research Center Ltd.

Askew SD (2017) Plant growth regulators applied in winter improve annual bluegrass (*Poa annua*) seedhead suppression on golf greens. Weed Technol 31:701–713

Askew WB, Goatley JM, Askew SD, Hensler, KL, McKissack DR (2013). A comparison of turfgrasses for cemeteries and other low-input areas. Int Turfgrass Soc Res J 12:245–250

Askew SD, McNulty BMS (2014) Methiozolin and cumyluron for preemergence annual bluegrass (*Poa annua*) control in creeping bentgrass (*Agrostis stolonifera*) putting greens. Weed Technol 28:535–542

Baldwin CM, Brede AD (2011) Plant growth regulator selection and application rate influence annual bluegrass control in creeping bentgrass putting. Appl Turf Sci doi: 10.1094/ATS-2011-0517-02-RS

Baldwin CM, Liu H, McCarty LB, Luo H, Toler JE (2009) Nitrogen and plant growth regulator influence on 'Champion' bermudagrass putting green under reduced sunlight. Agron J 101:75–81

Beam JB, Askew SD (2005) Prohexadione-calcium effects on bermudagrass, Kentucky bluegrass, perennial ryegrass, and zoysiagrass. Int Turf Soc Res J 10:286–295

Bhowmik PC, Bingham SW (1990) Preemergence activity of dinitroaniline herbicides used for weed control in cool-season turfgrasses. Weed Technol 4:387–393

Bingham SW, Schmidt RE (1967) Residue of bensulide in turfgrass soil following annual treatment for crabgrass control. Agron J 59:327–329

Brewer JR, Askew SD (2021) Investigating low-dose herbicide programs for goosegrass (*Eleusine indica*) and smooth crabgrass (*Digitaria ischaemum*) control on creeping bentgrass greens. Weed Technol 35:604–610

Callahan LM, McDonald ER (1992) Effectiveness of bensulide in controlling two annual bluegrass (*Poa annua*) subspecies. Weed Technol 6:97–103

Dernoeden PH (1982) Effects of growth retardants applied three successive years to a Kentucky bluegrass turf. Proc Northeast Weed Sci Soc 36:339–343

Dernoeden PH, Christians NE, Krouse JM, Roe RG (1993) Creeping bentgrass rooting as influenced by dithiopyr. Agron J 85:560–563

Diehl KH, Elmore ME (2024) Goosegrass (*Eleusine indica*) ecotypes affected by cultural management and plant growth regulators in turfgrass. Proc Northeastern Weed Sci Soc 77:56

Ervin EH, Zhang X (2008) Applied physiology or natural and synthetic plant growth regulators on turfgrass. Pages 171–203 *in* M. Pessarakli, ed., Handbook of Turfgrass Management and Physiology. Boca Raton, FL: CRC Press

Fagerness M, Yelverton FH (2001) Plant growth regulator and mowing height effects on seasonal root growth of penncross creeping bentgrass. Crop Sci 41:1901–1905

Fagerness MJ, Yelverton FH, Isgrigg J, Cooper RJ (2002) Plant growth regulators and mowing height affect ball roll and quality of creeping bentgrass putting greens. HortScience 35:755–759

Gaussoin RE, Branham BE (1987) Annual bluegrass and creeping bentgrass germination response to flurprimidol. HortScience 22:441–442

Haley JE, Fermanian TW (1989) Flurprimidol effect on the emergence and growth of annual bluegrass and creeping bentgrass. Agron J 81:198–202

Hanson KV, Branham BE (1987) Effects of four growth regulators on photosynthate partitioning in 'Majestic' Kentucky bluegrass. Crop Sci 27:1257–1260

Hart SE, Lycan DW, Murphy JA (2004) Response of creeping bentgrass to (*Agrostis stolonifera*) to fall applications of bensulide and dithiopyr. Weed Technol 18:1072–1076

Henry GM, Moore M, Tucker KA (2020) Response of creeping bentgrass (*Agrostis stolonifera*) and weed species to plant growth regulators. Int Turfgrass Soc Res J 14:791–796

Hoisington NR, Flessner ML, Schiavon M, McElroy JS, Baird JH (2014) Tolerance of bentgrass (*Agrostis*) species and cultivars to methiozolin. Weed Technol 28:501–509

Johnson BJ (1982) Combinations of herbicides for winter and summer weed control in turf. Agron J 74:37–40

Johnson BJ (1987) Tolerance of bentgrass to dates and frequency of preemergence herbicide treatments. Agron J 79:992–996

Johnson BJ (1994) Creeping bentgrass quality following preemergence and postemergence herbicide applications. HortScience 29:880–883

Johnson BJ (1996) Reduced rates of preemergence and postemergence herbicides for large crabgrass (*Digitaria sanguinalis*) and goosegrass (*Eleusine indica*) control in bermudagrass (*Cynodon dactylon*). Weed Sci 44:585–590

