Annual bluegrass weevil (Listronotus maculicollis) and paclobutrazol control annual bluegrass (Poa annua) in creeping bentgrass fairways

Authors: Diehl, Katherine H., Elmore, Matthew T., Koppenhöfer, Albrecht M., Murphy, James A., and Kostromytska, Olga S.

Source: Weed Technology, 36(1) : 137-144

Published By: Weed Science Society of America

URL: https://doi.org/10.1017/wet.2021.106

Weed Technology

www.cambridge.org/wet

Annual bluegrass weevil (*Listronotus maculicollis*) and paclobutrazol control annual bluegrass (*Poa annua*) in creeping bentgrass fairways

Katherine H. Diehl[1], Matthew T. Elmore[2], Albrecht M. Koppenhöfer[3], James A. Murphy[4] and Olga S. Kostromytska[5]

[1]Graduate Research Assistant, Department of Plant Biology, Rutgers University, New Brunswick, NJ, USA; [2]Assistant Extension Specialist, Department of Plant Biology, Rutgers University, New Brunswick, NJ, USA; [3]Extension Specialist, Department of Entomology, Rutgers University, New Brunswick, NJ, USA; [4]Extension Specialist, Department of Plant Biology, Rutgers University, New Brunswick, NJ, USA and [5]Postdoctoral Research Associate, Department of Entomology, Rutgers University, New Brunswick, NJ, USA

Research Article

Cite this article: Diehl KH, Elmore MT, Koppenhöfer AM, Murphy JA, Kostromytska OS (2022) Annual bluegrass weevil (*Listronotus maculicollis)* and paclobutrazol control annual bluegrass (*Poa annua*) in creeping bentgrass fairways. Weed Technol. **36**: 137–144. doi: 10.1017/wet.2021.106

Received: 30 June 2021
Revised: 15 October 2021
Accepted: 1 December 2021
First published online: 26 January 2022

Associate Editor:
Barry Brecke, University of Florida

Nomenclature:
Paclobutrazol; annual bluegrass weevil; *Listronotus maculicollis* Kirby; annual bluegrass; *Poa annua* L.; creeping bentgrass; *Agrostis stolonifera* L.

Keywords:
Plant growth regulators; annual bluegrass control; biological control; integrated pest management; turfgrass

Author for correspondence:
Katherine Diehl, Graduate Research Associate, Department of Plant Biology, Rutgers University, 59 Dudley Rd., New Brunswick, NJ 08091 Email: katherine.diehl@rutgers.edu

Abstract

The annual bluegrass weevil (ABW) is a pest of fine turfgrass, but recent research has found that withholding insecticides for ABW control can reduce annual bluegrass cover. The objective of this research was to evaluate threshold-based insecticide and paclobutrazol programs for annual bluegrass control. The effect of three insecticide programs (preventive, threshold, and no insecticide) and four rates of paclobutrazol (0, 70, 105, or 210 g ha^{-1} applied monthly) were evaluated. Replicate experiments were conducted from April to November in both 2018 and 2019 on a mixed creeping bentgrass and annual bluegrass fairway in North Brunswick, NJ. By the conclusion of both experiments, all paclobutrazol programs exhibited reduced annual bluegrass cover compared with the nontreated plots. In threshold and no-insecticide programs, reduction in annual bluegrass cover was enhanced by paclobutrazol applied at 105 g ha^{-1} in both years, and at 70 g ha^{-1} in the 2019 experiment. Paclobutrazol at 210 g ha^{-1} resulted in annual bluegrass cover of <20% regardless of insecticide program. In 2019, threshold-based ABW control without paclobutrazol provided similar annual bluegrass control as monthly applications of paclobutrazol at 70 and 105 g ha^{-1} with the preventive insecticide program. A reduction in turfgrass quality from threshold-based insecticide programs persisted for a shorter duration than the no-insecticide program, regardless of paclobutrazol treatment. Threshold-based ABW insecticide programs that allow ABW feeding damage to occur can result in reduced annual bluegrass cover. These reductions were further enhanced by paclobutrazol applications. The combination of threshold-level insecticide with moderate rates of paclobutrazol (70 to 105 g ha^{-1}) provided reductions in annual bluegrass cover that were similar to the highest rate of paclobutrazol (210 g ha^{-1}) without ABW damage. Turfgrass managers who integrate the threshold-level insecticide approach and monthly paclobutrazol applications may achieve greater annual bluegrass control than either strategy alone if temporary reductions in turf quality can be tolerated.

Introduction

Annual bluegrass s one of the most well-studied weeds of cool season turfgrass (Beard et al. 1978). Tolerant to low mowing heights and well adapted to turfgrass systems, annual bluegrass exhibits r-species behavior, producing large amounts of seed to rapidly colonize new areas and reestablish transient populations throughout the year (Kaminski and Dernoeden 2007; Lush 1988; Tutin 1952). Annual bluegrass is more prone to injury from abiotic and biotic stress than other cultivated cool-season turfgrass species, including creeping bentgrass, and typically requires more supplemental management to mitigate annual bluegrass decline and provide acceptable turfgrass quality in the summer (Hempfling et al. 2017; Inguagiato et al. 2008, 2009, 2012; Ong et al. 1978; Schmid et al. 2017). Infestations are difficult to eradicate, thus even though annual bluegrass is considered to be a weed, management practices to optimize its growth are often adopted to preserve the integrity of the sward.

The use of postemergence herbicides such as amicarbazone, bispyribac-sodium, and ethofumesate for annual bluegrass control in cool-season turfgrass is often limited by the poor tolerance that creeping bentgrass has to them (McCullough and Hart 2006; McCullough et al. 2010; Meyer and Branham 2006; Yu et al. 2015). In addition, selective herbicides are typically not suitable for severe infestations where rapid annual bluegrass control would leave large voids in the turf sward (Lycan and Hart 2006). Alternatively, the gibberellic acid (GA) biosynthesis inhibitors paclobutrazol and flurprimidol, often referred to as plant growth regulators (PGRs), offer more gradual annual bluegrass control (Johnson and Murphy 1996; McCullough et al. 2005; Patton et al. 2019; Woosley et al. 2003).

