ANNUAL BLUEGRASS WEEVIL, PACLOBUTRAZOL, AND OVERSEEDING FOR ANNUAL BLUEGRASS CONTROL IN BENTGRASS FAIRWAYS

by

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A thesis submitted to the

School of Graduate Studies

Rutgers, The State University of New Jersey

In partial fulfillment of the requirements

For the degree of

Master of Science

Graduate Program Plant Biology

written under the direction of

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New Brunswick, New Jersey

May 2020

ABSTRACT OF THE THESIS

Annual Bluegrass Weevil, Paclobutrazol, and Overseeding for Annual Bluegrass Control in Bentgrass Fairways

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The annual bluegrass weevil (ABW; *Listronotus maculicollis*) is a common pest of annual bluegrass (*Poa annua*) in cool season turf. Larvae can cause substantial plant injury in highly managed turf areas, and golf course managers often apply insecticides preventatively for ABW control. Although its host specificity for annual bluegrass is well documented, little is known about how ABW management influences long-term annual bluegrass cover. The objective of this research was to compare the effects of threshold-based and industry-standard insecticide programs on annual bluegrass populations on golf course fairways alone and in combination with herbicide and overseeding programs. The first experiment was conducted over a two-year period at two locations in New Jersey to evaluate the effects of three ABW insecticide programs (preventative, threshold, and no-insecticide), monthly paclobutrazol applications, and creeping bentgrass (*Agrostis stolonifera* L.) overseeding on annual bluegrass control. The preventative insecticide program was an industry standard program designed to prevent ABW damage to annual bluegrass. The threshold program was designed to allow ABW larvae damage to occur only until turfgrass quality was compromised. The no-insecticide program was included for comparison. Overseeding did not affect annual bluegrass cover at either location. Insecticide program only affected annual bluegrass cover on one site. At this site, the no-insecticides program provided more annual bluegrass control than the other insecticide programs in the absence of paclobutrazol. When paclobutrazol was applied, annual bluegrass was completely controlled at the conclusion of the two-year experiment, regardless of insecticide program. Lower paclobutrazol rates (210, 105, 70, or 0 g ha^{-1}) were evaluated in combination with the aforementioned insecticide programs in a second experiment. Research was conducted from 2018 to 2019 on adjacent sites at Rutgers Horticulture Farm No. 2 in North Brunswick, NJ on a simulated creeping bentgrass fairway. At the conclusion of the 2018 experiment, annual bluegrass control varied by insecticide program for the 105 and 0 g ha^{-1} paclobutrazol rates. The preventative program resulted in the greatest annual bluegrass cover (33% and 83%, for the 105 and 0 g ha^{-1} paclobutrazol rates, respectively) compared to the threshold and no-insecticide programs (8 and 13% and 56 and 68% for the 105 and 0 g ha^{-1} paclobutrazol rates, respectively). At the conclusion of the 2019 experiment, the preventative program resulted in more annual bluegrass cover (56%) at 105, 70, and 0 g ha^{-1} paclobutrazol rates than the threshold and no-insecticide programs (36% and 26%, respectively). Insecticide programs did not affect annual bluegrass control at highest paclobutrazol rate in either year. These findings indicate that threshold-based insecticide control of ABW can reduce annual bluegrass cover compared to industry-standard preventative insecticide program. In North Brunswick, NJ, the ABW offered similar selective annual bluegrass control as one year's worth of monthly paclobutrazol applications (70 and 105 g ha^{-1}).

ACKNOWLEDGEMENTS

I would like to acknowledge my advisor Dr. Matt Elmore, without whom none of this would have been possible. Thank you for selecting me, believing in me, challenging me and supporting me for the last three years. I attribute my achievements in graduate school and beyond to your mentorship, under which I have grown into the scientist I am today. I am grateful to my committee members, Dr. Jim Murphy and Dr. Albrecht Koppenhöfer, for their support and guidance throughout my time at Rutgers.

Thank you to the Golf Course Superintendents Association of America Environmental Institute for Golf, the Golf Course Superintendents Association of New Jersey, the New Jersey Turfgrass Foundation, and the Rutgers Center for Turfgrass Science for funding this research. I'd like to thank and acknowledge Frank Tichenor, and the crew and members of Forest Hill Field Club, for graciously hosting our research trials. I would also like to thank TJ Lawson and the crew at Hort Farm 2 for all the work they do maintaining our research plots.

I'd like to thank those who helped with this research and to get me where I am today. Thank you to all my friends and family for the love and support. I am especially grateful to Dan Tuck, for the support, encouragement, and inspiration he imparted throughout this project. I'd also like to thank Dr. Jatinder Aulakh, and Dr. Olga Kostromytska for their mentorship.

Finally, I'd like to acknowledge my first plant science mentor, and crazy plant lady, my mom. Through her teaching and influence, I was able to realize my passion for botany.

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INTRODUCTION

Annual bluegrass (*Poa annua* L.) is widely considered to be one of the most problematic weeds of cool-season turfgrass (Beard et al. 1978, Tutin 1952). Distributed worldwide, annual bluegrass is a winter annual that behaves as a short-lived perennial in cool climates. It can tolerate and produce viable seed at extremely low heights of cut, making it so prevalent on golf course greens and fairways such that it often exists as the predominant species in managed stands of cool-season turfgrass (Beard et al. 1978). It can be differentiated from other cool-season turfgrasses by its yellowish green color and characteristic v-shaped leaves that join at the tip in a canoe-shape (Beard et al. 1978).

Despite ubiquity in cool-season turfgrass, susceptibility to biotic and abiotic stressors make annual bluegrass more difficult to manage than creeping bentgrass (*Agrostis stolonifera* L.), and it is commonly considered a weed (Beard 1964, Inguagiato et al. 2008, Espevig et al. 2014, Hoffman et al. 2014, Kostromytska and Koppenhöfer 2014).

To minimize annual bluegrass encroachment, reduce inflorescence production and increase turfgrass quality, turfgrass managers often use a combination of plant growth regulator (PGR) regimens, selective herbicides and cultural practices (Ervin and Zhang 2008, Rana et al. 2017). While researchers have explored annual bluegrass control in putting greens, less research is available concerning control in cool-season fairways. Because fairways comprise approximately 10 times more golf course acreage than putting greens, this information is of significant economic importance to turfgrass managers (Lyman et al. 2007).

Weed biology

Annual bluegrass can produce seedheads at mowing heights as low as 2 mm and often thrives in golf course greens and fairways (Zontek 1973, Beard et al. 1978, Vargas and Turgeon 2004). Behaving as a winter annual or short lived-perennial, annual bluegrass is self-pollinating and reproduces primarily by seed (Tutin 1957). Annual bluegrass seed requires as little as 24 hours after pollination to become viable and new plants can emerge relatively quickly once seed is removed from the plant (Koshy 1969). Seeds are produced in a large flush in the spring and in continuous smaller flushes throughout the growing season (Lush 1988, Kaminski and Dernoeden 2007). Populations of annual bluegrass plants may produce up to 650,000 seeds m^{-2} each year, with the amount of seed in the seed bank peaking in late spring (Lush 1988). In the mid-Atlantic United States most annual bluegrass seedlings (21-51% of the annual total) emerge between early October and November when daily temperatures average 20°C, but seedlings continue to emerge in smaller flushes throughout the year (Kaminski and Dernoeden 2007). The density of the turfgrass canopy can limit seedling emergence in the autumn, and often more seedlings will emerge if bare ground is exposed from winterkill, cultivation practices, etc. (Lush 1988, Busey 2003, Kaminski and Dernoeden 2007).

Abiotic stress

Annual bluegrass growth is most robust in temperate climates and is particularly sensitive to temperature extremes and fluctuations (Beard et al. 1978, Espevig et al. 2014, Hoffman et al. 2014). Compared to other cool-season turfgrass species, it is more sensitive to cold acclimation and deacclimation, and therefore more prone to winter injury during periods of freezing and thawing (Hoffman et al. 2014). A growth chamber experiment comparing six turfgrass species found annual bluegrass to be the most sensitive to low temperatures and least likely to recover from cold injury (Espevig et al. 2014). The same study found creeping bentgrass to be more cold tolerant (LT_{50} < -30°C) compared to annual bluegrass (LT_{50} -13°C to -14°C).

While cold injury is most dependent on soil temperature, moisture stress can play a role as well (Beard 1970, Beard et al. 1978). In saturated soils, frozen water creates an ice cover encasing the plant that can induce low temperature kill (Beard et al. 1978). Annual bluegrass is more susceptible to injury under ice cover than creeping bentgrass or Kentucky bluegrass (*Poa pratensis* L.), which can both sustain longer periods of exposure to ice cover before necrosis (Beard 1964).

Annual bluegrass is sensitive to heat stress as well, and turfgrass managers often refer to direct and indirect heat injury as “summer die-off” (Bogart 1972, Beard et al. 1978). Heat stress symptoms are the results of both direct and indirect plant responses. As temperatures exceed 27°C, annual bluegrass begins to exhibit symptoms of heat stress that may include wilting and chlorosis (Bogart 1972). Longer periods of heat exposure can initiate drought stress as well, as higher temperatures increase photorespiration and evapotranspiration (Huang et al. 1997). Drought stress has particularly dramatic effects on annual bluegrass root systems - so much that annual bluegrass was once thought to have root systems innately smaller than other cool-season grasses (Beard 1970). However, this is not the case. Grown under ideal conditions, annual bluegrass roots are similar in size to those of creeping bentgrass and Kentucky bluegrass, but annual bluegrass roots are dramatically reduced when carbohydrate reserves are depleted (Beard et al. 1978).

Plants with underdeveloped root systems are less drought-tolerant than plants with healthy root systems because they are less capable of acquiring water located deeper in the soil profile (Huang et al. 1997). When fertilized and irrigated sufficiently, the plant shows little signs of heat stress above ground, and heat stress can often go unnoticed (Vargas and Turgeon 2004). While the plant may appear healthy above ground, it may still be substantially weakened by root decline and vulnerable to future abiotic or biotic stress.

Biotic stress

Annual bluegrass is also susceptible to numerous turfgrass diseases including summer patch (*Magnaporthe poae*), dollar spot (*Clarireedia jacksonii*) and Pythium blight (*Pythium* spp.). Several of these diseases are more severe on annual bluegrass than creeping bentgrass or perennial ryegrass, especially during the summer months (Vargas 2005, Chen 2016). Anthracnose epiphytotics (*Colletotrichum cereale*), a stress-related turfgrass disease that is particularly severe on annual bluegrass putting greens, became increasingly problematic throughout the 1990s, until researchers identified management practices that alleviated the impact of this disease on annual bluegrass (Inguagiato et al. 2008, 2009, 2012; Hempfling et al. 2017, Schmid et al. 2017).

CONTROLING ANNUAL BLUEGRASS IN BENTGRASS FAIRWAYS

Cultural practices

In mixed stands of creeping bentgrass and annual bluegrass managed at fairway height, clipping removal reduced the amount of viable annual bluegrass seeds in the soil by 60% (Gaussoin and Branham 1989). Along with substantial reduction of the annual bluegrass seedbank, clipping removal reduced annual bluegrass cover by 12% over three years compared to non-treated control.

To preserve the desirable turfgrass cover and discourage annual bluegrass germination, Kaminski and Dernoeden (2007) recommend timing invasive cultural practices, such as aerification or vertical mowing, until after peak annual bluegrass germination.

Mineral nutrients can also influence the competitiveness of annual bluegrass in turfgrass. Adams (1980) reported that lowering the mowing height and increasing N fertilizer increased annual bluegrass infestation on a perennial ryegrass sports field. As height of cut was lowered from 2.5 cm to 1.25 cm, annual bluegrass cover increased along with nitrogen rate from 5% cover to 20-48% (Adams 1980). Dest and Guillard (1987) also reported a significant increase in creeping bentgrass cover when fairways were deprived of nitrogen and phosphorus for three years, and Waddington et al. (1978) observed more annual bluegrass germination in creeping bentgrass plots receiving P and K fertilization.

Overseeding

In cases of severe infestation, a nonselective herbicide may be applied to the existing stand to re-establish with a more desirable species. This can be problematic because during the renovation and re-establishment process, turfgrass is not playable and the course suffers loss of revenue. An alternative to traditional renovation is a gradual transition through overseeding. Rather than a traditional renovation, where all existing turfgrass is removed and replaced, overseeding refers to the practice of introducing new seed to an existing stand of turfgrass to facilitate a gradual conversion to creeping bentgrass. In theory, overseeding with creeping bentgrass reduces annual bluegrass cover while preserving the playability of the turfgrass (Reicher and Hardebeck 2002). However, there is controversy over the efficacy of this method in creeping bentgrass fairways (Gaussoin and Branham 1989, Reicher and Hardebeck 2002). Reicher and Hardebeck (2002) reported that three years of fall and spring overseeding ‘Penneagle’ creeping bentgrass increased creeping bentgrass cover by 36% on perennial ryegrass fairways but only by 3% on a primarily annual bluegrass fairway. Additionally, mechanical damage that may occur during overseeding can lead to an increase in annual bluegrass cover, as annual bluegrass seed establishes faster than creeping bentgrass seed (Busey 2003). The optimal time to overseed creeping bentgrass has also been debated. Traditionally, fall overseeding was favored, but recent studies have shown that in annual bluegrass putting greens, overseeding in June and July results in more long-term creeping bentgrass cover than fall overseeding (Henry et al. 2005). With all types of control, it is important to note that some creeping bentgrass cultivars are more competitive with annual bluegrass than others. Older varieties like ‘Penncross’ are less competitive than newer cultivars (Henry et al. 2005). Choosing a competitive creeping bentgrass cultivar can be especially important when overseeding into a mixed stand (Gaussoin and Branham 1989, Henry et al. 2005).

Post-emergent herbicides

Pre-emergent control of annual bluegrass with herbicides can be inconsistent, as germination and seedling emergence occurs throughout the year (Kaminski and Dernoeden 2007). In situations where a weed population is already established, post-emergent herbicides are the only effective chemical options. However, selective post-emergence herbicide options in cool-season turfgrass, especially creeping bentgrass fairways are limited (Fagerness et al. 2000, Meyer and Branham 2006, Senseman 2007, Dayan et al. 2009, McCullough and Hart 2010, Bigelow 2012). As of this writing, amicarbazone and ethofumesate are the only readily available herbicides on the market selective enough to control annual bluegrass in creeping bentgrass fairways (Thompson 2017).

Amicarbazone is a photosystem II-inhibiting herbicide used for annual bluegrass control in fairways (Senseman 2007, Dayan et al. 2009). It is both foliar and root absorbed, and causes susceptible plants to experience chlorosis, stunting and necrosis (Dayan et al. 2009, Perry et al. 2012). Annual bluegrass absorbs amicarbazone at a higher rate than creeping bentgrass and metabolizes it twice as slowly, possibly accounting for the herbicides selectivity on cool-season turfgrass (Yu et al. 2015). Selectivity for annual bluegrass decreases as the temperature rises (McCullough et al. 2010, Yu et al. 2015). Therefore, to avoid creeping bentgrass injury, amicarbazone can be only applied between

20-25°C which limits its use in cool-season turfgrass to the spring and fall (McCullough et al. 2010). Research indicates that spring applications provide less control than fall applications, but only spring applications are recommended on the product label (Anonymous 2015, McCullough et al. 2010, McCullough et al. 2013). Jeffries et al. (2013) found that applying a higher rate of amicarbazone less frequently can further reduce creeping bentgrass injury, but all rates provided < 24% annual bluegrass control (Jeffries et al. 2013).