Johnson BJ, Murphy TR (1995) Effect of paclobutrazol and flurprimidol on suppression of *Poa annua* spp. *reptans* in creeping bentgrass (*Agrostis stolonifera*) greens. Weed Technol 9:182–186

Johnson BJ, Murphy TR (1996) Suppression of a perennial subspecies of annual bluegrass (*Poa annua* spp. *reptans*) in a creeping bentgrass (*Agrostis stolonifera*) green with plant growth regulators. Weed Technol 10:705–709

King R, Blundell C, Evans L, Mander L, Wood J (1997) Modified gibberellins retard growth of cool-season turfgrasses. Crop Sci 37:1878–1883

Koski AJ (1997) Influence of paclobutrazol on creeping bentgrass (*Agrostis stolonifera* L.) root production and drought resistance. Int Turfgrass Soc Res J 8:699–709

Koukourikou-Petridou MA (1996) Paclobutrazol affects growth of almond fruits and germination of almond seeds. Plant Growth Regul 20:267–269

Kreuser WC, Obear GR, Michael DJ, Soldat DJ (2018) Growing degree-day models predict the performance of paclobutrazol on bentgrass putting greens. Crop Sci 58:1402–1408

Kreuser WC, Soldat DJ (2011) A growing degree day model to schedule trinexapac-ethyl applications on golf putting greens. Crop Sci 51: 2228–2236

Lowe DB, Whitwell T (1999) Plant growth regulators alter the growth of 'Tifway' bermudagrass (*Cynodon transvaalensis* × *C. dactylon*) and selected turfgrass weeds. Weed Technol 13:132–138

Mage F, Powell L (1990) Inhibition of stratification and germination of apple seeds by paclobutrazol. HortScience 25:577

McCarty LB, Willis TG, Toler JE, Whitwell T (2011) 'TifEagle' bermudagrass response to plant growth regulators and mowing height. Agron J 103:988–994

McCullough PE, Gomez de Barreda D, Jialin Y (2013) Selectivity of methiozolin for annual bluegrass (*Poa annua*) control in creeping bentgrass as influenced by temperature and application timing. Weed Sci 61:209–216

McCullough PE, Liu H, McCarty LB (2005) Trinexapac-ethyl application regimens influence creeping bentgrass putting green performance. HortScience 40:2167–2169

McElroy JS, Boyd AP, Peppers JM, Brown AM (2018) Can PGRs control goosegrass in golf putting greens? Proc South Weed Sci Soc 71:255

McElroy JS, Head WB, Whetje GR, Spak D (2017) Identification of goosegrass (*Eleusine indica*) biotypes resistant to preemergence-applied oxadiazon. Weed Technol 31:675–681

Nakayama IM, Kobayashi Y, Kamiya H, Sakurai A (1992) Effects of a plant-growth regulator, prohexadione-calcium (BX 112), on the endogenous levels of gibberellins in rice. Jpn Soc Plant Physiol 33:59–62

Pasian CC, Bennett MA (2001) Paclobutrazol soaked marigold, geranium, and tomato seeds produce short seedlings. HortScience 36:721–723

Peppers JM, Brewer JR, Askew SD (2021) Plant growth regulator and low-dose herbicide programs for annual bluegrass seedhead suppression in fairway and athletic-height turf. Agron J 113:3800–3807

Peppers JM, McElroy JS, Orlinski PM, Baird J, Petelewicz P, Joseph MM, Sierra-Augustinus IA, Schiavon M, Askew SD (2024) Methiozolin rate and application frequency influences goosegrass and smooth crabgrass control. Weed Technol 38:1–9

Petelewicz P, Orlinski PM, Baird JH (2021) Suppression of annual bluegrass in creeping bentgrass putting greens using plant growth regulators. HortTechnology 31:155–165

Pressman E, Shaked R (1988) Germination of annual celery (*Apium graveolens*) seeds: inhibition by paclobutrazol and its reversals by gibberellins and benzyladinine. Physiol Plant 73:323–326

Reicher ZJ, Sousek MD, Patton AJ, Van Dyke A, Kreuser WC, Inguagiato JC, Miele KM, Brewer J, Askew SD, Hathaway A, Nikolai TA, Kowalewski A, McDonald B (2020) Adding a late fall application of Proxy (ethephon) before two traditional spring applications improves seedhead control of annual bluegrass. Crop Forage Turfgrass Manag doi: 10.1002/cft2.20031

Reicher Z, Sousek M, Patton A, Weisenberger D, Hathaway A, Calhoun R (2015) Annual bluegrass control on putting greens from three or four years of season-long applications of herbicides or plant growth regulators in three states. Crop Forage Turfgrass Manag doi: 10.2134/cftm2014.0050

Sawyer CD, Wakefield RC, Jagschitz JA (1983) Evaluation of growth retardants for roadside turf. Proc Northeast Weed Sci Soc 37:372–375

[US EPA] U.S. Environmental Protection Agency (2018) Product cancellation order for certain pesticide registrations and amendments to terminate uses. Federal Register 83 FR 47477