PGRs have many applications in turfgrass management, and because annual bluegrass is more sensitive to paclobutrazol and flurprimidol than desirable turfgrass species, repeated PGR applications can reduce the competitive advantage of annual bluegrass on putting greens and fairways, thus reducing annual bluegrass populations over time (McCullough et al. 2005, Patton et al. 2019, Woosley et al. 2003). Considerably less research is available regarding paclobutrazol for annual bluegrass control on golf course fairways, even though they comprise approximately 10 times more acreage than putting greens (Lyman et al. 2007).

Paclobutrazol and flurprimidol efficacy against annual bluegrass is contingent on application frequency. Research carried out by Woosley et al. (2003) noted that monthly applications of paclobutrazol (0.28 and 0.14 kg ha^{-1}) from March to August resulted in 85% annual bluegrass control in creeping bentgrass fairways. McCullough et al. (2005) found that regimens of paclobutrazol (0.42 to 0.56 kg ha^{-1}) applied sequentially provided better annual bluegrass control than single spring or summer applications to creeping bentgrass fairways. Bigelow et al. (2007) found that a monthly application of flurprimidol reduced annual bluegrass cover from >30% to <10% on creeping bentgrass fairways. Diehl et al. (2021) reported that 2 yr of monthly application of paclobutrazol (280 g ha^{-1}) eliminated annual bluegrass in a simulated creeping bentgrass fairway (initially 80% cover), whereas 35% cover remained in nontreated plots. Yet, at a second site with more perennial annual bluegrass populations, 2 yr of the same paclobutrazol regime was less effective. Although the effects of PGR rate and frequency for annual bluegrass control in fairways is relatively well understood, far less is known about how they interact with other pest management practices.

Recent research has identified a native and endemic pest, the annual bluegrass weevil (ABW), as a biological control for annual bluegrass in creeping bentgrass fairways (Diehl et al. 2021). The ABW has been recognized as a pest of cool-season turfgrass in the northeastern United States since 1931, and its ovipositional preference for annual bluegrass over creeping bentgrass is well documented (Britton 1932; Cameron and Johnson 1971; Kostromyska and Koppenhöfer 2014, 2016). This preference is showcased by overwintering ABW adults as they emerge in spring and lay their eggs inside the grass stem between the leaf sheaths (Cameron and Johnson 1971). Those eggs hatch into larvae and go through five instars before pupating into new adults, completing the life cycle. Although small larvae are able to tunnel the stem, they eventually become too large and exit the plant. Fourth and fifth instar generations feed on the base of the plant, severing stems and potentially damaging the crown, which can cause substantial plant injury (Cameron and Johnson 1971). Although ABW may produce up to three generations each year, the first-generation larvae typically cause the most severe turfgrass damage (Cowles et al. 2008; Vittum et al. 1999). For this reason, turf managers often apply insecticides to control adults before egg-laying and then apply more insecticide to control larvae (McGraw and Koppenhöfer 2017). As a result of repeated insecticide applications, widespread pyrethroid-resistant ABW have been reported, including several cases of cross-resistance (Koppenhöfer et al. 2018; Kostromytska et al. 2018). Such excessive insecticide use warrants the development of alternatives to synthetic insecticides for the management of ABW.

Previous research by these authors investigated whether paclobutrazol at 280 g ha^{-1} applied monthly enhances biological control of annual bluegrass by the ABW in a 2-yr field study. This paclobutrazol program was extremely effective alone and we were not able to observe whether it was enhanced by annual bluegrass control from the ABW (Diehl et al. 2021). Therefore, the objective of this research was to determine whether ABW larvae could control annual bluegrass alone or in combination with applications of paclobutrazol. Various rates of paclobutrazol were selected to observe the rate-response of this interaction. We hypothesized that withholding insecticides as a way of controlling ABW would reduce annual bluegrass cover in creeping bentgrass fairways and that paclobutrazol applied monthly would further increase that control.

Materials and Methods

Research was conducted in 2018 and 2019 on two adjacent sites infested with annual bluegrass and a history of ABW infestation on a simulated creeping bentgrass fairway at Rutgers Hort Farm No. 2 in North Brunswick, NJ (40.47027289438639°N, 74.4219104919815°W). Annual bluegrass cover was initially uniform and visually estimated to be 80% and 74% in April 2018 and 2019, respectively. The fairway was grown on a Nixon silt loam (fine-loamy, mixed, semiactive, mesic Typic Hapludults), pH 6.1, and mown thrice weekly to 1 cm with a triplex reel mower. Irrigation was provided to optimize annual bluegrass growth, and nitrogen fertilizer was applied as needed at 10 to 25 kg ha^{-1}, totaling 90 to 135 kg N ha^{-1} annually. Fungicides were applied every 3 wk from April to October to prevent turfgrass diseases including dollar spot (caused by *Clarireedia jacksonii*), brown patch (caused by *Rhizoctonia solani*), summer patch (caused by *Magnaporthe poae*), and anthracnose (caused by *Colletotrichum graminicola*). Each July, imidacloprid (Merit; Bayer, Research Triangle Park, NC; 0.34 kg ha^{-1}) was applied to all plots to control white grub (Coleoptera: Scarabaeidae).

Treatments were applied to 1.0- by 2.0-m plots, arranged in a complete factorial design (paclobutrazol rate and insecticide program), replicated four times, and arranged in a randomized complete block design. Treatments were applied using a CO_2-powered backpack sprayer equipped with a AI9504EVS nozzle (Teejet Technologies, Springfield, IL) at a carrier volume of 420 L ha^{-1} at 310 kPa. Paclobutrazol and systemic insecticides were watered in with 2.5- to 7.5-mm irrigation within 24 h after application.

Four rates of paclobutrazol were evaluated: high (210 g ha^{-1}), middle (105 g ha^{-1}), low (70 g ha^{-1}), and a nontreated control. Paclobutrazol was applied on a monthly basis beginning at annual bluegrass seedhead shatter (May 2, 2018, and May 3, 2019) and ending in October (19th in 2018, and 18th in 2019). Rates were selected based on a dose-response greenhouse experiment using the same biotype of annual bluegrass present at the experiment site (data not presented) and rates commonly used by practitioners.