For those managing cool-season turfgrass, the increase in amicarbazone efficacy with temperature is negated by a loss of selectivity. Ethofumesate has similar use limitations in creeping bentgrass, with frequent applications required, inconsistent efficacy and reports of creeping bentgrass injury (Meyer and Branham 2006, McCullough and Hart 2010).

Bispyribac-sodium is another selective herbicide available for annual bluegrass control in creeping bentgrass. Bispyribac-sodium is an acetolactate synthase (ALS) inhibiting herbicide registered for use on creeping bentgrass tees and fairways (Shimizu et al. 2002). Its efficacy on annual bluegrass is well demonstrated (McCullough and Hart 2005, 2010). However, it is not being manufactured as of this writing and its future in postemergence annual bluegrass control is uncertain (Thompson 2017). Reicher et al. (2017) demonstrated that in a creeping bentgrass fairway, a single application of 49 g ha^{-1} bispyribac-sodium in June reduced annual bluegrass cover to < 5% (relative to 14% in the untreated control). Research indicates that bispyribac-sodium applications at low temperatures result in creeping bentgrass injury and poor annual bluegrass control. To control annual bluegrass without injuring creeping bentgrass, bispyribac-sodium should be applied every 2-3 weeks, but only when temperatures are between 21-26°C, as creeping bentgrass injury also increases with heat stress (McCullough and Hart 2005, 2010, Anonymous 2010). Rana et al. (2017) found that two sites treated with bispyribac-sodium had 12 and 20% creeping bentgrass injury in the spring and 46 and 78% injury when the same applications were made in the fall. Applications when temperatures are 20-30°C typically result in less creeping bentgrass injury (Park et al. 2002, McCullough and Hart 2005, Rana et al. 2017).

There are caveats to controlling annual bluegrass with herbicides including substantial loss of cover that reduce turfgrass quality and playability. For example, it is not recommended to apply ethofumesate or amicarbizone on fairways with > 20% annual bluegrass (Thompson 2017, Anonymous 2015). This can be problematic in mixed stands where initial annual bluegrass cover is difficult to quantify.

Plant growth regulators

Plant growth regulators (PGRs) play a significant role in annual bluegrass management. Turfgrass managers use gibberellic acid (GA) synthesis inhibitors to suppress vertical plant growth and increase plant tillering, increasing turfgrass density and reducing required mowing. Other benefits include increased turfgrass color and quality, and reduced ball roll on greens and reduced seedhead production on fairways (Bigelow 2012, Fagerness et al. 2000). Some PGRs are also used for annual bluegrass control, and repeated applications can effectively reduce annual bluegrass cover in creeping bentgrass fairways (Shoop et al. 1986, Eggens et al. 1989, Woosley et al. 2003, Bigelow et al. 2007). These PGRs can be used alone or in combination with each other or herbicides for various levels of annual bluegrass control (Shoop et al. 1986, Eggens et al. 1989, Woosley et al. 2003, Bigelow et al. 2007, Jeffries et al. 2013). In cool-season turfgrass, the most commonly used PGRs are the gibberellin (GA) biosynthesis inhibitors flurprimidol, paclobutrazol and trinexapac-ethyl (Bigelow 2012, Kane and Miller 2003).

Plants produce many forms of GA, which primarily function to promote cell division and elongation, but are also involved in seed germination and bolting in biennial plants (Rademacher 2000). The biosynthesis of GA can be simplified into three main stages, characterized by subcellular location and the enzymes involved. The first stage takes place in proplastids, where the C_5 compound isopentenyle diphosphate (IPP) is synthesized from mevalonic acid (MVA) and transformed into *ent*-kaurene with the help of terpene cyclases. The second stage occurs in the endoplasmic reticulum, where monooxygenases oxidize *ent*-kaurene to form GA_{12}-aldehyde. The final stage occurs in the cytosol, where dioxygenases enzymes further oxidize GA_{12}-aldehyde to form final versions of different GAs (Rademacher 2000).

The mode of action for GA-inhibiting PGRs refers to the stage of GA-biosynthesis inhibition. Flurprimidol and paclobutrazol have similar modes of action, inhibiting early stages of biosynthesis by preventing *ent*-kaurene from forming *ent*-kaurenoic acid, the precursor to GA_{12}-aldehyde (Ervin and Zhang 2007). Flurprimidol and paclobutrazol are also both root-absorbed (Ervin and Zhang 2007). Trinexapac-ethyl is foliar-absorbed and inhibits the final stage of GA biosynthesis, preventing the oxidation of GA_{12}-aldehyde.

While GA-inhibiting PGRs are primarily used to reduce turfgrass clipping yield and improve turfgrass quality, plant growth response varies by plant species and by PGR

(Watschke and DiPaola 1995, Rademacher 2000). Some PGRs result in more (or longer) suppression than others and may also be used to selectively manage sensitive species through continuous suppression (Shoop et al. 1986, Adams 1996, Johnson and Murphy 1996, Bell et al. 2002, McCullough et al. 2005).

Trinexapac-ethyl inhibits GA biosynthesis later in the pathway than flurprimidol and paclobutrazol, and is generally used to reduce clipping yield and improve turfgrass quality but does not directly result in annual bluegrass reduction (Johnson and Murphy 1995, Fagerness et al. 2000, McCullough et al. 2005, Bigelow et al. 2007).

Flurprimidol, a root-absorbed PGR, was among the first PGRs recognized for annual bluegrass control. Shoop et al. (1986) reported that spring applications (0.84 and 1.12 kg/ha) significantly reduced annual bluegrass cover on creeping bentgrass fairways. They also found that flurprimidol reduced clipping weight for longer periods of time in annual bluegrass than creeping bentgrass and suggested this gave creeping bentgrass a competitive advantage (Shoop et al. 1986). Haley and Fermanian (1989) found pre-emergent applications of flurprimidol inhibited annual bluegrass and creeping bentgrass seedling emergence. Reporting post-emergent applications injured seedlings of both species, they suggested that flurprimidol should not be applied concurrently with creeping bentgrass overseeding (Haley and Fermanian 1989). Bigelow et al. (2007) found spring applications of flurprimidol (0.56 to 0.84 kg ha^{-1}) followed by sequential applications (0.28 to 0.56 kg ha^{-1}) made every 3 to 6 weeks reduced annual bluegrass cover by 31-35% compared to the non-treated control on a creeping bentgrass fairway. Similarly, Johnson and Murphy (1996) found that on a creeping bentgrass putting green, three sequential applications of flurprimidol made during the spring and fall resulted in 16% reptans-type annual bluegrass control.

Perhaps the most widely used PGR for annual bluegrass control is paclobutrazol. Like flurprimidol, paclobutrazol is root-absorbed and is registered for use on creeping bentgrass fairways and putting greens (Anonymous 2013). On putting greens, frequent applications of low rates (0.14 kg ha^{-1} every 3 weeks or 0.11 kg ha^{-1} every 2 weeks) provide annual bluegrass control without causing significant creeping bentgrass injury (Johnson and Murphy 1996, Bell et al. 2002, McCullough et al. 2005). In a study comparing flurprimidol and paclobutrazol regimens for annual bluegrass control on putting greens, paclobutrazol (0.3 kg ha^{-1}) provided > 72% control while flurprimidol provided < 42% annual bluegrass control (Johnson and Murphy 1995).

On fairways, sequential applications are also necessary, but higher rates (0.56 kg ha^{-1}) applied less frequently (every 3 to 6 weeks) and lower rates applied more frequently can provide similar control (Woosley et al. 2003, McCullough et al. 2005). On fairways with mixed stands of annual bluegrass and creeping bentgrass, monthly applications of paclobutrazol (0.14 and 0.28 kg ha^{-1}) provided > 85% annual bluegrass control and improved turfgrass quality (Woosley et al. 2003). Sequential applications of 0.42 to 0.56 kg ha^{-1} provided the most annual bluegrass control on fairways, but lower rates also provided control and better turfgrass quality (McCullough et al. 2005). While generally safe on creeping bentgrass, higher rates can cause chlorosis on the tips of annual bluegrass and reduce overall turfgrass quality in predominantly annual bluegrass turf stands (Woosley et al. 2003).

Alone, paclobutrazol applied every 2-3 weeks generally provided better annual bluegrass control and resulted in less creeping bentgrass injury than either ethofumesate or amicarbazone (Woosley et al. 2003, Jeffries et al. 2013). There may be benefits to adding paclobutrazol to herbicide programs. For example, recent studies show that tank-mixing paclobutrazol and amicarbazone reduces amicarbazone injury on creeping bentgrass putting greens (Woosley et al. 2003, Jeffries et al. 2013). Although paclobutrazol applications still provided better control than ethofumesate, adding sequential spring applications of paclobutrazol after applying ethofumesate in the fall/winter provided more annual bluegrass control than either treatment alone (Woosley et al. 2003).

Biological control

Some biological control agents for annual bluegrass control have been explored as well. The bacterial strain *Xanthomonas campestris* pv. Poae, isolated from annual bluegrass, is a host-specific plant pathogen commercialized as a bioherbicide in Japan (Imaizumi et al. 1997, 1999). In a field experiment it provided excellent annual bluegrass control (> 90%) without injury to Zoysiagrass (*Zoysia tenuifolia*) putting greens (Imaizumi et al. 1997). However, field studies since failed to replicate these results, and research indicates that efficacy is dependent on environmental factors including temperature (Imaizumi et al. 1999). Sensitivity to environmental factors is a common problem with living biological herbicides such as *Xanthomonas* (Harding and Raizada 2015). Inconsistent field efficacy along with high production cost can limit the development and use of new biological control agents (Harding and Raizada 2015).

One host-specific pest that has not been explored as a biological control agent is the annual bluegrass weevil (ABW), *Listronotus maculicollis* Kirby (Coleoptera: Curculionidae). The ABW struck us as an excellent biological control candidate because of its innate selectivity for annual bluegrass and abundance in cool-season turfgrass (Kostromytska and Koppenhöfer 2014).

ANNUAL BLUEGRASS WEEVIL

Formally classified as *Hyperodes* sp. (Vittum and Tashiro 1987) and commonly known as the annual bluegrass weevil (ABW), the ABW is one of the most problematic turfgrass pests in the Northeastern United States (Vittum et al. 1999). This pest causes most severe plant injury when turfgrass is maintained at fairway to putting green height. Injury including yellowing, browning and dead turf, is most noticeable on annual bluegrass, where as little as 10 ABW larvae per 0.09 m^2 can be sufficient to cause damage along golf course collars and approaches, tees, putting greens and fairways (Vittum et al. 1999, McGraw and Koppenhöfer 2009, Kostromytska and Koppenhöfer 2014). This makes ABW infestations especially problematic on cool-season golf courses, where turfgrass is kept short and quality standards are high (Vittum et al. 1999).

The first record of ABW damage on turfgrass dates back to 1931, when turfgrass injury was observed at the Farmington Country Club in Farmington, Connecticut (Britton 1931). Weevils collected from the course were originally identified as *Hyperodes porcellus* but later reassigned to the genus *Listronotus* (Britton 1931, Vittum et al. 1999).

Over the next 40 years, reports of ABW damage increased throughout New York and northern New Jersey (Cameron and Johnson 1971). In 1970, a connection was made between ABW damage and the late spring dieback of annual bluegrass, which was initially attributed to heat and drought stress (Schread 1970). By the mid 1970's, the ABW was officially recognized as a pest of cool-season turfgrass (Vargas and Turgeon 2004).

Since its discovery, the ABW has primarily been a pest of the northeastern United States. However, recent evidence suggests the ABW is expanding its distribution north and southwest. As of 2017, ABW damage has been reported on golf courses from southern Quebec and southern Ontario, Canada, south to northern Virginia and along the foothills of the Appalachians in Virginia and North Carolina and west through West Virginia to eastern Ohio (Simard et al. 2007, McGraw and Koppenhöfer 2017).

Lifecycle

Although considered a turfgrass pest, the ABW does not complete its whole life cycle in the turfgrass. The adults overwinter up to 60 m away from the maintained turf in tree lines or in the rough and emerges in early spring to feed and reproduce on fairways and greens (Cameron and Johnson 1971, Diaz and Peck 2007). Feeding by the adults on leaves and stems causes only negligible damage. Once on these lower heights of cut, the females lay eggs between the grass's leaf sheaths (Cameron and Johnson 1971). Roughly 1-2 weeks after the eggs are laid, they hatch into larvae, which rely on the plant tissue for nutrients and shelter. Young larvae (first through third instars) tunnel the stems, causing limited damage. However, once they become too large to feed within the stems (fourth and fifth instar), they exit and feed at the base of the plants from shallow burrows in the ground, severing stems and damaging the crown. This damage causes the plant significant stress that can sometimes be fatal. Pupation occurs in the soil or thatch near the surface.

For a turfgrass pest, the ABW is rather host-specific. As suggested by its name, the ABW exhibits a strong preference for annual bluegrass over creeping bentgrass (Kostromytska and Koppenhöfer 2014). Kostromytska and Koppenhöfer (2014) demonstrated (through choice and no-choice laboratory, greenhouse and microplot field experiments) that egg-laying ABW adults exhibit both ovipositional and feeding preference for annual bluegrass over creeping bentgrass. This is especially relevant in turfgrass because ABW damage is the result of the larvae completing their development inside and around their grass host. Therefore, the grass the ABW adults choose to lay their eggs in will be more prone to ABW injury. Interestingly, even in no-choice experiments when ABW adults did lay eggs in creeping bentgrass, the number of eggs was lower and the larvae were smaller and slower to develop than those found annual bluegrass (Kostromytska and Koppenhöfer 2014). Furthermore, bentgrass has a higher tolerance for ABW damage than annual bluegrass, and this may explain why creeping bentgrass has a higher damage threshold than annual bluegrass (McGraw and Koppenhöfer 2009, Kostromytska and Koppenhöfer 2014, 2016). In fairways with a mix of annual bluegrass and creeping bentgrass, injury to annual bluegrass was visible with as few as 10 larvae per 0.09 m^2 in stands with close to 100% annual bluegrass, but as many as 150 larvae per 0.9 m^2 were needed before similar injury was observed on pure creeping bentgrass (McGraw and Koppenhöfer 2009). In greenhouse experiments, creeping bentgrass tolerated three to four times higher densities of ABW larvae than annual bluegrass before visible damage was observed (Kostromytska and Koppenhöfer 2016).

Larvae developthrough five instars. During the first two stages the larvae are small and remain within the grass sheath (Vittum et al. 1999). Third instars eventually eat their way out of the stem, and then continue to feed at the base of the stems from the outside (Vittum et al. 1999). Maximum turfgrass injury occurs as the first generation reaches the fourth and fifth instar in late spring (Vittum et al. 1999). After the fifth instar, larvae pupate in the top 2.5 cm of soil, and eventually the new adults emerge which initially have a reddish hue and lighter color (Schread 1970). After a few days the cuticle is fully sclerotized, it becomes difficult to distinguish one generation of adults from the other. A generation refers to the completion of one cycle from egg to adult. At the latitude of New Jersey, ABW populations complete 2-3 generations per year, but the timing of these generations varies with environmental factors (Cowles et al. 2008). Nonetheless, the timing of the first generation is the most predictable and first-generation larvae cause the most significant turfgrass injury (Vittum et al. 1999). After the first generation, larval development becomes less synchronized and turfgrass damage tends to be more spread out but less severe. However, later generations larvae may still cause visible damage especially if the plant is under other pressures such as drought stress (Potter 1998, Vittum et al. 1999).

ABW Control

ABW control relies heavily on insecticides. To maximize insecticide efficacy, it is critical to apply at the correct stage of weevil development. Instead of using calendar-based application dates, turfgrass managers may use multiple scouting strategies including monitoring of adult and larval populations, growing degree-day models and phenological indicators to time their applications (McGraw and Koppenhöfer 2017). On average, an 18-hole golf course spends > 9,000 US dollars on four insecticide applications for ABW control every year (McGraw and Koppenhöfer 2017).

Overreliance on insecticides has resulted in a growing number of resistant ABW populations over the past decade. Since pyrethroid resistance was first confirmed in southern New England in 2009, resistance to pyrethroids has been confirmed in New York, New Jersey and Pennsylvania (Kostromytska et al. 2018). In 2017, McGraw and Koppenhöfer surveyed 293 golf courses of which 19% reported having or suspecting to have pyrethroid-resistant populations. Kostromytska et al. (2018) reported that out of 10 ABW populations, 7 had moderate to high resistance to pyrethroids and several other chemical classes. Koppenhöfer et al. (2018) showed in field test that the most resistant populations were resistant against all insecticides presently available for adult control and against all but two insecticides presently available for control of larvae. Controlling these resistant ABW populations requires upwards of five applications a year, costing > 10,000 US dollars (McGraw and Koppenhöfer 2017).

RESEARCH OBJECTIVE

Although research has demonstrated the selectivity of ABW for annual bluegrass, no research has explored its efficacy as a selective biological control agent for annual bluegrass in turfgrass. The objective of this research was to determine if ABW larvae could control annual bluegrass alone or in combination with commonly used herbicidal and cultural control strategies. This research seeks to identify the efficacy of these various strategies to control annual bluegrass and provide guidance to turfgrass managers on an integrated approach for annual bluegrass control.

We hypothesized that delaying ABW control until substantial annual bluegrass damage was apparent would selectively control annual bluegrass in creeping bentgrass fairways. We further hypothesized the degree of annual bluegrass control would change in response to herbicidal and cultural programs. For herbicidal control, paclobutrazol was selected, as its efficacy for annual bluegrass control in cool season fairways is well documented. Overseeding was included as a cultural practice to further encourage creeping bentgrass competition, as summer overseeding has shown promise for long-term, gradual fairways conversions and June seeding is concurrent with maximum ABW damage (Henry et al. 2005).

In addition to the paclobutrazol and overseeding programs, three insecticide programs were created to represent various levels of ABW damage. These programs consisted of an industry-standard that controlled small larvae to prevent any ABW damage; a ‘threshold’ program, where larvae were not controlled until substantial annual bluegrass damage was observed. The third program served as a control where no insecticides were applied for ABW control.

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CHAPTER 2. Annual bluegrass weevil (*Listronotus maculicollis)*, paclobutrazol and interseeding effects on annual bluegrass (*Poa annua)* in creeping bentgrass (*Agrostis stolonifera*) fairways.

ABSTRACT

The annual bluegrass weevil (ABW; *Listronotus maculicollis*) is a common pest of annual bluegrass (*Poa annua*) in cool season turf. Larvae can cause substantial plant injury at low mowing heights, and golf course managers often apply insecticides preventatively for ABW control. The objective of this study was to determine if threshold-based insecticide control of ABW larvae could reduce annual bluegrass populations in mixed species golf course fairway turf. Creeping bentgrass (*Agrostis stolonifera* L.) overseeding, three insecticide programs, and paclobutrazol (280 g ha$_{-1}$, applied monthly) were investigated for annual bluegrass control in field experiments conducted over 2 years at two locations. The first site was a simulated creeping bentgrass fairway in North Brunswick, NJ, the second was a mixed cool-season fairway in Bloomfield, NJ. Treatments were replicated four times and arranged as a spit-split-plot RCBD. Overseeding (whole-plot factor) did not affect annual bluegrass cover at either location. Paclobutrazol (split-plot factor) reduced annual bluegrass cover each year at both locations. Insecticide program (split-split plot factor) only affected annual bluegrass cover at the North Brunswick site. At North Brunswick, all paclobutrazol treated plots had 0% annual bluegrass cover at the conclusion of the 2-year experiment. In the absence of paclobutrazol, annual bluegrass cover was lower in the no-insecticide program (23%), than the threshold and preventative programs (37 and 44%). After 2 years, paclobutrazol

(280 g ha^{-1}) provided excellent annual bluegrass control. Withholding ABW insecticides also reduced annual bluegrass in North Brunswick, though control was marginal. Thus, monthly applications of paclobutrazol during the growing season eliminated annual bluegrass after 2 years and omitting ABW insecticidal control also reduced annual bluegrass, though its efficacy was site-specific.

INTRODUCTION

Annual bluegrass (*Poa annua)* is among the most widely distributed and difficult to control weeds in cool-season turf (Beard et al. 1978, Tutin 1952). As a winter annual that can survive as a short-lived perennial in cool climates, annual bluegrass produces large amount of seed that germinates and emerges throughout the growing season (Lush 1988, Kaminski and Dernoeden 2007). It's adaptability to low mowing heights and aggressive reproductive behavior make it highly competitive in turfgrass systems (Beard et al. 1978). Although seldom introduced intentionally, small infestations of annual bluegrass can spread rapidly and ultimately dominate a turf stand. When infestations are severe, many turf managers chose to abandon weed control efforts and manage this undesirable turfgrass to preserve the integrity of the stand.

While certainly well-adapted for survival in turf systems, annual bluegrass is susceptible to common turf diseases including summer patch (*Magnaporthe poae*), dollar spot (*Clarireedia jacksonii*), Pythium blight (*Pythium* spp.), and is more prone to injury from stress-related anthracnose epiphytotics (*Colletotrichum cereale*) than other turfgrass species, especially in the summer months (Vargas 2005, Chen 2016, Inguagiato et al. 2008; 2009; 2012; Hempfling et al., 2017; Schmid et al., 2017). Annual bluegrass is also more prone to injury from insect pests such as the annual bluegrass weevil (ABW; *Listronotus maculicollis*) (Kostromytska et al. 2014, 2016). Consequently, annual bluegrass management differs from that of other cool-season turfgrasses due to the species sensitivity to biotic and abiotic stresses (Beard et al. 1978, Espevig et al. 2014, Hoffman et al. 2014). For annual bluegrass to perform well as turf, supplementary pest and disease control is often required, costing time and resources.

There are few options for turf managers to remove annual bluegrass, aside from renovations, which are costly and labor intensive. One of the major challenges in cool-season turf is lack of herbicides registered for creeping bentgrass fairways. Herbicide selectivity in creeping bentgrass is often a limiting factor (McCullough and Hart 2006, McCullough et al. 2010, Yu et al. 2015, Meyer and Branham 2006). In the US, sequential applications of the gibberellic acid (GA) biosynthesis-inhibitor paclobutrazol ((R,R)- 1-(4-chlorophenyl)-4,4-dimethyl-2-(1H-1,2,4-triazol-1-yl)pentan-3-o)). Paclobutrazol is an effective annual bluegrass control available for creeping bentgrass putting greens and fairways (Patton et al. 2019, Reicher et al. 2017, McCullough et al. 2005, Woosley et al. 2003). The inhibition of GA biosynthesis by paclobutrazol suppresses plant growth, an effect prolonged in annual bluegrass (Woosley et al. 2003).

Cultural practices such as overseeding creeping bentgrass can also be deployed for annual bluegrass control but may not result in immediate population reductions (Gaussoin and Branham 1989). Overseeding, a common practice on ryegrass athletic fields, consists of introducing new seed to an existing stand of turfgrass (Reicher and Hardebeck 2002). When successful, introduced seed germinates and fills in openings in the turfgrass canopy, preventing weed encroachment. Reicher and Hardebeck (2002) found overseeding perennial ryegrass athletic fields reduced annual bluegrass cover by 36%, while overseeding ‘Penncross’ creeping bentgrass fairways only resulted in a 3% reduction. However, research since has suggested that creeping bentgrass establishment may be improved by using newer, more competitive cultivars. Seeding date also impacts overseeding establishment. Murphy et al. (2005) and Henry et al. (2005) evaluated the effect of overseeding date and various creeping bentgrass cultivars for creeping bentgrass establishment in annual bluegrass fairways and putting greens, respectively. Both studies concluded that summer seeding (June-August) resulted in more bentgrass establishment after a year than traditional fall seeding (September). The effect of seeding date on establishment success was most apparent with older cultivars, while newer cultivars like 'PennA-4', with higher shoot density (> 2000 shoots dm^{-2}) were faster to establish than Penncross (1369 shoots dm^{-2}) regardless of seeding date (Murphy et al. 2005, Henry et al. 2005, Beard et al. 1978). The authors attributed the success of creeping bentgrass seeding in June and July to high soil temperatures (27°C or above) that reduced annual bluegrass emergence (Murphy et al. 2005, Beard et al. 1978).

One pest often responsible for the decline of annual bluegrass during the month of June is the ABW. The ABW is a common pest of short mown turfgrass areas throughout the Northeastern United States and its larvae can cause severe damage to golf course greens, collars, approaches, tees, and fairways, particularly where turf stands contain a high percentage of annual bluegrass (McGraw and Koppenhöfer 2009, Vittum et al. 1999, Kostromytska and Koppenhöfer 2014, 2016). The ABW adult showcases ovipositional preference for annual bluegrass over creeping bentgrass which is the basis of selective annual bluegrass damage (Simard et al. 2009, Kostromytska and Koppenhöfer 2014, McGraw and Koppenhöfer 2017). Despite ubiquity in cool-season turf and host-specificity, ABW has not been investigated as a biological control agent for annual bluegrass (Vittum et al. 1999, Kostromytska & Koppenhöfer 2014). Although it is well documented that ABW damage is more severe on annual bluegrass than creeping bentgrass, we are not aware of any reports examining its efficacy for annual bluegrass control in field experiments.

The objective of these experiments was to test the efficacy of the ABW for annual bluegrass control in creeping bentgrass alone and in combination with creeping bentgrass overseeding and monthly paclobutrazol applications. We hypothesized that manipulating insecticide programs to allow for ABW damage would reduce annual bluegrass cover in creeping bentgrass fairways. We further hypothesized that ABW efficacy would increase in conjunction with creeping bentgrass overseeding and paclobutrazol programs.

MATERIALS AND METHODS

A field experiment was conducted at two separate locations with annual bluegrass infestations and a history of ABW. From 2017 to 2018, research was conducted on a simulated golf fairway at Rutgers Horticulture Farm No. 2 (Hort Farm 2) in North Brunswick, NJ (40°28'12.3"N, 74°25'16.9"W). The was a mature annual bluegrass and creeping bentgrass fairway on Nixon silt loam soil with a pH of 6.1 and 87% annual bluegrass cover when the experiment was initiated in 2017. The creeping bentgrass variety in the fairway was unknown, but it displayed density and growth habit similar to Penncross. From 2018 to 2019 a replicate experiment was also conducted at Forest Hill Field Club (Forest Hill) in Bloomfield, NJ (40°48'07.8"N 74°10'43.6"W) on a mixed cool-season fairway of perennial ryegrass on a Boonton silt loam soil with ≤15% creeping bentgrass and 75% annual bluegrass cover at the beginning of the experiment. Annual bluegrass at Forest Hill was well-established and displayed characteristics of *P. annua* L. f. *reptans* (Hausskn) T. Koyama (denser, finer in texture, weakly stoloniferous). Contrarily, the stand of annual bluegrass at Hort Farm 2 was established in 2016, and had a more upright growth habit and prolific seedhead production than observed at Forest Hill.

At each location the experiment duration was 2 years to evaluate compounding treatment effects. Plots were irrigated to optimize annual bluegrass growth, and nitrogen fertilizer totaling 90 to 135 kg ha^{-1} was applied annually to maintain full turf cover. At Hort Farm 2, plots were typically mowed thrice per week to 0.95 cm using a triplex reel mower. The site in Bloomfield, NJ was mowed thrice per week to 0.95 cm and irrigated at the discretion of the superintendent. Fungicides were applied to both sites each year to prevent diseases common to annual bluegrass. Rotations of fungicides; tebuconazole, propiconazole, fludioxonil, iprodione, pyraclostrobin, cyazofamid, flutolanil, polyoxin D, azoxystrobin, and combination product chlorothalonil and acibenzolar-S-methyl, were applied at 3-week intervals from April through October to control dollar spot (caused by *Clarireedia jacksonii),* brown patch (caused by *Rhizoctonia solani),* summer patch (caused by *Magnaporthe poae*), and anthracnose (caused by *Colletotrichum graminicola*). In July, spinosad (Conserve, Dow AgroSciences, Indianapolis, IN; 0.30 kg ha^{-1} () and imidacloprid (Merit, Bayer, Research Triangle Park, NC; .34 kg ha^{-1}) were applied for black cutworm (*Agrotis ipsilon* Hufnagel) and white grub (Coleoptera: Scarabaeidae) control respectively. In 2017, two fungicide applications were inadvertently omitted in June and July at Hort Farm 2.

Treatments tested were with and without overseeding (‘007’ creeping bentgrass), three insecticide programs for various levels of ABW control, and with or without monthly applications of paclobutrazol for annual bluegrass control in a 2 by 3 by 2 factorial with four replications arranged in a split-split plot experimental design. Whole plots were 4.0 m by 2.0 m, sub-plots 2.0 m by 2.0 m and sub-sub-plots 1.0 m by 2.0 m. Overseeding served as the whole-plot factor, insecticide program as the sub-plot, and paclobutrazol as the sub-sub-plot. Paclobutrazol and insecticide treatments were applied with a CO_2-powered backpack sprayer equipped with a AI9504EVS nozzle (Teejet Technologies, Springfield, IL) at a carrier rate of 420 L ha^{-1} at 310 kPa spray pressure. Insecticides were irrigated into the thatch with approximately 2.5 mm water immediately following application. Paclobutrazol was irrigated with 2.5 to 7.5 mm of water within 24 hr after application.

Paclobutrazol (sub-sub-plot factor)

Paclobutrazol (Trimmit 2SC, Syngenta Crop Protection, Greensboro, NC; 280 g ha^{-1}) was applied at 280 g ha^{-1} every 28 d (±7 d) from annual bluegrass seedhead shatter in May through November, except it was not applied closer than 3 weeks prior to anticipated seeding date and for 4 weeks after the actual seeding date to prevent creeping bentgrass injury following overseeding (Kaminski et al. 2004). At Forest Hills, the monthly paclobutrazol rate was reduced to 210 g ha^{-1} from July 2018 onward to improve turfgrass quality.