The three insecticide programs evaluated for annual bluegrass control used different insecticides and application timings to allow for various levels of ABW damage (Table 1). To optimize insecticide applications, the site was scouted frequently to elucidate the trajectory of larval development. Adults and larvae were sampled thrice weekly from May through June. Adults were collected using a leaf blower (Echo ES-250 Shred "N' Vac; ECHO Inc. Lake Zurich, IL) with inverted air flow and fitted with a mesh insert to capture adults. Larval densities were estimated by taking four cores (5.2 cm in diam, 5.0 cm in depth) with a turf plugger (Duich Ball Mark Plugger BMP1-M) from each 1- by 2-m plot. Larvae were collected

Table 1. Annual bluegrass weevil insecticide programs and application timings in North Brunswick, NJ, in 2018 and 2019.[a]

Program	Rate	Target larval stage	Application date	
AI	g ai ha^{-1}	—1 to 5 instar—	2018	2019
		Preventive program		
Cyantraniliprole	163	1 to 3	May 14	May 7
Indoxacarb	252	3 to 5	May 30	May 15
Spinosad	454	3 to 5	July 23	July 18
Cyantraniliprole	290	3 to 5	July 30	–
		Threshold program[b]		
Cyantraniliprole	290	3 to 5	May 30	May 24, June 4[c]
Spinosad	454	3 to 5	July 23	July 18
Cyantraniliprole	290	3 to 5	July 30	–
		No insecticide program		

[a]Overwintering generation development was monitored weekly from May through June and used to schedule initial insecticide applications.
[b]Insecticides were applied to the threshold program once visual evaluations determined turfgrass quality was unacceptable (i.e., <6 on a 1 to 9 scale where 9 = excellent turf quality).
[c]Due to natural variations in annual bluegrass weevil pressure, blocks 1 and 2 reached the damage threshold on May 24, 2019, blocks 3 and 4 met the damage threshold 10 d later.

using a standard salt solution extraction method as described by Koppenhöfer et al. (2018); and larval densities were used to inform insecticide application timings (McGraw and Koppenhöfer 2009).

The preventive insecticide program was based on a current industry standard with excellent efficacy. The objective of this program was to prevent ABW damage. Cyantraniliprole was applied at 160 g ha^{-1} to target first- and second-instar larvae approximately 2 wk after peak densities of overwintered adults were observed. This was followed by indoxacarb applied at 250 g ha^{-1} approximately 2 wk later to control larger and later-emerging larvae. Spinosad (450 g ha^{-1}) was applied in July to protect turfgrass from ABW larvae of later generations.

The threshold program used a strategy that would be practical for a turfgrass manager wishing to use ABW as part of an integrated program for annual bluegrass control. No insecticides were applied until visual evaluations deemed turfgrass quality to be unacceptable (ranked from 1 to 9, poor to excellent; where 6 was acceptable), as described by the National Turfgrass Evaluation Program (Kranz and Morris 2007). Once the damage threshold was met, cyantraniliprole was applied at 290 g ha^{-1} to prevent further ABW damage. Spinosad (450 g ha^{-1}) was applied in July to protect turfgrass from ABW larvae of later generations. 2019 an additional 290 g of cyantraniliprole was applied to both the preventive and threshold programs on July 30, to control ABW from causing further damage by later generations. No insecticides were ever applied for ABW control in the no-insecticide program.

To evaluate the efficacy of ABW control in the insecticide programs, larval densities were assessed as described above on June 4, 2018, and May 23, 2019, when larvae averages exceeded L3, but before most advanced larvae pupated into new adults.

To determine turfgrass species composition, annual bluegrass cover was evaluated visually on a 0% (no cover) to 100% (complete cover) scale monthly from May through November. At the end of each growing season in October or November, two 91- by 91-cm grids fitted with 100 evenly spaced intersects each were placed over each plot, and the plant species (annual bluegrass or creeping bentgrass) at each intersect was recorded to estimate percent cover. Turfgrass quality was assessed monthly based on uniformity of cover, density, and color on a 1 to 9 scale (poor to excellent, where 6 was acceptable; Kranz and Morris 2007). Annual bluegrass quality and creeping bentgrass quality were also evaluated independently each month. To determine green cover, lightbox photos were taken each month of the growing season in 2018 using a digital camera (Canon PowerShot G16; Canon U.S.A., Inc., Melville, NY) with saved calibrated settings as described by Karcher and Richardson (2003). Digital images were not collected in 2019. Photographs were subjected to digital image analysis with TurfAnalyzer software (Green Research Services, LCC, Fayetteville, AR; threshold set to hue: 50–140, saturation: 10–100, brightness: 0–100; Karcher et al. 2017).

Model assumptions were tested through residual analysis (Shapiro-Wilk statistic) using SAS software (v9.4; Statistical Analysis Software, Cary, NC) and no transformations were required. Data were subjected to ANOVA using the GLIMMIX procedure in SAS with replication (block) as a random effect and insecticide program and paclobutrazol rate as fixed effects (McIntosh 1983). Fisher's protected LSD test ($\alpha = 0.05$) was used to separate means. Data were analyzed separately by year, because natural ABW larval densities varied, and main effect by year interactions occurred on several dates. A Pearson's correlation coefficient was calculated in SAS between annual bluegrass cover determined using grid intersect counts and by visual estimation.

Results and Discussion

Insecticide Program Efficacy

In 2018 and 2019, the preventive insecticide program controlled 90% of ABW larvae relative to nontreated plots (data not presented). Threshold insecticide efficacy was not fully realized in 2018, because larvae were sampled just 5 d after cyantraniliprole (290 g ha^{-1}) was applied. Even so, threshold insecticide use resulted in reduced larval densities compared to the no-insecticide program in 2018 (522 larvae m^{-2} relative to 1,626 larvae m^{-2} in the nontreated plots, and 37 larvae m^{-2} in the preventive program). In 2019, larvae were sampled before the damage threshold was met and threshold plots had not been treated. Overall larval densities were higher in 2019 than in 2018 with 2,704 larvae m^{-2} in the nontreated plots, but the preventive program still provided 90% ABW control (272 larvae m^{-2}).