Insecticide Program (sub-plot factor)

Three insecticide programs; preventative, threshold, and no-insecticide were created to evaluate ABW for annual bluegrass control (Table 2.1). Growing degree-days (base temperature 10°C, starting on 1 March; GDD_{10}), phenological indicators, and larval sampling were used as a guide to predict ABW activity and time first generation insecticide applications. First generation larvae were sampled weekly per methods described in Koppenhöfer et al. (2018). The preventative program began with the systemic insecticide cyantraniliprole (Ference, Syngenta Crop Protection, Greensboro, NC) at 160 g ha^{-1} to control first to third instar larvae (around 111 GDD_{10} and late bloom of flowering dogwood, *Cornus florida* L.). This was followed by the non-systemic insecticide indoxacarb (Provaunt, Syngenta Crop Sciences, Greensboro, NC; 250 g ha^{-1} at 194 GDD_{10} and onset of full bloom of hybrid Catawba rhododendron (*Rhododendron catawbiense* Michx.) to control any surviving mid-size larvae. The threshold program also utilized the systemic insecticide cyantraniliprole, but applications were withheld until a turfgrass quality damage threshold (turfgrass quality < 6.0 on a 1 to 9 scale in non-treated plots) was met. At this time, cyantraniliprole was applied at 290 g ha^{-1} to control larvae and prevent further plant injury. The non-systemic insecticide spinosad (450 g ha^{-1}) was applied to both preventative and threshold treatments to control second generation ABW larvae on 15 August 2017 and 12 July 2018 at Hort Farm 2 and on 12 July 2018 and 8 August 2019 at Forest Hill. An additional cyantraniliprole (290 g ha^{-1}) application was made on 30 July 2018 to protect preventative and threshold plots from a third ABW generation at Hort Farm 2. At Forest Hill, the damage threshold was not met in 2018 or 2019 and cyantraniliprole was not applied to threshold treatments, but spinosad was applied in July.

Overseeding (whole-plot factor)

The overseeding treatment consisted of seeding '007' creeping bentgrass (50 kg PLS ha^{-1}). The Hort Farm 2 site was overseeded on 12 June 2017 and 2018, 1 week after the turfgrass quality threshold was met and the threshold insecticide treatment was applied. Plots at Forest Hill were overseeded on 21 June 2018 and 12 June 2019. To prepare the sites, a vertical mower (Ryan Reno-Thin Power Rake, Schiller Grounds Care, Johnson Creek, WI) was used to cut 0.6 cm deep perpendicular slits on the entire site, including plots not receiving overseeding treatment. Seed was then mixed with sand and evenly distributed to the appropriate plots using a shaker jar inside a frame (to prevent wind-aided seed drift). Seed was then brushed in two directions using a hand broom. Following overseeding, cyazofamid (0.44 kg ha^{-1}), TriCure wetting agent (12.7 L ha^{-1}) and fertilizer (12-24-8; 49 kg P_2O_5 ha^{-1}) were applied to the entire trial and followed immediately with 15 mm of irrigation.

Data Collection and Analysis

To evaluate insecticide program efficacy, larval densities were evaluated in early June when most ABW were third-instar larvae or above. At this time most eggs have hatched and larvae are large enough to be seen (Koppenhöfer et al. 2018). To determine larval densities, six turf cores (5.2 cm diameter, 5.0 cm depth) were removed from each plot with a turf plugger (Duich Ball Mark Plugger BMP1-M). Cores were transported to the laboratory in plastic bags and processed within 8 h of field sampling. Cores were examined for larvae, quartered and submerged in a saturated NaCl solution for further extraction as described in Koppenhöfer et al. (2018). Extracted larvae were counted and preserved in 90% ethanol. Counts were used to estimate larval densities per m^2 in each plot using the following equation. Six cores had a total surface area of 127.4 cm^2:

$$\text{larvae m}^2 = \frac{(\text{larvae per } 127.4\ \text{cm}^2) \times 10000\ \text{cm}^2}{127.4\ \text{cm}^2}$$

To objectively determine the turfgrass species composition a grid count was conducted twice annually in June and October. A 91 by 91 cm grid fitted with 100 evenly spaced intersects was placed over each plot to determine the species present at each intersect. Annual bluegrass cover was visually estimated on a 0 (no cover) to 100 (complete cover) percent scale monthly during the growing season each year. Turfgrass quality, annual bluegrass quality, and creeping bentgrass quality were evaluated visually on a 1 (poor) to 9 (excellent) scale where 6 is considered acceptable. Lightbox photos were taken monthly with a Nikon camera and subjected to digital image analysis with TurfAnalyzer software (threshold set to hue: 50-140, saturation: 10-100, brightness: 0-100) to determine percent green cover (Karcher et al. 2017).

Data were subjected to ANOVA using the GLIMMIX procedure of SAS (v9.4, SAS Institute) to analyze as a split-split-plot design with replication as a random effect. Fisher's Protected LSD was used to separate means where appropriate ($\alpha = 0.05$). Locations were analyzed separately as treatment by location interactions occurred on multiple dates. Data met assumptions of ANOVA according to the Shapiro-Wilk test for normality.

RESULTS

Data for each location are presented separately. Except for annual bluegrass cover at the Hort Farm 2 location, the highest order interactions significant on multiple rating dates are presented. Overseeding had no consistent impact on annual bluegrass cover or turfgrass quality at either location throughout the course of the experiment and will not be discussed (Tables 2.2-5).

Annual bluegrass weevil larval densities

Larvae were sampled before the damage threshold was met in 2017 and seven days after the damage threshold was met in 2018; thus, the efficacy of the threshold treatment could not be assessed in 2017. At Hort Farm 2, the preventative insecticide program resulted in 97% ABW larvae control in both 2017 and 2018 (Table 2.6). In 2018 paclobutrazol treatments had fewer ABW larvae than non-paclobutrazol treatments regardless of insecticide program (Table 2.7). Since this occurred in 2018 and not 2017 we speculate that this was likely an artifact of lower annual bluegrass cover in paclobutrazol treated plots (7% cover in May 2018 compared to 87% in the May 2017).

At Forest Hill, the preventative program provided 90% control of ABW larvae in 2018, and 52% control in 2019. Despite an average ABW density of 257 larvae m^{-2} in non-treated plots the turfgrass quality threshold was never met and thus cyantraniliprole was not applied in 2018 or 2019.

Annual bluegrass cover

Hort Farm 2

Across insecticide programs paclobutrazol reduced annual bluegrass cover on every evaluation date from May 2017 to April 2019 (Table 2.2, Figure 2.1). By 17 November 2017, annual bluegrass cover in paclobutrazol treated plots was 13%, compared to 38% cover in the non-treated plots. At conclusion of the experiment in April 2019, annual bluegrass cover in paclobutrazol plots was 0% while cover in non-treated plots was 35% (Figure 2.1).

Insecticide program first affected annual bluegrass cover on 2 July 2017, when cover was 9% lower in the no-insecticide program than the preventative program. No effect was observed thereafter, but this may be of little biological significance as cover was similar from August 2017 through June 2018 (Figure 2.2). Treatment differences were observed again in July 2018, disappeared in August 2018, but then persisted from September 2018 until the experiment concluded in April 2019. On 22 July 2018 (roughly 1 month after the damage threshold was met) annual bluegrass cover was 13 and 18% in the no-insecticide and threshold treatments compared to 28% in the preventative treatments. Annual bluegrass cover remained lower in the threshold and non-treated plots until October 2018, when threshold-treated plots were similar to the preventative program (14 and 18%, compared to 8% in the no-insecticide) (Figure 2.2). This trend persisted through the winter and was observed again on the final rating date (25 April 2019), when cover was lower in the no-insecticide program (12%) than both threshold (19%) and preventative programs (22%; Figure 2.2).

The interaction between paclobutrazol and insecticide effects on annual bluegrass cover was significant in July and August 2018 and at the final evaluation in April 2019. On these dates, paclobutrazol treatment resulted in similar annual bluegrass cover regardless of insecticide program (Figure 2.3). Insecticide program affected annual bluegrass cover only in the absence of paclobutrazol, where trends were similar to those presented for the main effect. On dates where the interaction was significant, annual bluegrass cover was lowest in the no-insecticide plots (19-26%). In July 2018, the threshold program resulted in 29% annual bluegrass compared to 44% for the preventative program, but these two programs provided similar cover in August 2018 (34 and 38%) and there were no differences between the two programs for the remainder of the experiment (37 to 44%) (Figure 2.3). In April 2019, annual bluegrass cover was 0% for all paclobutrazol treated plots, regardless of insecticide program. Of those not treated with paclobutrazol, the no-insecticide program had lower cover (23%) than both threshold and preventative programs (37% and 44% respectively) in April 2019.

Grid intersect counts determined annual bluegrass coverage was higher than estimated by visual ratings taken around the same date, but the rank order of treatment means supported visual evaluations (Figure 2.1, Table 2.8). The main effect of paclobutrazol was significant at every date for both locations. As determined by grid count the effect of insecticide program was not significant at either location, but trends at Hort Farm 2 support visual ratings.

Forest Hill

At Forest Hill, only paclobutrazol affected annual bluegrass cover (Table 2.3). The main effect of insecticide program was not significant and the turfgrass quality damage threshold was not met either year. Annual bluegrass cover was 70% at the start of the experiment in May 2018; by October 2018, paclobutrazol treatments had 29% annual bluegrass cover (relative to 66% in the non-treated (Figure 2.4). In October 2019, paclobutrazol treatments had 61% annual bluegrass cover compared to 80% in the non-treated (Figure 2.4).

Turfgrass quality

Hort Farm 2

In 2017, the ABW damage threshold was met on 12 June and threshold treatments were applied on the same date. Insecticide program affected turfgrass quality only on 22 June in 2017 and turf quality was 6.7 in the preventatively treated plots compared to 5.5 and 5.8 in the threshold and non-treated, respectively (Figure 2.5). On 18 July 2017, anthracnose visibly reduced turfgrass quality of the preventative insecticide program (Figures 2.5-6). By August, turf quality was > 6.0 for all insecticide programs and there were no differences in turfgrass quality, or percent green cover as measured by digital analysis from lightbox photos between insecticide programs for the rest of the year (Figure 2.5-6).

Insecticide program affected turfgrass quality from May to August in 2018 (Table 2.4). On each date, the preventative program resulted in the highest turfgrass quality (Figure 2.5). From May to July 2018, the threshold and no-insecticide plots displayed similar turfgrass quality. Turfgrass quality reductions were mostly concomitant with annual bluegrass cover reductions.

Paclobutrazol also affected turfgrass quality on several dates when averaged across insecticide and overseeding main effects (Table 2.4). Each year, turfgrass quality differences between paclobutrazol treatments were most pronounced in May and early June, when spring generation ABW larvae were feeding (data not presented). From late June until October, paclobutrazol treatment reduced turfgrass quality compared to the non-treated plots, but turfgrass quality for both treatments was acceptable (> 6).

In May, June, and October 2018, the interaction of insecticide program and paclobutrazol was significant for turfgrass quality (Table 2.10). On 31 May when damage from ABW larvae was first apparent, turf quality was lower in threshold and no insecticide treatments not treated with paclobutrazol (≤ 6.5) compared to preventative and paclobutrazol treatments (≥ 7.7). These treatment differences can be attributed to less annual bluegrass cover in paclobutrazol treated plots following six months of paclobutrazol treatment during the 2017 growing season; thus, turf quality was less affected by ABW damage.

Forest Hill

Insecticide program did not affect turfgrass quality at Forest Hill, but paclobutrazol had a season-long effect (Figure 2.6). Paclobutrazol reduced turfgrass quality to 5.5 on 7 June 2018 as large patches of annual bluegrass comprised much of the turfgrass stand. Starting in July, the monthly paclobutrazol rate was lowered to 210 g ha^{-1} to reduce turfgrass injury and paclobutrazol did not affect turfgrass quality for the remainder of the experiment.

DISCUSSION

Multi-year, sequential paclobutrazol application can be extremely effective for annual bluegrass control in creeping bentgrass. Paclobutrazol resulted in nearly 100% annual bluegrass control on the simulated creeping bentgrass fairway located at the Hort Farm 2 location. Similar paclobutrazol regimens on creeping bentgrass fairways provided 85%

annual bluegrass control after one year in previous research (Woosley et al. 2003). The efficacy of paclobutrazol is also supported by the work of Patton et al. (2019) and Reicher et al. (2017) on putting greens. We attributed excellent efficacy to Hort Farm 2's blended canopy, where annual bluegrass was well-mixed throughout the stand of bentgrass. Paclobutrazol was less effective at Forest Hill, where turfgrass species grew in distinctive patches. Previous research has also demonstrated variable paclobutrazol efficacy across locations (Patten et al. 2019, Reicher et al. 2015, Jefferies et al. 2013).

Withholding insecticides for ABW control reduced annual bluegrass cover in creeping bentgrass. Applying insecticides for ABW control only after turfgrass quality declined below an acceptable threshold reduced annual bluegrass cover only temporarily. In this threshold-based approach, turfgrass quality quickly recovered and was similar to the preventative program 1 month after application in both years. This rapid recovery in turfgrass quality was attributed to annual bluegrass regrowth from surviving meristems rather than seed (observational data).

Insecticide programs affected annual bluegrass cover only at Hort Farm 2 but not at the golf course location. Annual bluegrass cover may have affected the efficacy of ABW insecticide programs at both sites and across years. At Hort Farm 2, the no-insecticide program reduced annual bluegrass cover more in 2018 than 2017. Annual bluegrass cover was lower across all treatments in spring 2018 (38%, in the absence of paclobutrazol) than spring 2017 (88%) at Hort Farm 2. Part of this decline may have been an artifact of turfgrass disease following delayed fungicide applications in June 2017. Even though observed ABW larval density was lower in 2018 than 2017, there were fewer annual bluegrass plants present (due to greater creeping bentgrass cover) and larvae densities on annual bluegrass plants may have been similar across both years. Furthermore, the amount of annual bluegrass cover affects when the damage threshold will be met, as annual bluegrass influence on overall turfgrass quality is contingent on the amount of annual bluegrass present in each plot. Consequently, higher creeping bentgrass coverage in 2018 at Hort Farm 2 allowed for more severe ABW damage to annual bluegrass before the damage threshold was met.

ABW damage was less obvious at the Forest Hill golf course location than at the research farm despite both locations having similar larval densities. At Forest Hill, ABW damage was minor and threshold-based insecticide applications were never applied. Visible ABW damage was hardly observed at Forest Hill. Differences in turfgrass composition may have contributed to this lack of visible damage. The creeping bentgrass at Hort Farm 2 was intermixed with the annual bluegrass, which grew erect from crowns, not stolens, with longer, wider blades, than bluegrass at Forest Hill. It also produced more inflorescence each year. The Forest Hill annual bluegrass did not appear to be injured as severely as the biotype present at Hort Farm 2. The annual bluegrass, creeping bentgrass, and perennial ryegrass at Forest Hill existed in patches, which are less conducive to interspecific plant competition that would allow creeping bentgrass or perennial ryegrass cover to increase if annual bluegrass is weakened by ABW or paclobutrazol.

Golf course superintendents may be able to reduce annual bluegrass cover by allowing ABW damage to occur. However, this research suggests that unless ABW are allowed to cause severe annual bluegrass damage, the annual bluegrass may rapidly recover. Allowing severe annual bluegrass damage may only be practical where annual bluegrass comprises a small percentage of the turfgrass stand or is mixed well with creeping bentgrass. Paclobutrazol was extremely effective in reducing annual bluegrass cover regardless of insecticide program. The paclobutrazol rate (280 and 210 g ha^{-1}) used in this research is higher than commonly used by golf course superintendents. Future research should evaluate the effect of lower paclobutrazol rates in combination with threshold-based insecticide applications for ABW control. Additionally, because turfgrass composition and natural ABW populations likely play large roles, more research is required to confirm and quantify the influence each of these factors have on annual bluegrass control in fairways.

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Table 2.1 Annual bluegrass weevil insecticide programs and application dates at Hort Farm 2 (North Brunswick, NJ) in 2017 and 2018, and at Forest Hill Field Club (Bloomfield, NJ) in 2018 and 2019. ABW larvae development was monitored weekly from May through July.

				Application dates			
				Hort Farm 2		Forest Hill	
Program	AI	Rate	Target larval stage	2017	2018	2018	2019
		$g\ ha^{-1}$	1 to 5 instar				
Preventative†0							
	cyantraniliprole	160	1 to 3	2 May	14 May	17 May	14 May
	indoxacarb	250	3 to 5	23 May	25 May	31 May	4 June
	spinosad	450	3 to 5	15 August	12 July	12 July	8 August
Threshold‡							
	cyantraniliprole§	290	3 to 5	12 June	4 June	31 May	-
	spinosad	450	3 to 5	15 August	12 July	12 July	8 August
No insecticide							
	-	-	-	-	-	-	-

† First-generation instar stages were monitored to schedule the initial insecticide application.

‡ Insecticides were applied to the threshold program once visual evaluations determined turfgrass quality was unacceptable (i.e., < 6 on a 1 to 9 scale; 9 = excellent turf quality).

§ Cyantraniliprole (290 $g\ ha^{-1}$) was re-applied to preventative and threshold programs on 30 July 2018 to arrest 3rd generation annual bluegrass weevil larvae.

Table 2.2 Analysis of variance of annual bluegrass cover response to overseeding, paclobutrazol, and insecticide program on a simulated creeping bentgrass fairway at Hort Farm 2 in North Brunswick, NJ from study initiation in 2017 to final rating in 2019.

		2017							**2018**						**2019**
Source of variation	**df**	**23 May**	**21 Jun.**	**27 Jul.**	**20 Aug.**	**15 Sep.**	**12 Oct.**	**17 Nov.**	**14 May**	**20 Jun.**	**22 Jul.**	**27 Aug.**	**21 Sep.**	**26 Oct.**	**25 Apr.**
		Probability of significant F test													
S†	1	NS‡	NS	NS	NS	NS	*	NS	NS	**	NS	NS	NS	NS	NS
P	1	**	***	***	***	***	***	***	***	***	***	***	***	***	***
S × P	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
I	2	NS	NS	*	NS	NS	NS	NS	NS	NS	*	NS	*	***	**
I × S	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I × P	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	*	NS	NS	**
I × S × P	2	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS

†Abbreviations: S = overseeding ('007' creeping bentgrass, 50 kg PLS ha^{-1}); P = paclobutrazol (280 g ha^{-1}, applied monthly); I = insecticide program (preventative, threshold, and no insecticide).

‡NS, non-significant; *, **, ***, significant when $\alpha \leq 0.05$, 0.01 and 0.001, respectively.

Table 2.3 Analysis of variance of annual bluegrass cover response to overseeding, paclobutrazol, and insecticide program on a mixed cool-season fairway at Forest Hill Field Club in Bloomfield, NJ from study initiation in 2018 to last rating in 2019.

		2018							2019						
Source of variation	**df**	**24 May**	**21 Jun.**	**19 Jul.**	**14 Aug.**	**6 Sep.**	**19 Oct.**	**18 Nov.**	**13 Apr.**	**2 May**	**26 Jun.**	**1 Aug.**	**10 Sep.**	**18 Oct.**	**21 Nov.**
		Probability of significant F test													
S†	1	NS‡	NS	NS	NS	NS	NS	NS	NS	NS	**	NS	NS	NS	NS
P	1	NS	***	***	***	***	***	**	***	***	***	***	***	***	***
S × P	1	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I × S	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I × P	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
I × S × P	2	*	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

†Abbreviations: S = overseeding (‘007’ creeping bentgrass, 50 kg PLS ha^{-1}); P = paclobutrazol (280 g ha^{-1}, applied monthly); I = insecticide program (preventative, threshold, and no insecticide).

‡NS, non-significant; *, **, ***, significant when $\alpha \leq 0.05$, 0.01 and 0.001, respectively.

Table 2.4 Analysis of variance of turfgrass quality response to overseeding, paclobutrazol, and insecticide program on a simulated creeping bentgrass fairway at Hort Farm 2 in North Brunswick, NJ in 2017 and 2018.

		2017							2018						
Source of variation	**df**	**22 Jun.**	**6 Jul.**	**18 Jul.**	**16 Aug.**	**1 Sep.**	**6 Oct.**	**26 Oct.**	**31 May**	**22 Jun.**	**22 Jul.**	**27 Aug.**	**21 Sep.**	**10 Oct.**	**26 Oct.**
		Probability of significant F test													
S†	1	NS‡	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
P	1	***	NS	***	**	***	NS	**	***	*	**	***	**	NS	*
S × P	1	NS	NS	**	NS	NS	NS	*	NS	NS	NS	NS	NS	**	NS
I	2	***	NS	NS	NS	NS	NS	NS	*	*	**	*	NS	NS	NS
I × S	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I × P	2	NS	NS	NS	NS	NS	NS	NS	**	**	NS	NS	NS	**	NS
I × S × P	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS

†Abbreviations: S = overseeding ('007' creeping bentgrass, 50 kg PLS ha^{-1}); P = paclobutrazol (280 g ha^{-1}, applied monthly); I = insecticide program (preventative, threshold, and no insecticide).

‡ NS, non-significant; *, **, ***, significant when $\alpha \leq 0.05$, 0.01 and 0.001, respectively.

Table 2.5 Analysis of variance of the turfgrass quality response to overseeding, paclobutrazol, and insecticide program on a mixed cool-season fairway at Forest Hill Field Club in Bloomfield, NJ in 2018 and 2019.

		2018							2019							
Source of variation	**df**	**24 May**	**7 Jun.**	**19 Jul.**	**14 Aug.**	**30 Aug.**	**19 Oct.**	**19 Nov.**	**13 Apr.**	**2 May**	**4 Jun.**	**1 Aug.**	**10 Sep.**	**18 Oct.**	**21 Nov.**
		Probability of significant F test													
S†	1	NS‡	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*
P	1	NS	***	**	**	***	*	***	*	*	*	NS	NS	NS	NS
S × P	1	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I × S	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I × P	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
I × S × P	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

†Abbreviations: S = overseeding (‘007’ creeping bentgrass, 50 kg PLS ha^{-1}); P = paclobutrazol (280 g ha^{-1}, applied monthly); I = insecticide program (preventative, threshold, and no insecticide).
‡NS, non-significant; *, **, ***, significant when $\alpha \leq 0.05$, 0.01 and 0.001, respectively.

Table 2.6 Analysis of variance for estimated annual bluegrass weevil (ABW) larval densities in overseeding, paclobutrazol, and insecticide program at Hort Farm 2 (North Brunswick, NJ) and at Forest Hill (Bloomfield, NJ) in spring of 2017, 2018, and 2019.

		ABW larval density			
		Hort Farm 2		Forest Hill	
Source of variance	**df**	**7 June 2017**	**24 May 2018**	**13 June 2018**	**4 June 2019**
		Probability of significant F test			
S†	1	-‡	NS	NS	NS
P	1	**	***	*	*
S × P	1	NS§	***	NS	NS
I	2	-	NS	-	NS
I × S	2	-	NS	-	NS
I × P	2	NS	**	NS	NS
I × S × P	2	-	NS	-	NS

†Abbreviations: S = overseeding (‘007’ creeping bentgrass, 50 kg PLS ha^{-1}); P = paclobutrazol (280 g ha^{-1}, applied monthly); I = insecticide program (preventative, threshold, and no insecticide).

‡ The factor of overseeding was omitted from the 2017 Hort Farm 2 and 2018 Forest Hill analyses, as it had not yet occurred.

§ NS, non-significant; *, **, ***, significant when $\alpha \leq 0.05$, 0.01 and 0.001, respectively.

Table 2.7 Annual bluegrass weevil larval densities averaged across insecticide programs at Hort Farm 2 (North Brunswick, NJ) and at Forest Hill (Bloomfield, NJ) for each spring generation.

		ABW larval densities			
		Hort Farm 2		**Forest Hill**	
Source of variation	**Treatment**	**7 June 2017**	**24 May 2018**	**13 June 2018**	**4 June 2019**
		ABW larvae m^{-2}			
Insecticide program					
	Preventative	29 b[†]	15 c	69 b	134 b
	Threshold[‡]	1020 a	216 b	598 a	235 a
	No-insecticide	961 a	476 a	706 a	279 a
Paclobutrazol					
	Paclobutrazol	667	39 a	428	129
	Non-treated	664	432 b	487	304

[†] Mean separation within columns, means with the same letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$).
[‡] At Hort Farm 2, larvae were sampled 9 days after cyantraniliprole (290 g ha^{-1}) was applied to the threshold treatments in 2018. On all other dates, larvae were sampled before the damage threshold was met and no insecticides were applied to threshold program.

Table 2.8 Effects of overseeding, paclobutrazol, and insecticide program on annual bluegrass cover as determined by grid intersect counts on a simulated creeping bentgrass fairway at Hort Farm 2 in North Brunswick, NJ from 2017 to 2019.

	2017		2018		2019
Treatment	**6 June**	**1 November**	**9 May**	**12 November**	**17 April**
			Percent annual bluegrass cover†		
			Overseeding		
Non-treated	57	21	27	8	12
Overseeded‡	61	19	25	7	10
			Paclobutrazol		
Non-treated	66 a¶	31 a	43 a	14 a	22 a
Paclobutrazol§	5 b	9 b	9 b	1 b	1 b
			Insecticide program		
Preventative	63	19	27	9	14 a
Threshold	57	22	26	7	13 a
No-insecticide	57	18	25	6	8 b

† Presence or absence of annual bluegrass was counted under 100 evenly spaced intersects within a 91 by 91-cm grid in each plot.
‡ Plots were overseeded with '007' creeping bentgrass (50 kg PLS ha^{-1}) on 12 June 2017 and 2018.
§ Paclobutrazol (280 g ha^{-1}) was applied monthly from May through October.
¶ Mean separation within columns and factors (overseeding, paclobutrazol, and insecticide program), means with the same letter are not significantly different according to Fisher's Protected LSD (α = 0.05).

Table 2.9 Effects of overseeding, paclobutrazol, and insecticide program on annual bluegrass cover as determined by grid intersect counts on a mixed cool-season fairway at Forest Hill Field Club in Bloomfield, NJ in 2018 and 2019. The analysis of variance results are also presented for main effects only as interactive effects were not significant.

		2018		2019	
Treatment		**24 May**	**19 Nov.**	**2 May**	**18 Nov.**
		Annual bluegrass cover†			
		Overseeding			
Non-treated		72¶	70	82	69
Overseeded‡		67	65	77	68
		Paclobutrazol			
Non-treated		69	75 a	84 a	75 a
Paclobutrazol§		70	60 b	48 b	61 b
		Insecticide program			
Preventative		69	72	81	68
Threshold		72	70	80	70
No-insecticides		67	62	76	65
Main effect	**df**	**ANOVA**			
		Probability of a significant F test			
Overseeding	1	NS£	NS	NS	NS
Paclobutrazol	1	NS	***	**	***
Insecticide program	2	NS	NS	NS	NS

† Determined by grid intersect count where presence or absence of annual bluegrass was determined under 100 evenly spaced intersects within a 91 by 91-cm grid in each plot.

‡ Plots were overseeded with '007' creeping bentgrass (50 kg PLS ha^{-1}) on 21 June 2018 and 12 June 2019.

§ Paclobutrazol (210 g ha^{-1}) was applied monthly from May through October.

¶ Means separation within a columns and factors (overseeding, paclobutrazol, and insecticide program) by Fisher's Protected LSD test (P = 0.05).

£ NS, non-significant; *, **, ***, significant when α ≤ 0.05, 0.01 and 0.001, respectively.

Table 2.10 Turfgrass quality as affected by insecticide program and paclobutrazol (monthly applications at 280 g ha^{-1}) on a simulated creeping bentgrass fairway at Hort Farm 2 in North Brunswick, NJ in 2018.

Insecticide program	**Paclobutrazol**	**31 May 2018**	**22 June 2018**	**10 October 2018**
			Turfgrass quality†	
Preventative				
	Non-treated	7.8 a‡	7.4 a	7.4 abc
	Paclobutrazol	8.0 a	6.3 b	7.3 abc
Threshold				
	Non-treated	6.4 b	6.5 b	7.5 ab
	Paclobutrazol	7.9 a	6.6 b	7.3 c
No-insecticide				
	Non-treated	6.5 b	6.4 b	7.3 bc
	Paclobutrazol	7.8 a	6.5 b	7.5 a

† Turfgrass quality was evaluated visually on a 1 (poor) to 9 (excellent) scale where 6 is considered acceptable.

‡ Means averaged across main effect of overseeding with separation within columns and factor of insecticide program. Means with the same letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$).

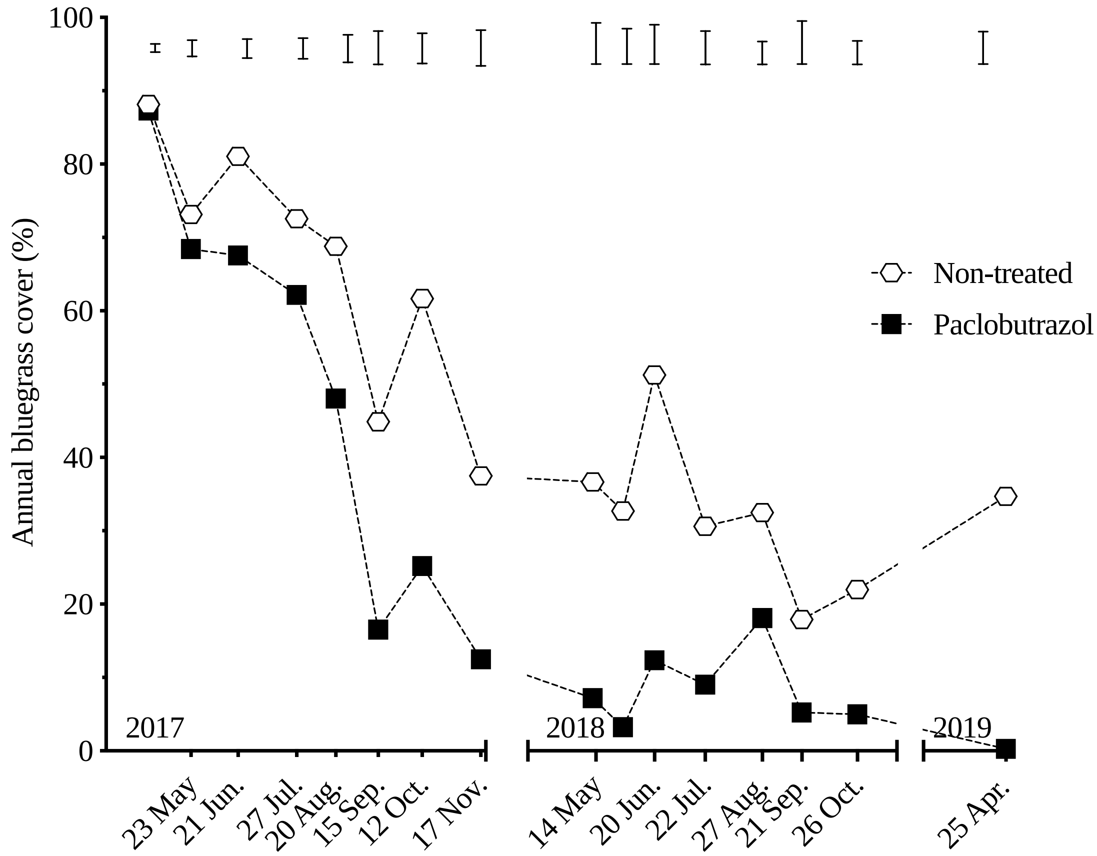

Figure 2.1 Annual bluegrass cover as affected by paclobutrazol (280 g ha^{-1}, applied monthly) on percent annual bluegrass cover on a simulated creeping bentgrass fairway at Hort Farm 2 in North Brunswick, NJ from study initiation in 2017 to final rating in 2019. Means are presented across insecticide and overseeding main effects. Error bars represent Fishers' Protected LSD (α = 0.05), NS = not significant.