Annual Bluegrass Cover

The main effects of paclobutrazol and insecticides were significant on multiple dates each year, and a significant interaction between paclobutrazol and insecticides was detected at the final evaluation of both 2018 and 2019 experiments.

In 2018, paclobutrazol used at all rates reduced annual bluegrass cover starting in June (Table 2). In October and November 2018, middle and high rates of paclobutrazol reduced annual bluegrass cover to <30% compared to >65% cover when no paclobutrazol was applied. The low rate (70 g ha^{-1}) of paclobutrazol reduced annual bluegrass cover compared to no paclobutrazol use on several dates in 2018, but was generally not as effective as the middle and high rates. In 2019, paclobutrazol used at all rates reduced annual bluegrass cover similarly from August through October.

These results concur with those from previous paclobutrazol research; monthly applications of paclobutrazol provided annual bluegrass control in creeping bentgrass fairways, and few differences

Table 2. Effects of paclobutrazol rate (0, 70, 105, or 210 g ha^{-1}, applied monthly from May to October) on annual bluegrass cover (averaged across annual bluegrass weevil insecticide programs) in 2018 and 2019 on a simulated creeping bentgrass fairway in North Brunswick, NJ.

	Annual bluegrass cover in 2018						
Rate	May 14	June 22	July 22	August 24	September 21	October 30	November 30
g ha^{-1}	%						
0	80 a[a]	74 a	69 a	55 a	59 a	65 a	69 a
70	80 a	58 b	49 b	53 a	46 ab	38 b	35 b
105	75 b	53 bc	43 bc	40 b	35 bc	26 c	18 c
210	72 b	42 c	40 c	32 b	30 c	23 c	11 c
Pr > F	0.01	0.001	0.04	0.0001	0.005	0.0001	0.0001

	Annual bluegrass cover in 2019					
Rate	May 1	June 7	July 9	August 16	September 10	October 25
g ha^{-1}	%					
0	73	23	26 ab	26 a	45 a	40 a
70	73	21	17 c	13 b	25 b	23 b
105	75	20	22 bc	19 b	27 b	20 bc
210	75	21	29 a	13 b	21 b	13 c
Pr > F	NS[b]	NS	0.002	0.001	0.0002	0.0001

[a]Common letters indicate means are not different according to Fisher's protected LSD ($\alpha = 0.05$) on dates of significance.
[b]Abbreviation: NS, not significant.

between rates occurred after several months of applications (McCullough et al. 2005; Woosley et al. 2003). Similar to observations by McCullough et al. (2005), in our study, annual bluegrass coverage across all treatments was also highest in the spring and declined through summer into fall. In 2018, monthly applications of paclobutrazol at 105 and 210 g ha^{-1} provided 74% to 84% annual bluegrass control at the end of the season. These results are similar to those reported by Woosley et al. (2003), that a year of monthly paclobutrazol applications (140 g ha^{-1} and 280 g ha^{-1}) resulted in 85% annual bluegrass control on fairways.

Irrespective of paclobutrazol rate, the main effect of insecticides use also influenced annual bluegrass cover on many rating dates in 2018 and 2019 (Table 3). Treatment effects were similar both years, but greater ABW larval densities likely explain greater annual bluegrass cover reductions in threshold and no-insecticide programs during June and July 2019 compared to 2018. On most dates in 2018 and 2019, the no-insecticide program had less annual bluegrass cover than the preventive program (Table 3). The threshold and preventive programs resulted in similar annual bluegrass cover on most dates in 2018 when averaged across paclobutrazol rates. In 2019, both the threshold and no-insecticide programs resulted in less annual bluegrass cover than the preventive program in June, July, and October.

Main effect interactions were detected in autumn 2018 and 2019 ($P < 0.009$ and 0.001, respectively) at the conclusion of both experiments (Figure 1 A and B). At the conclusion of both experiments, the threshold and no-insecticide programs resulted in less annual bluegrass cover than preventive programs when treated with the middle rate of paclobutrazol or no paclobutrazol. Annual bluegrass cover was lowest in all treatments that received the high rate of paclobutrazol and in the threshold and no-insecticide programs that received middle rates of paclobutrazol (8% to 20%). In 2019 but not 2018, the low rate of paclobutrazol combined with threshold and no-insecticide programs also resulted in the lowest annual bluegrass cover.

In both years, annual bluegrass cover was highest (83% and 56%) in the preventive program not treated with paclobutrazol, and all rates of paclobutrazol (regardless of insecticide use) reduced cover relative to that treatment. Similar to previous findings by Diehl et al. (2021) in which paclobutrazol was applied at 280 g ha^{-1}, no differences between insecticide programs were observed in plots that received the high paclobutrazol rate. Of the programs that aimed to preventively treat ABW, all paclobutrazol rates resulted in reduced annual bluegrass cover. Interestingly, the non-paclobutrazol-treated threshold and no-insecticide programs had similar cover to that of preventive programs that received low and middle rates of paclobutrazol in October 2019. Cover in the no-insecticide program not treated with paclobutrazol was similar to that of the threshold program treated with paclobutrazol.

Main effects were significant in autumn grid count data taken November 2018, and October 2019 ($P < 0.001$; data not presented). Interactions were not significant in 2018 or 2019; however, grid count data correlated with visual observations (2018, $r = 0.87$, $P < 0.001$; 2019, $r = 0.70$, $P < 0.001$) taken the same month (Figure 1).

Turfgrass Quality

The main effects of paclobutrazol rate and insecticide programs affected turfgrass quality ($P < 0.05$) on several dates. Interactions were not significant on any date and will not be presented.

Averaged across insecticide programs, turfgrass quality was reduced to unacceptable (<6) levels in plots treated with 210 g ha^{-1} paclobutrazol from May 31 and July 22, 2018, and in May 2019 (Figure 2). This coincides with peak feeding of ABW larvae. The no-paclobutrazol treatment resulted in higher turfgrass quality on several dates in 2018, likely a function of high annual bluegrass cover in the turf sward.