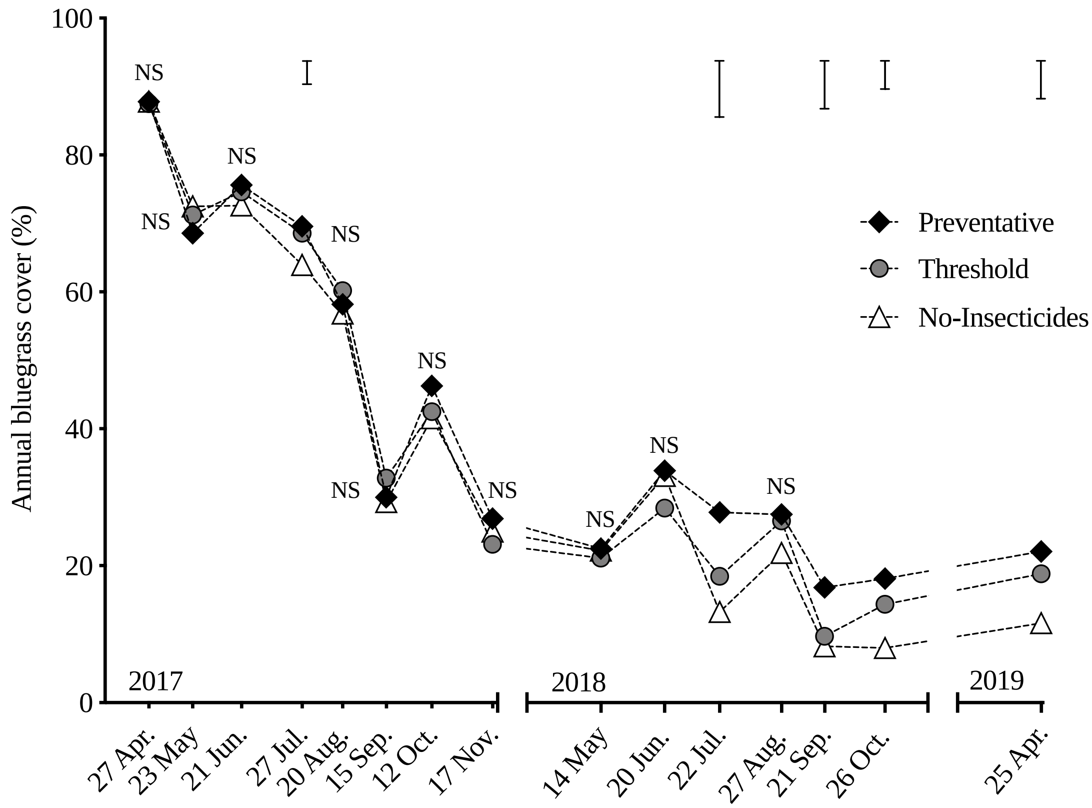

Figure 2.2 Annual bluegrass cover as affected by insecticide program (preventative, threshold, and no-insecticide) on a simulated creeping bentgrass fairway at Hort Farm 2 in North Brunswick, NJ from 2017 to 2019. Means are presented across paclobutrazol and overseeding main effects. Error bars represent Fishers' Protected LSD (α = 0.05), NS = not significant.

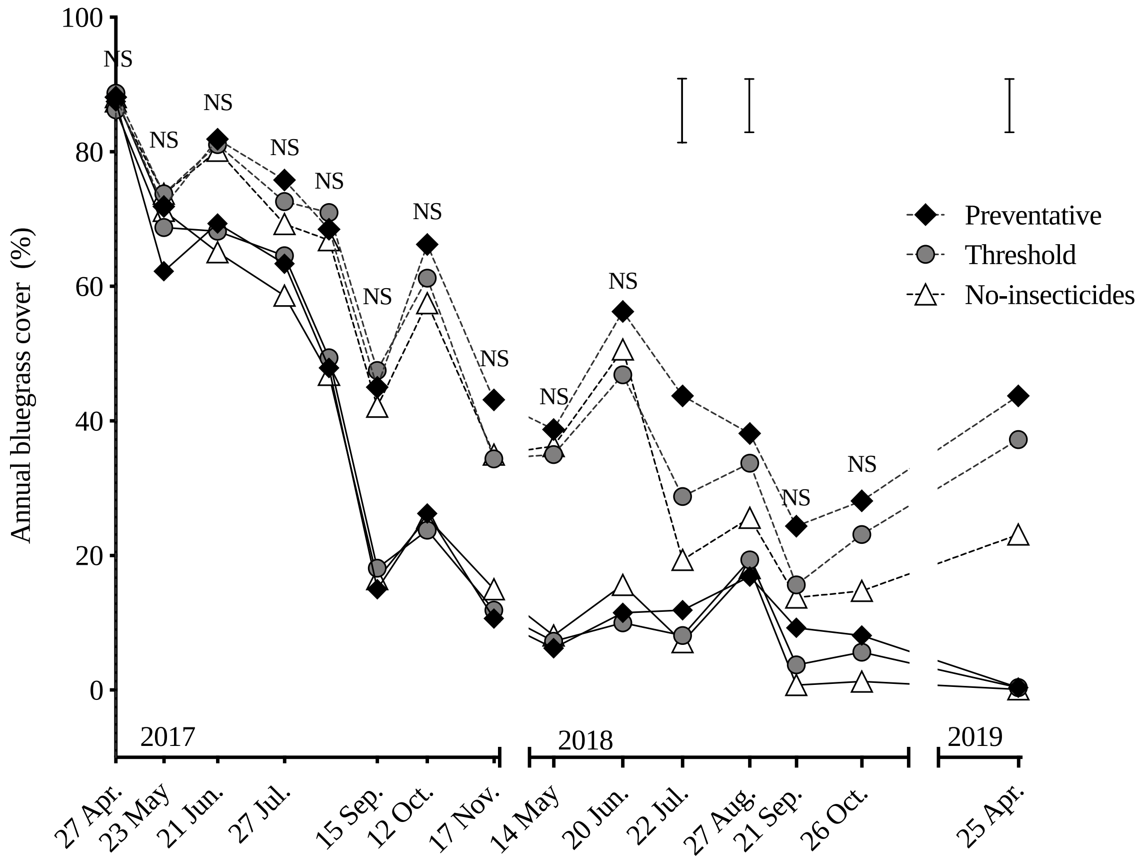

Figure 2.3 Annual bluegrass cover as affected insecticide program (preventative, threshold, and no-insecticide) and paclobutrazol in North Brunswick, NJ from study initiation in 2017 to the final rating in 2019. Paclobutrazol (280 g ha^{-1}, applied monthly) treatments are represented with a dotted line, nontreated with a solid line. Means presented are averaged across the main effect creeping bentgrass overseeding. Error bars represent Fishers' Protected LSD (α = 0.05), NS = not significant.

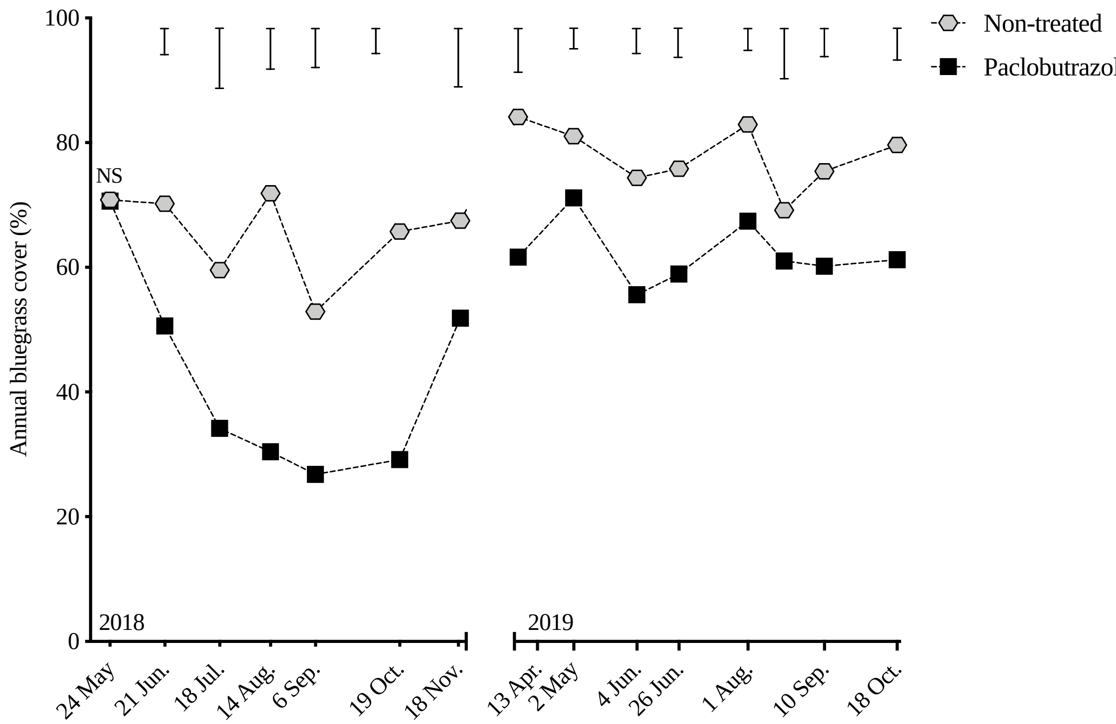

Figure 2.4 Annual bluegrass cover as affected by paclobutrazol (210 g ha^{-1}, applied monthly) on a mixed cool-season fairway in Bloomfield, NJ from 2018 to 2019. Means presented are averaged across main effects of insecticide program and creeping bentgrass overseeding. Error bars represent Fishers' Protected LSD (α = 0.05), NS = not significant.

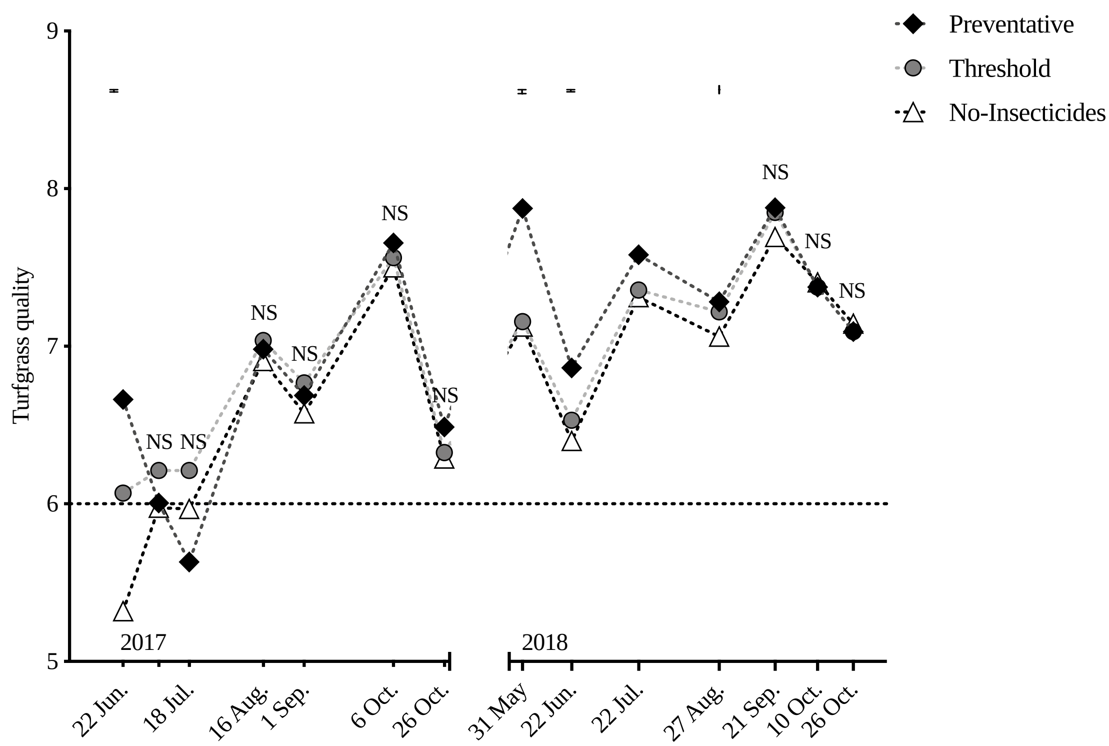

Figure 2.5 Effects of insecticide program on turfgrass quality of a simulated creeping bentgrass fairway in North Brunswick, NJ from 2017 to 2018. Means presented are averaged across main effects of paclobutrazol and creeping bentgrass overseeding. Turfgrass quality was evaluated visually on a 1 (poor) to 9 (excellent) scale where 6 is considered acceptable. Error bars represent Fishers' Protected LSD (α = 0.05), NS = not significant.

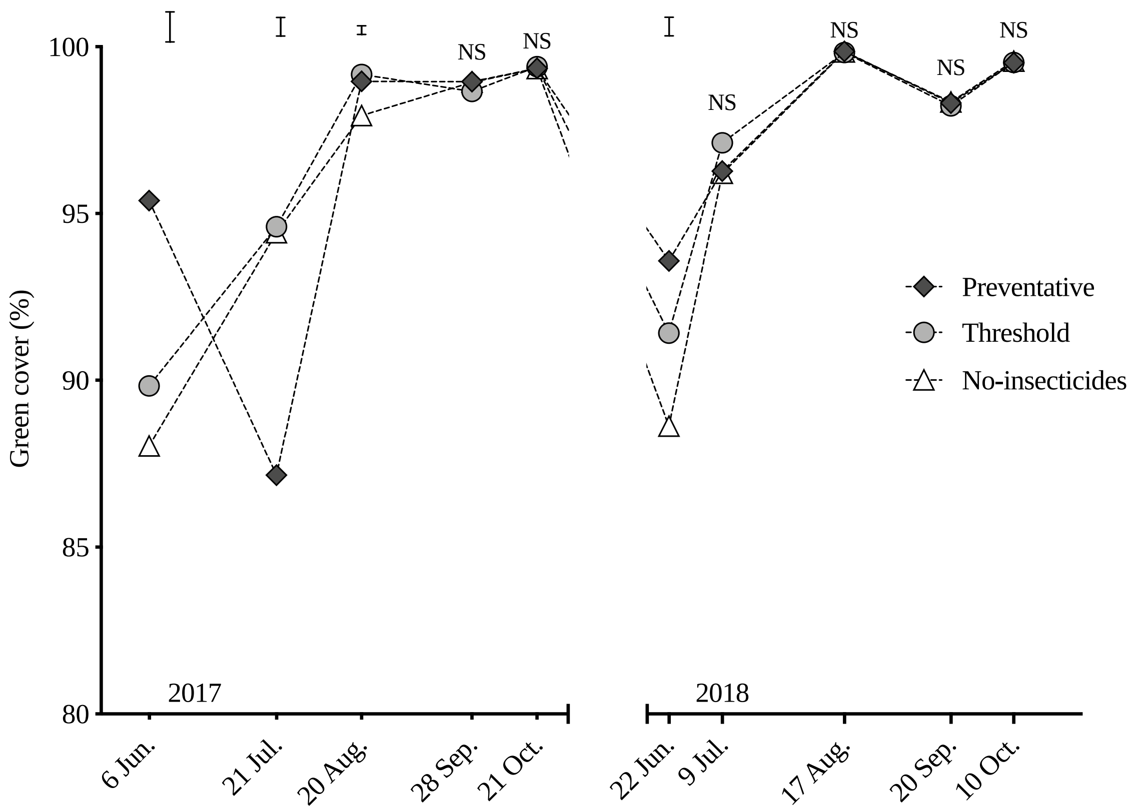

Figure 2.6 Effects of insecticide program on percent green cover of a simulated creeping bentgrass fairway in North Brunswick, NJ from 2017 to 2018. Means are averaged across main effects of paclobutrazol and creeping bentgrass overseeding. Percent green cover taken from lightbox photos subjected to digital analysis using TurfAnalyzer Software. Error bars represent Fishers' Protected LSD (α = 0.05), NS = not significant.

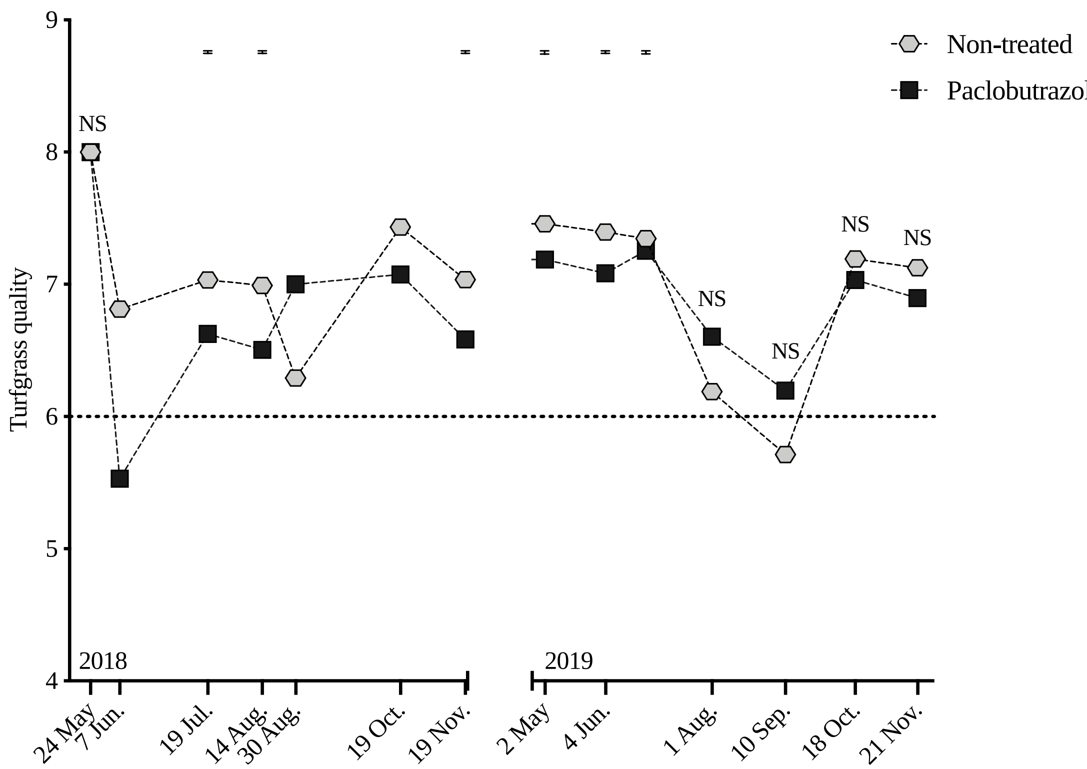

Figure 2.7 Main effects of paclobutrazol (210 g ha^{-1}, applied monthly) on turfgrass quality (ranked on a 1 to 9 scale, where 6 is considered acceptable) on a mixed fairway at Forest Hill Field Club in Bloomfield, NJ. From 2018 to 2019. Means are averaged across main effects of creeping bentgrass overseeding and insecticide program. Error bars represent Fishers' Protected LSD ($\alpha = 0.05$), NS = not significant.

CHAPTER 3. Annual bluegrass weevil (*Listronotus maculicollis)*, and paclobutrazol for annual bluegrass (*Poa annua)* control in creeping bentgrass (*Agrostis stolonifera*) fairways.

ABSTRACT

The annual bluegrass weevil (*Listronotus maculicollis*; ABW) is a common turf pest with ovipositional preference for annual bluegrass (*Poa annua*), over creeping bentgrass (*Agrostis stolonifera*). Research presented in Chapter 2 indicates the withholding ABW insecticidal control can reduce annual bluegrass cover on creeping bentgrass fairways. The objective of this study was to evaluate threshold-based ABW insecticide programs for annual bluegrass control in creeping bentgrass fairways alone, and in combination with various rates of paclobutrazol. The effect of three insecticide programs (preventative, threshold, and no-insecticide) and four rates of paclobutrazol (0, 70, 105, or 210 g ha^{-1} applied monthly) on annual bluegrass cover were evaluated 2018 and 2019 on a simulated creeping bentgrass fairway at Rutgers Horticulture Farm No. 2 in North Brunswick, NJ. Treatments were arranged in a 3 by 4 factorial, randomized complete block design. In 2018, the preventative insecticide had the most annual bluegrass when no paclobutrazol was applied and at the 105 g ha^{-1} rate. Trends were similar in 2019, as the preventative insecticide program resulted in the greatest annual bluegrass cover for all but the 210 g ha^{-1} paclobutrazol program compared to no-insecticide and threshold programs. There were no differences between insecticide programs treated with 210 g ha^{-1} of paclobutrazol either year. Threshold and no-insecticide programs resulted in less annual bluegrass cover than the preventative program except when paclobutrazol was

applied at 210 g ha^{-1}. In 2019, threshold-based ABW insecticide programs provided similar annual bluegrass control as the preventative insecticide program combined with monthly applications of paclobutrazol at 70 and 105 g ha^{-1}. Threshold-based ABW insecticide management provided annual bluegrass control similar to a full season of monthly paclobutrazol applications.

INTRODUCTION

Annual bluegrass (*Poa annua* L.) is one of the most problematic weeds of cool-season turfgrass (Tutin 1952, Beard et al. 1978). Competitive in disturbed soils and highly adaptive to different climates, annual bluegrass can be found on all seven continents including Antarctica (Chwedeorzewska et al. 2015). Annual bluegrass can tolerate mowing heights as low as 2 mm, produces large amounts of seed and rapidly colonizes in open areas, making it a formidable weed in turfgrass systems (Tutin 1957, Beard et al. 1978, Lush 1988).

Adapted for survival in turfgrass systems, annual bluegrass populations are often transient, re-establishing from seed throughout the year (Lush 1988). They exhibit r-species behavior, allocating substantial resources to facilitate prolific reproduction efforts (Ong et al. 1978). Consequently, annual bluegrass is more sensitive to abiotic and biotic stress than other cool-season turfgrass species like creeping bentgrass (*Agrostis stolonifera* L.) (Beard 1964). Compared to creeping bentgrass, annual bluegrass is more prone to injury from temperature extremes, turfgrass diseases such as anthracnose (caused by *Colletotrichum cereale*) and summer patch (caused by *Magnaporthe poae)*, and pests like the annual bluegrass weevil (ABW) (*Listronotus maculicollis* Kirby) (Inguagiato et al. 2008, Espevig et al. 2014, Hoffman et al. 2014, Kostromytska and Koppenhöfer 2014, 2016).

Compared to species like creeping bentgrass, annual bluegrass requires more intensive management to survive, especially in the summer months. Supplemental irrigation, fungicides, and other pesticides are necessary to maintain high quality annual bluegrass turf (Inguagiato et al. 2008, 2009, 2012, Hempfling et al. 2017, Schmid et al.

2017). When annual bluegrass infestations are severe, many turf managers adopt these management practices to preserve the integrity of the stand.

In cool-season turfgrass, lack of reliable annual bluegrass control likely contributes to the widespread adoption of supplemental management. For post-emergent herbicides, creeping bentgrass safety is often a limiting factor (Fagerness et al. 2000, Meyer and Branham 2006, Senseman 2007, Dayan et al. 2009, McCullough et al. 2010, Bigelow 2012). As of this writing, amicarbazone and ethofumesate are the only readily available herbicides for creeping bentgrass fairways (Thompson 2017). Efficacy of amicarbazone and ethofumesate is temperature dependent, and both are subject to rate restrictions in creeping bentgrass that limit efficacy (Fagerness et al. 2000, Meyer and Branham 2006, Senseman 2007, Dayan et al. 2009, McCullough and Hart 2009, Bigelow 2012).

Sequential applications of the gibberellic acid (GA) biosynthesis inhibitor paclobutrazol is an effective annual bluegrass control option in creeping bentgrass greens and fairways (Shoop et al. 1986, Eggens et al. 1989, Woosley et al. 2003, Bigelow et al. 2007). Plant growth regulators (PGRs) have many applications in turfgrass management, each affecting specific physiological pathways to alter plant growth (Ervin and Zhang 2002). Paclobutrazol and flurprimidol inhibit earlier stages of GA biosynthesis by preventing *ent*-kaurene from forming *ent*-kaurenoic acid, the precursor to GA_{12}-aldehyde (Ervin and Zhang 2002). Annual bluegrass is particularly sensitive to paclobutrazol, and continuous applications of the PGR can offer annual bluegrass control on greens and fairways (Adams 1926, Shoop et al. 1986, Johnson and Murphy 1996, Bell et al. 2002, McCullough et al. 2005). Successful control of annual bluegrass with PGRs is contingent on time and frequency of application, but this gradual transition is suitable for areas with large infestations where rapid annual bluegrass control would leave large voids in the turf canopy. This gradual transition makes PGRs a popular option for high-value putting greens (Johnson and Murphy 1996, Bell et al. 2002, McCullough et al. 2005). However, there is still considerably less research available regarding paclobutrazol for annual bluegrass control on golf course fairways, which comprise approximately 10 times more acreage than putting greens (Lyman et al. 2007). Woosley et al. (2003) reported that 1 year of spring and summer applications of paclobutrazol (0.28 and 0.14 kg ha^{-1}) 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 on creeping bentgrass fairways.

While some biological controls for annual bluegrass control have been explored, sensitivity to environmental factors often prevent their use in the field setting (Imaizumi et al. 1999). Inconsistent field efficacy along with high production cost can limit the development and use of new biological control agents (Harding and Raizada 2015).

However, there is a native pest that warrants investigation; the annual bluegrass weevil (*Listronotus maculicollis*; ABW). The aptly named turfgrass pest showcases significant ovipositional preference for annual bluegrass over creeping bentgrass. The ABW is found throughout much of eastern North America from North Carolina to southern Quebec to Ohio and has been recognized as a pest of cool-season turfgrass since its discovery in 1931 (Britton 1931, Cameron and Johnson 1971, Vittum 1999). Emerging in spring, overwintering adults lay their eggs inside the grass stem between the leaf sheaths (Cameron and Johnson 1971). Those eggs hatch into larvae and go through five instar stages before pupating into new adults, completing their life cycle. While small larvae tunnel the stem, they eventually become too large and exit the plant. Fourth and fifth instars feed on the base of the plant, severing stems and potentially damaging the crown and inflicting substantial plant injury (Cameron and Johnson 1971). While there may be up to three generations of ABW each year, the first-generation larvae typically cause the most severe turfgrass damage (Vittum et al. 1999, Cowles et al. 2008). For this reason, turf managers apply insecticides to control adults before egg-laying or young and mid-size larvae (McGraw and Koppenhöfer 2017). A 2016 survey found golf courses sprayed on average 3.9 insecticide applications for ABW each year at a total cost of US $9,270 (McGraw and Koppenhöfer 2017). Golf courses that reported having pyrethroid-resistant ABW populations (twenty percent of the 293 surveyed) applied up to 10 insecticides a year to achieve similar control (McGraw and Koppenhöfer 2017).

The objective of this research was to determine if ABW larvae could control annual bluegrass alone or in combination with plant growth regulation strategies. We hypothesized that withholding insecticides for ABW control would reduce annual bluegrass cover in creeping bentgrass fairways and that paclobutrazol applied monthly would further increase control. Various rates of paclobutrazol were selected to observe the rate-response of this interaction.

MATERIALS AND METHODS

Research was conducted from 2018 and 2019 on two adjacent simulated creeping bentgrass fairways infested with annual bluegrass and with histories of ABW infestation at Rutgers Horticultural Farm No. 2 in North Brunswick, NJ (40°28'12.3"N 74°25'16.9"W). When the experiments were initiated in April 2018 and 2019, annual bluegrass cover was uniform and visually estimated to be 80 and 74%, respectively. The soil was a silt loam with a pH of 6.1. Plots were mown thrice weekly to 1.5 cm with a triplex reel mower. Irrigation was provided for optimum annual bluegrass growth and nitrogen fertilizer was spoon-fed (90 to 135 kg N ha^{-1} annually). Fungicides were applied in a rotation at 3-week intervals 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*) using the same active ingredients as described in Chapter 2. In July of each year, imidacloprid (0.45 kg ha^{-1}) was applied to all plots for white grub (Coleoptera: Scarabaeidae) control.

Two factors were evaluated: insecticide program and paclobutrazol rate, totaling 12 treatments. Treatments were applied to 1.0 by 2.0 m plots, replicated four times and arranged in a randomized complete block design (RCBD). Insecticide and paclobutrazol treatments were applied using a CO_2-powered backpack sprayer 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 into the thatch with 2.5 to 7.5 mm of overhead irrigation within 24 hours of application.

Insecticide programs

The three insecticide programs evaluated are designated as preventative, threshold, and no-insecticide (Table 3.1). The preventative program was based on a typical industry standard designed to prevent turfgrass damage from ABW. All applications in the preventative program were targeted to control specific larval instars. 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 and debris. The vacuum was dragged on the ground at full power, at walking speed of 3 mph for one minute. ABW adults were counted each pass. Several passes were performed each day around noon and daily fluctuations were used to estimate ABW activity. ABW larvae were sampled using a standard salt solution extraction method, and larval densities were used to inform insecticide application timings (Koppenhöfer et al. 2018). The preventative program began with cyantraniliprole, a systemic insecticide at 160 g ha^{-1} approximately 2 weeks after peak densities of overwintered adults were observed, to target first- and second-instar larvae. This was followed by indoxacarb at 252 g ha^{-1} approximately 2 weeks later to control larger as well as later-emerging larvae.