Averaged across paclobutrazol programs, withholding insecticides for ABW control resulted in reduced turfgrass quality in threshold and no-insecticide programs on several dates in May 2018 and 2019 when ABW larvae were feeding (Figure 3). Insecticide use also affected turfgrass quality from June to August in 2018 and May to July 2019; the no-insecticide programs resulted in lower quality turfgrass than other programs on most dates. In June 2018 and 2019, following damage from the first ABW generation, quality was lower in the no insecticide program (4.9 and 4.3), greater in the threshold program (6.2 and 5.8) and greatest in the preventive program (7.1 and 7.3, in 2018 and 2019, respectively). Turfgrass in the no-insecticide program did

Table 3. Effect of annual bluegrass weevil insecticide programs on annual bluegrass cover.[a]

ABW program	Annual bluegrass cover in 2018					
	June 22	July 22	August 24	September 21	October 30	November 30
	%					
Preventive	70 a[b]	52 ab	50 a	45 a	40	39 a
Threshold	60 a	60 a	48 a	46 a	41	31 b
No insecticides	41 b	40 b	38 b	37 b	33	29 b
Pr > F	0.0001	0.02	0.02	0.04	NS	0.009
	Annual bluegrass cover in 2019					
ABW program	May 1	June 7	July 9	August 16	September 10	October 22
	%					
Preventive	76	41 a	34 a	23 a	24	33 a
Threshold	72	14 b	19 b	18 ab	29	23 b
No insecticides	73	9 b	16 b	13 b	27	15 c
Pr > F	NS	0.002	0.0001	0.008	NS	0.0001

[a]Averaged across paclobutrazol rates 0, 70, 105, or 210 g ha^{-1}, applied monthly from May to October in 2018 and 2019, on a simulated creeping bentgrass fairway in North Brunswick, NJ.
[b]Common letters indicate means are not different according to Fisher's protected LSD ($\alpha = 0.05$) on dates of significance.
[c]Abbreviations: ABW, annual bluegrass weevil; NS, not significant.

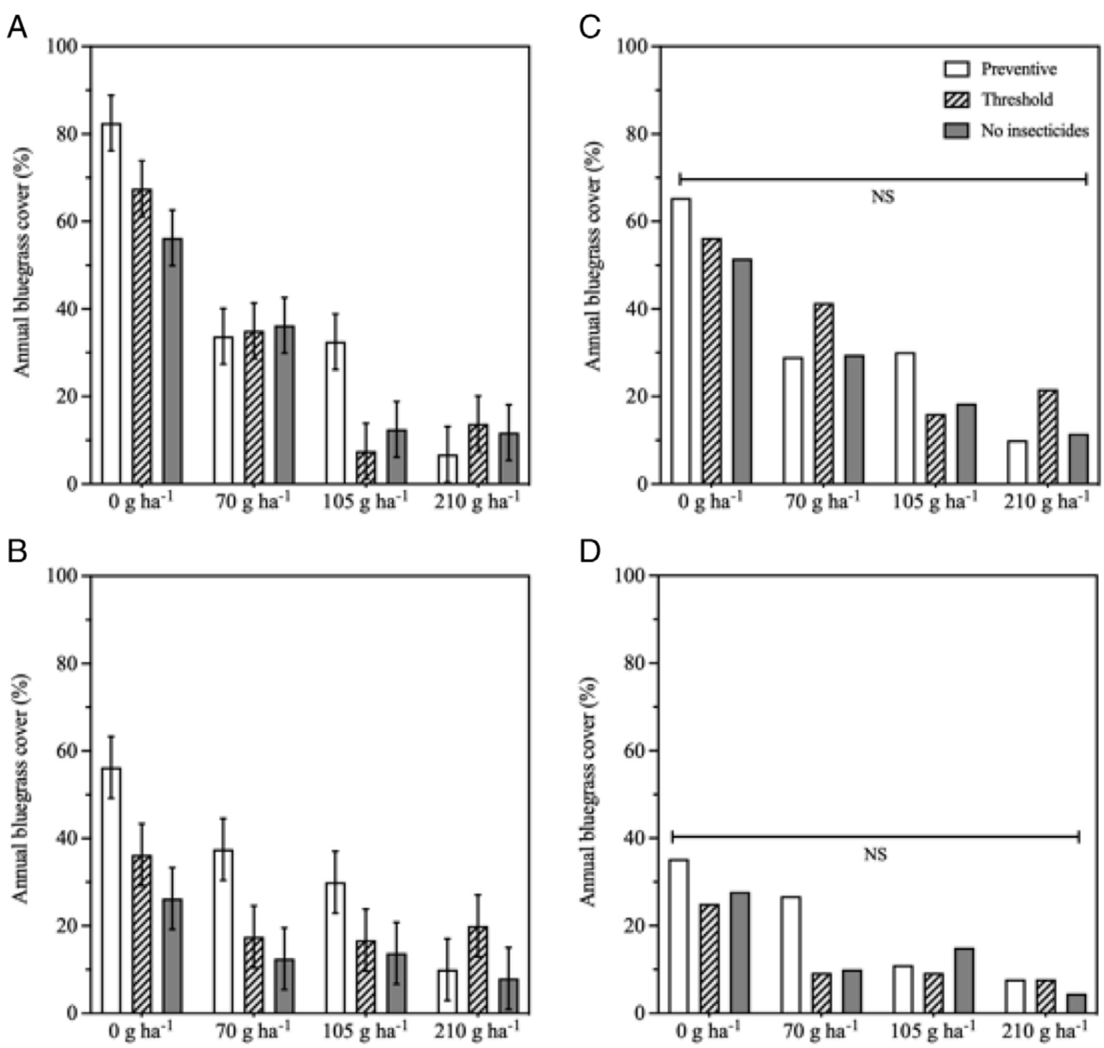

Figure 1. Effect of paclobutrazol and annual bluegrass weevil insecticide program on visual annual bluegrass cover on November 30, 2018 (A) and October 22, 2019 (B), and on annual bluegrass cover as counted on grid intersects when in November 2018 (C) and October 2019 (D). Experiments were located adjacently on a simulated creeping bentgrass fairway in North Brunswick, NJ. Error bars indicate Fisher's protected LSD ($\alpha = 0.05$) values. NS indicates not significant.

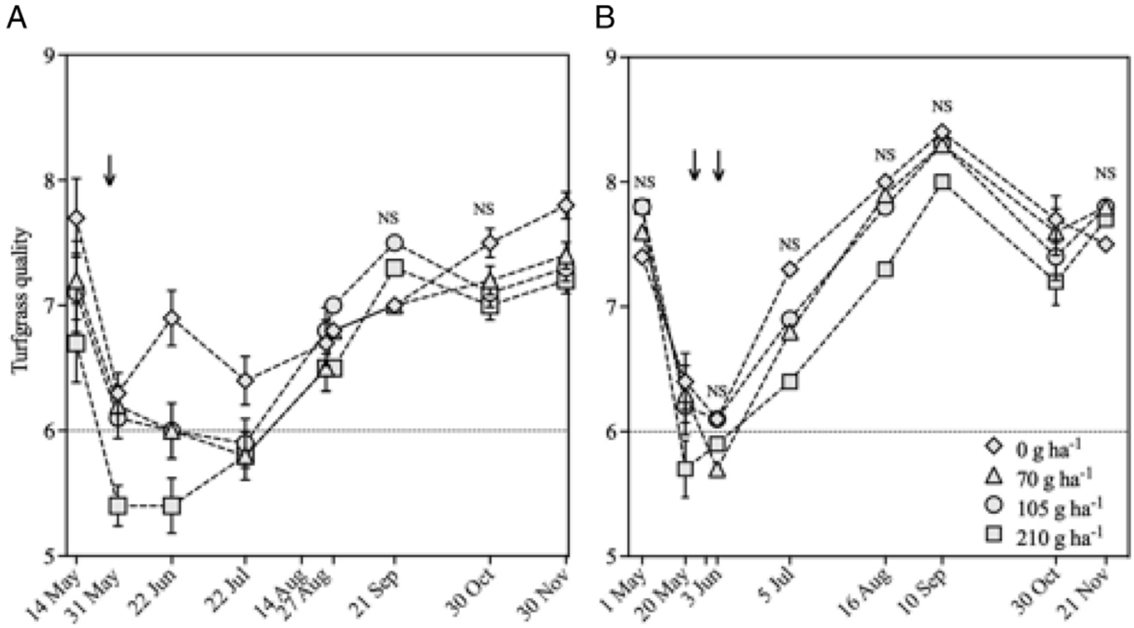

Figure 2. Effect of paclobutrazol rate (0, 70, 105, or 210 g ha^{-1} applied monthly) on turfgrass quality (evaluated on a 1-to-9 [poor to excellent] scale, with 6 being acceptable) in 2018 (A) and 2019 (B). Experiments were located on adjacent simulated creeping bentgrass fairways in North Brunswick, NJ. Means presented are combined across insecticide programs. Arrows indicate when threshold-based insecticides were applied (May 30, 2018, and May 24 and June 4 in 2019, to reps 1–2 and 3–4, respectively). Error bars indicate Fisher's protected LSD (α = 0.05) values on dates of significance. NS indicates not significant.

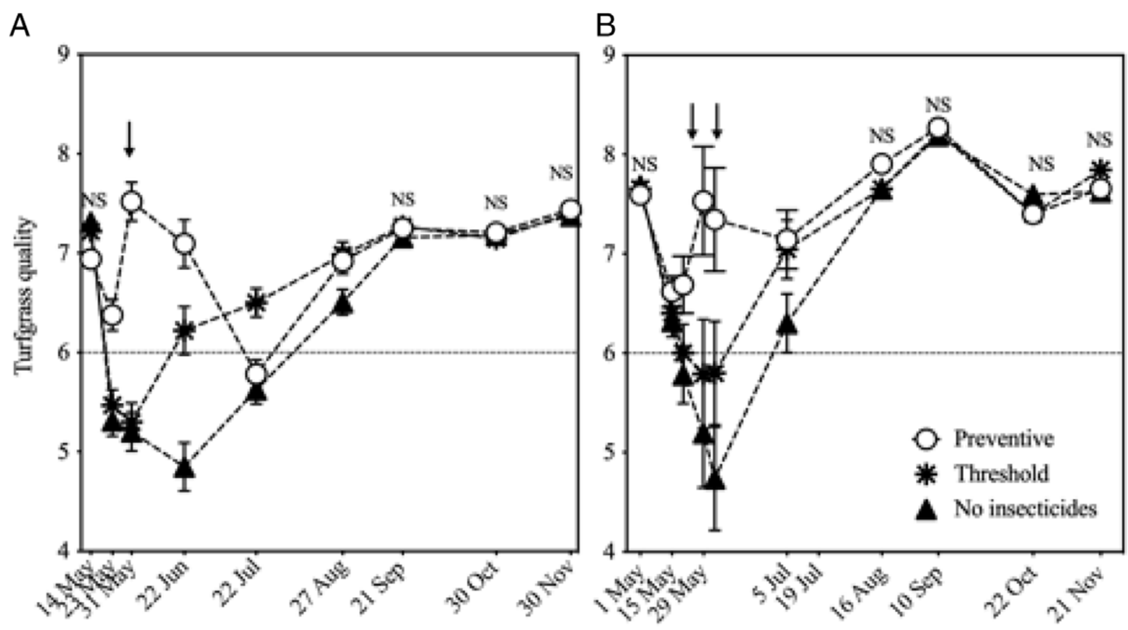

Figure 3. Main effect of annual bluegrass weevil insecticide program (preventive, threshold, and no insecticide) on turfgrass quality (evaluated on a 1-to-9 [poor to excellent] scale, with 6 being acceptable) in 2018 (A) and 2019 (B). Arrows indicate when threshold-based insecticides were applied (May 30, 2018, and May 24 and June 4 in 2019, to reps 1–2 and 3–4, respectively). Experiments were located on adjacent simulated creeping bentgrass fairways in North Brunswick, NJ. Error bars indicate Fisher's protected LSD (α = 0.05) values on dates of significance. NS indicates not significant.

not recover to acceptable quality until August 27, 2018, and July 5, 2019. In 2019, quality of the threshold and preventive programs were similar by July 5 (7.0 and 7.1 respectively), while the no-insecticide program displayed lower, although acceptable, quality (6.3) on the same date. Annual bluegrass recovery following ABW damage was attributed to annual bluegrass emerging from surviving crowns. Such resilience following seemingly severe ABW injury likely explains the fleeting effect the ABW often had on turfgrass quality after larvae were controlled. This may also explain why ABW damage did not always translate into season-long annual bluegrass control. Creeping bentgrass quality was not influenced by the insecticide program at any time (data not presented).

In 2018, green cover data obtained through image analysis support turfgrass quality observations (Figure 4). One day after the

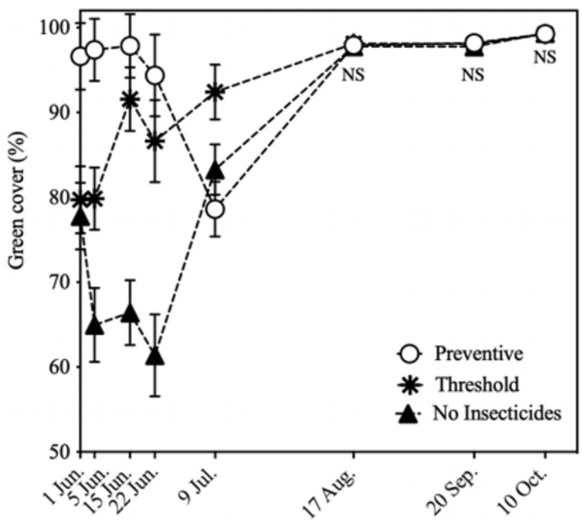

Figure 4. Main effect of annual bluegrass weevil insecticide program (preventive, threshold, and no insecticide) on percent green cover, as estimated by image analysis of lightbox photos taken in 2018. Threshold-based insecticides were applied May 30, 2018. Error bars indicate Fisher's protected LSD ($\alpha = 0.05$) values on dates of significance. NS indicates not significant.

cyantraniliprole application to threshold treatments on June 1, 2018, green cover was lower in threshold and no-insecticide programs (80%, relative to 99% in the preventive). Four days later, presumably due to ABW feeding, green cover in the no-insecticide plots was 65% but remained unchanged in the threshold and preventive treatments. Green cover remained lower (61% to 66%) in the no-insecticide treatments in the following weeks, while it increased in the threshold treatments (80% to 92%). The preventive program had >79% cover on each date. All programs had >98% green cover in August and there were no differences between programs for the rest of the year.

Research Implications

Threshold-based ABW control provided annual bluegrass control with transient reductions in turfgrass quality. Annual bluegrass quickly recovered from ABW damage after insecticides were applied, but monthly applications of paclobutrazol at moderate rates (105 g ha^{-1}) slowed annual bluegrass recovery, and consistently increased the efficacy of threshold-based and no-insecticide programs for annual bluegrass control. Efficacy of the threshold-based program was not consistently enhanced by monthly applications of paclobutrazol at 70 g ha^{-1}, whereas 210 g ha^{-1} was effective regardless of ABW insecticide program. Although the no insecticide program effectively controlled annual bluegrass, it resulted in poor turfgrass quality for a long period of the growing season and is not a practical strategy for turfgrass managers. The threshold-based insecticide program resulted in poor turfgrass quality for short (<3 wk) periods. Annual bluegrass control provided by the threshold-insecticide program combined with paclobutrazol at 105 g ha^{-1} was similar to that provided by paclobutrazol at 210 g ha^{-1} when insecticides were applied to prevent ABW damage.

The use of threshold-based ABW insecticidal control adheres to the principles of integrated pest management for both the ABW and annual bluegrass. Applying insecticides according to this threshold approach reduces paclobutrazol rates necessary for annual bluegrass control, saving practitioners time and money if limited and temporary reductions in turf quality can be accepted.

Future research should evaluate the effect of initial annual bluegrass cover on annual bluegrass control with threshold-based ABW control. More creeping bentgrass and less annual bluegrass cover might allow ABW to cause more annual bluegrass damage before unacceptable turfgrass quality necessitates an insecticide application, resulting in greater annual bluegrass control. Further research should also evaluate ABW efficacy for annual bluegrass control in stands of other turf species, because we hypothesize that the stoloniferous vegetative growth habit of the bentgrass aided in its establishment over weakened annual bluegrass during the summer months.

Acknowledgments. This work was supported by the New Jersey Turf Foundation, Environmental Institute for Golf, Golf Course Superintendents Association of New Jersey, and Rutgers New Jersey Agricultural Experiment Station's Center for Turfgrass Science. No conflicts of interest have been declared.

References

Beard J, Vargas JM, Rieke PE, Turgeon AJ (1978) Annual bluegrass (*Poa annua* L.) description, adaptation, culture, and control. Michigan State University Agricultural Experiment Station Research Report 352:3–26

Bigelow CA, Hardebeck GA, Bunnell BT (2007) Monthly flurprimidol applications reduce annual bluegrass populations in a creeping bentgrass fairway. Appl Turfgrass Sci 4:1–7

Britton WE (1932) Weevil grubs injure lawns. Connecticut Agricultural Experiment Station Bulletin 338. 593 p

Cameron RS, Johnson NE (1971) Biology of a species of *Hyperodes* (Coleoptera: Curculionidae), a pest of turfgrass. Ithaca, NY: Cornell University Extension. 31 p

Cowles RS, Koppenhöfer AM, McGraw BA, Alm SR, Ramoutar D, Peck DC, Vittum P, Heller P, Swier S (2008) Insights into managing annual bluegrass weevils. USGA Turfgrass and Environmental Research 15:1–11. https://usgatero.msu.edu/v07/n15.pdf Accessed: April 1, 2020

Diehl KH, Elmore MT, Koppenhöfer AM, Murphy JT, Kostromytska OS (2021) Annual bluegrass weevil, paclobutrazol, and overseeding for annual bluegrass control in cool-season fairways. Crop Sci 61:1458–1467

Hempfling JW, Schmid CJ, Wang R, Clarke BB, Murphy JA (2017) Best management practices effects on anthracnose disease of annual bluegrass. Crop Sci 57:602–610

Inguagiato JC, Murphy JA, Clarke BB (2008) Anthracnose severity on annual bluegrass influenced by nitrogen fertilization, growth regulators, and verticutting. Crop Sci 48:1595–1607

Inguagiato JC, Murphy JA, Clarke BB (2009) Anthracnose disease and annual bluegrass putting green performance affected by mowing practices and lightweight rolling. Crop Sci 49:1454–1462

Inguagiato JC, Murphy JA, Clarke BB (2012) Sand topdressing rate and interval effects on anthracnose severity of an annual bluegrass putting green. Crop Sci 52:1406–1415

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

Kaminski JE, Dernoeden PH (2007) Seasonal *Poa annua* L. seedling emergence patterns in Maryland. Crop Sci 47:775–781

Karcher DE, Purcell CJ, Richardson MD, Purcell LC, Hignight KW (2017) A new Java program to rapidly quantify several turfgrass parameters from digital images. Page 109313 *in* ASA, CSSA and SSSA International Annual Meetings, Tampa, FL, October 22–25, 2017.

Karcher DE, Richardson MD (2003) Quantifying turfgrass color using digital analysis. Crop Sci 43:943–951

Koppenhöfer AM, Kostromytska OS, Wu S (2018) Pyrethroid-resistance level affects performance of larvicides and adulticides from different insecticide classes in populations of *Listronotus maculicollis* (Coleoptera: Curculionidae). J Econ Entomol 111:1851–1859

Kostromytska OS, Koppenhöfer AM (2014) Ovipositional preferences and larval survival of annual bluegrass weevil, *Listronotus maculicollis*, on *Poa annua* and selected bentgrasses (*Agrostis* spp.). Entomol Exp Appl 152:108–119

Kostromytska OS, Koppenhöfer AM (2016) Responses of *Poa annua* and three bentgrass species (*Agrostis* spp.) to adult and larval feeding of annual bluegrass weevil, *Listronotus maculicollis* (Coleoptera: Curculionidae). Bull Entomol Res 6:1–11

Kostromytska OS, Wu S, Koppenhöfer AM (2018) Cross-resistance patterns to insecticides of several chemical classes among *Listronotus maculicollis* (Coleoptera: Curculionidae) populations with different levels of resistance to pyrethroids. J Econ Entomol 111:391–398

Kranz JV, Morris K (2007) Determining a profile of protocols and standards used in the visual field assessment of turfgrasses: a survey of national turfgrass evaluation program sponsored university scientists. Appl Turfgrass Sci 4:1–6

Lush WM (1988) Biology of *Poa annua* in a temperate zone golf putting green *(Agrostis stolonifera/Poa annua)* II. the seed bank. J Appl Ecol 25:989–997

Lycan DW, Hart SE (2006) Seasonal effects on annual bluegrass (*Poa annua*) control in creeping bentgrass with bispyribac-sodium. Weed Technol 20:722–727

Lyman GT, Throssell CS, Johnson ME, Stacey GA, Brown CD (2007) Golf course profile describes turfgrass, landscape, and environmental stewardship features. Appl Turfgrass Sci 4:1–24

McCullough PE, Hart SE (2006) Temperature influences creeping bentgrass (*Agrostis stolonifera*) and annual bluegrass (*Poa annua*) response to bispyribac-sodium. Weed Technol 20:728–732

McCullough PE, Hart SE, Lycan DW (2005) Plant growth regulator regimens reduce Poa annua populations in creeping bentgrass. Appl Turfgrass Sci doi: 10.1094/ATS-2005-0304-01-RS

McCullough PE, Hart SE, Weisenberger D, Reicher ZJ (2010) Amicarbazone efficacy on annual bluegrass and safety on cool-season turfgrasses. Weed Technol 24:461–470

McGraw BA, Koppenhöfer AM (2009) Development of binomial sequential sampling plans for forecasting *Listronotus maculicollis* (Coleoptera: Curculionidae) larvae based on the relationship to adult counts and turfgrass damage. J Econ Entomol 102:1325–1335

McGraw BA, Koppenhöfer AM (2017) A survey of regional trends in annual bluegrass weevil (*Coleoptera: Curculionidae*) management on golf courses in eastern North America. J Integr Pest Manag doi: 10.1093/jipm/pmw014

McIntosh MS (1983) Analysis of combined experiments. Agron J 75:153–155

Meyer JW, Branham BE (2006) Response of four turfgrass specie to ethofumesate. Weed Technol 20:123–129

Ong CK, Colvill KE, Marshall C (1978) Assimilation of $^{14}CO2$ by the inflorescence of *Poa annua* L. and *Lolium perenne* L. Annal Bot 42:855–862

Patton AJ, Braun RC, Schortgen GP, Weisenberger DV, Branham BE, Sharp B, Sousek MD, Gaussoin RE, Reicher ZJ (2019) Long-term efficacy of annual bluegrass control strategies on golf course putting greens. Crop Forage Turfgrass Manag 5:180068. doi: 10.2134/ctfm2018.09.0068.

Schmid CJ, Clarke BB, Murphy JA (2017) Anthracnose severity and annual bluegrass quality as influenced by nitrogen source. Crop Sci 57:285–292

Tutin TG (1952) Origin of *Poa annua* L. Nature 169:160

Vittum PJ, Villani MG, Tashiro H (1999) Turfgrass Insects of the United States and Canada. Ithaca, NY: Cornell University Press. 422 p

Woosley PB, Williams DW, Powell AJ (2003) Postemergence control of annual bluegrass (*Poa annua* spp. *reptans*) in creeping bentgrass (*Agrostis stolonifera*) turf. Weed Technol 17:770–776

Yu J, McCullough PE, Grey T (2015) Physiological effects of temperature on turfgrass tolerance to amicarbazone. Pest Manag Sci 71:571–578