In the threshold program, 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). 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 to both preventative and threshold programs in July to protect turfgrass from ABW larvae of later generations. The threshold program was designed to simulate a strategy that would be practical for a turfgrass manager to use ABW as part of an integrated program for annual bluegrass control. Imidacloprid was applied to all treatments in July (for white grub control). No insecticides were ever applied for ABW control in the no-insecticide program.

Paclobutrazol programs

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

Data collection and analysis

To determine turfgrass species composition, annual bluegrass cover was evaluated visually on a 0 (no cover) to 100 (compete cover) percent scale monthly from May through November. At the end of each growing season in October or November, a 91 by 91 cm grid fitted with 100 evenly spaced intersects was placed in the center of each plot and the plant species (annual bluegrass or creeping bentgrass) at each intersect was determined to estimate percent cover. Turfgrass quality was assessed based on uniformity of cover, density, and color on a 1 to 9 scale (poor to excellent, where 6 was acceptable) monthly. Annual bluegrass quality and creeping bentgrass quality were also evaluated independently each month. At Hort Farm 2, monthly light box photos were taken of each plot at a fixed height and under uniform lighting using a Nikon camera with fixed settings (1/400 s shutter speed, F4.0 aperture and 3.2 mm focal length). Photos were subject to digital analysis using TurfAnalyzer software (Threshold settings; hue 50 to 140, saturation 10 to 100, brightness 0 to 100) to estimate the percent green cover per plot.

To evaluate the efficacy of the insecticide programs, larval densities were assessed on 4 June 2018 and 23 May 2019. Four cores (5.2 cm in diameter, 5.0 cm in depth) were taken from each plot with a turf plugger (Duich Ball Mark Plugger BMP1-M) and transported to the lab in sealed plastic bags. Within 8 hours of sampling, cores were quartered and immersed in a saturated table salt solution to extract larvae per methods described in Koppenhöfer et al. (2018). Larvae were preserved in 90% ethanol counted to determine average larval densities per m^2 using the same methods described in chapter 2.

Data were subjected to ANOVA using the GLIMMIX procedure in SAS (v9.4 SAS Institute) as a 3 by 4 factorial design with replication (block) as a random effect. Fisher's Protected LSD ($\alpha = 0.05$) was used to separate means.

RESULTS

Data are presented separately by year, as natural ABW larval densities varied and treatment by year interactions occurred on several dates.

In both 2018 and 2019, the preventative insecticide program provided excellent ABW control relative to the non-treated plots (Table 3.2). In 2018, larval densities were taken 5 days after the damage threshold was met and cyantraniliprole (290 g ha^{-1}) was applied. Thus, the threshold treatment may not have reached full efficacy by the sampling date. On 4 June 2018, there were significant differences between programs with lowest larval densities in the preventative program (97% control) followed by the threshold program (68% control), and the highest densities in the non-treated control (Table 3.2). In 2019, overall larval densities were higher, but the preventative program still provided

89% ABW control. There was no difference between threshold and no-insecticide treatments in 2019 as larvae were sampled before the damage threshold was met.

Annual bluegrass cover

The main effect of paclobutrazol was significant for annual bluegrass cover from May through November in 2018, and from July through October in 2019 (Table 3.3). The effect of insecticide program was significant on most dates in 2018 and 2019. The paclobutrazol-by-insecticide program interaction was significant on the last evaluation date each in 2018 and 2019. Therefore, annual bluegrass cover main effects are presented on all dates and interactive effects are presented on significant dates.

In 2018, all paclobutrazol rates reduced annual bluegrass cover similarly from May to August when averaged across insecticide programs (Figure 3.1). From September to November, cover was lowest in treatments receiving the middle (105 g ha^{-1}) and high (210 g ha^{-1}) rates of paclobutrazol. Cover in plots treated with the low rate (70 g ha^{-1}) of paclobutrazol was similar to the non-treated from July to September but was lower than the non-treated from October through November. In 2019, all rates of paclobutrazol reduced annual bluegrass cover similarly from July through October.

When averaged across paclobutrazol rates, the main effect of insecticide program influenced annual bluegrass cover on many rating dates in 2018 and in 2019. Annual bluegrass cover was consistently lowest in the no-insecticide program in both years (Figure 3.2). In 2018, insecticide program affected cover in every month from May through November except October. Cover in the threshold program was lower than the preventative program in June 2018, but the programs had similar cover from July through

October. In 2019, the main effect of insecticide program affected annual bluegrass cover from June through August and in October as the threshold and no-insecticide programs had less annual bluegrass cover than the preventative program. Unlike 2018, where the no-insecticide program resulted in less annual bluegrass cover than the threshold program, these programs resulted in similar annual bluegrass cover except in October during 2019.

In both years, interactive effects were detected in the autumn. At the conclusion of the 2018 experiment in November, annual bluegrass cover was lowest in the threshold and no-insecticide treatments for the middle rate (105 g ha^{-1}) of paclobutrazol and in the non-paclobutrazol treated, but the 70 and 210 g ha^{-1} rates of paclobutrazol were not affected by insecticide program (Figure 3.3). An interaction between main effects also occurred in October 2019 when the preventative insecticide program resulted in greatest annual bluegrass cover in all but the highest paclobutrazol (210 g ha^{-1}) rate. Annual bluegrass cover was highest (56%) in the preventative program not treated with paclobutrazol, and all rates of paclobutrazol (regardless of insecticide program) reduced cover relative to that treatment. Cover was lowest in all treatments receiving the high rate of paclobutrazol, and in the threshold and no-insecticide programs receiving low and middle rates of paclobutrazol (8 to 20%). Of the programs treated preventatively for ABW, cover was lower for plots receiving low and middle rates of paclobutrazol compared to the non-paclobutrazol treated. However, the non-paclobutrazol treated threshold and no-insecticide programs had similar cover to preventative programs receiving low and middle rates of paclobutrazol in October 2019. Cover in the no-insecticide program not treated with paclobutrazol was even lower, and similar to the threshold and no-insecticide programs receiving low and middle rates, and the threshold program receiving the high rate of paclobutrazol.

Turfgrass quality

Turfgrass quality was reduced to unacceptable levels only in plots treated with 210 g ha^{-1} paclobutrazol during June and July 2018. By August 2018, turfgrass quality was deemed acceptable for all treatments. There was no lasting effect of paclobutrazol on turfgrass quality in either year (data not presented).

The main effect of insecticide program affected turfgrass quality from June to August in 2018 and in June 2019. In June 2018 and 2019, 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 preventative (7.1 and 7.3, in 2018 and 2019 respectively) (Figure 3.4). In 2019, quality of the threshold and preventative programs were similar in July (7.0 and 7.1 respectively) and the no-insecticide program was of acceptable quality (6.3). In 2018, the no-insecticide program did not meet acceptable quality standards until September. There was no lasting effect of insecticide program on turfgrass quality either year. Creeping bentgrass quality was never influenced by insecticide program at any time (data not presented).

In 2018, turfgrass quality trends were similar to those observed in the percent green cover obtained from lightbox photos. On 1 June 2018, green cover was lower in threshold and no-insecticide programs (80%, relative to 99% in the preventative). Four days later, green cover in the no-insecticide plots was reduced to 65% but remained unchanged in the threshold and preventative treatments. Green cover remained lower (61-

66%) in the no-insecticide treatments the rest of June, while it increased in the threshold treatments (80-92%). The preventative 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.

DISCUSSION

All rates of paclobutrazol reduced annual bluegrass cover, but the effect of insecticide program varied by paclobutrazol rate. Similar to the experiments presented in Chapter 2 in which paclobutrazol was applied at 280 g ha^{-1}, differences between insecticide programs were never observed in plots receiving high (210 g ha^{-1}) rates of paclobutrazol. At the 105 g ha^{-1} paclobutrazol rate, annual bluegrass cover declined in a gradient across insecticide programs. Rates of 70 and 105 g ha^{-1} generally enhanced efficacy of the threshold and no-insecticide programs. By October 2019, annual bluegrass cover of plots not treated with paclobutrazol and receiving threshold-based or no ABW control was equivalent to plots receiving paclobutrazol (70 and 105 g ha^{-1}) and treated preventatively for ABW.

These findings are the first to illustrate the season-long effect spring ABW management can have on annual bluegrass cover. Both years, withholding ABW insecticidal control resulted in rapid annual bluegrass decline in June. When averaged across all rates of paclobutrazol, cover remained lower in no-insecticide plots the rest of the season. Not surprisingly, rapid annual bluegrass decline was accompanied by two months of unacceptable turfgrass quality when no insecticides were applied for ABW control. However, when a threshold-based cyantraniliprole application was made, turfgrass quality was only unacceptable for 21 days. Turfgrass recovery time was similar for threshold and no-insecticide programs both years, despite differences in ABW damage severity and annual bluegrass decline. Interestingly, turfgrass quality of the preventively treated plots was unacceptable in July 2018, but threshold-treatments were of acceptable quality. Despite attempts to prevent annual bluegrass decline, thinning of annual bluegrass in July 2018 was observed and disproportionately reduced quality of treatments with more annual bluegrass.

Annual bluegrass recovery following ABW damage was attributed to annual bluegrass emerging from surviving crowns. Annual bluegrass resilience following seemingly severe ABW injury likely explains the fleeting effect the ABW had on turfgrass quality. This resiliency may also prevent moderate ABW damage from translating into season-long annual bluegrass control.

Beginning in May 2019, annual bluegrass cover declined across all treatments, and larval densities in all insecticide programs were considerably higher than in 2018 (Table 3.2). Higher ABW pressure likely resulted greater loss of annual bluegrass cover in the threshold and no-insecticide programs in June 2019 compared to 2018.

Paclobutrazol

The results regarding the main effect of paclobutrazol concur with previous paclobutrazol research: monthly applications of paclobutrazol provided annual bluegrass control in creeping bentgrass fairways. Similar to observation by McCullough et al. (2005), annual bluegrass coverage was highest across all treatments in the spring and declined though summer into fall. In 2018, we found that monthly applications of 105 and 210 g ha^{-1}

paclobutrazol provided 74-84% annual bluegrass control (relative to the non-treated). This level of control was similar to previous results from Woosley et al. (2003), where one year of monthly paclobutrazol applications (140 g ha^{-1} and 280 g ha^{-1}) resulted in 85% annual bluegrass control on fairways. As previously reported by both Woosley et al. (2003) and McCullough et al. (2005), there were little differences between rates on long-term annual bluegrass control.

Conclusions

Overall, threshold-based ABW control can provide season-long annual bluegrass control without compromising turfgrass quality. Monthly applications of paclobutrazol at low to moderate rates (70 g ha^{-1} and 105 g ha^{-1}) can increase efficacy, but high rates (210 g ha^{-1}) resulted in uniform annual bluegrass control regardless of insecticide program. Annual bluegrass was quick to reestablish from undamaged growing points, and only severe ABW damage translated into lasting annual bluegrass reduction. Consequently, this approach may not be feasible for turfgrass managers responsible for large areas of annual bluegrass, as turfgrass quality standards would not permit necessary ABW damage to occur. However, paclobutrazol alone could be used to reduce annual bluegrass cover to the point where ABW damage can be tolerated without compromising quality.

The use of threshold-based ABW insecticidal control adheres to the principles of integrated pest management for both the ABW and annual bluegrass. Compared to preventative programs, this approach reduces the amount of pesticides applied for both ABW and annual bluegrass management, saving practitioners time and money if limited and temporary reductions in turf quality can be accepted.

Future research should evaluate the effect of initial creeping bentgrass cover on annual bluegrass control with threshold-based ABW control. We hypothesize that more creeping bentgrass cover may allow for more annual bluegrass damage to occur before meeting a damage threshold. Researchers should also further investigate the ecological impacts of ABW selectivity in mixed stands of turfgrass to better understand how annual bluegrass reduction effects plant biodiversity and ABW behavior.

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Table 3.1 Annual bluegrass weevil insecticide programs and application dates for a simulated creeping bentgrass fairway at Hort Farm 2 (North Brunswick, NJ) in 2018 and 2019.

Insecticide Program	AI	Rate	Target larval stage	Application dates	
				2018	2019
		g ha^{-1}	1 to 5 instar		
Preventative†					
	cyantraniliprole	163	1 to 3	14 May	7 May
	indoxacarb	252	3 to 5	30 May	15 May
	spinosad	454	3 to 5	23 July	18 July
	cyantraniliprole	290	3 to 5	30 July	-
Threshold‡					
	cyantraniliprole	290	3 to 5	30 May	24 May, 4 June§
	spinosad	454	3 to 5	23 July	18 July
	cyantraniliprole	290	3 to 5	30 July	-
No insecticide					
	-	-		-	-

† Spring generation larval stages were monitored weekly from May through June and used to schedule the initial insecticide application.
‡ 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).
§ Due to natural variations in ABW pressure, blocks 1 and 2 reached the damage threshold on 24 May 2019, blocks 3 and 4 met the damage threshold 10 days later.

Table 3.2 Spring generation annual bluegrass weevil (ABW) larval densities averaged across insecticide programs as sampled from a simulated creeping bentgrass fairway at Hort Farm 2 (North Brunswick, NJ) in 2018 and 2019.

	ABW larval densities (m^{-2})	
Insecticide Program	**4 June 2018**	**23 May 2019**
Preventative	30 b†	224 b
Threshold‡	430 b	2398 a
No-insecticide	1338 a	2053 a

† Means followed by the same letter do not differ according to Fisher's Protected LSD (α = 0.05).

‡ In 2018, larvae were sampled 5 days after cyantraniliprole (290 g ha^{-1}) was applied to threshold treatments. In 2019, larvae were sampled before the damage threshold was met and no insecticides were applied to threshold program.

Table 3.3 Analysis of variance of the annual bluegrass cover response to paclobutrazol rate (0, 70, 105, and 210 g ha^{-1}, applied monthly) and insecticide program (preventative, threshold, and no insecticide) on visual percent annual bluegrass cover in 2018 and 2019. Sites were located adjacently on a simulated creeping bentgrass fairway in North Brunswick, NJ and cover was visually estimated.

		2018							2019					
Source of variance	**df**	**14 May**	**22 Jun.**	**22 Jul.**	**24 Aug.**	**21 Sep.**	**30 Oct.**	**30 Nov.**	**1 May**	**3 Jun.**	**9 Jul.**	**16 Aug.**	**10 Sep.**	**22 Oct.**
		----------Probability of significant F test----------												
Paclobutrazol rate	3	**	**	*	***	**	***	***	NS	NS	*	**	***	***
Insecticide program	2	**	***	*	*	*	NS	**	NS	**	***	**	NS	***
Insecticide program × paclobutrazol rate	6	NS†	NS	NS	NS	NS	NS	**	NS	NS	NS	NS	NS	*

†NS, non-significant; *, **, ***, significant when $\alpha \leq 0.05$, 0.01 and 0.001, respectively

Table 3.4 Analysis of variance of the turfgrass quality response to paclobutrazol rate (0, 70, 105, and 210 g ha^{-1}, applied monthly) and insecticide program (preventative, threshold, and no insecticide) on turfgrass quality in 2018 and 2019. Sites located on adjacently on a simulated creeping bentgrass fairway in North Brunswick, NJ and turf quality was evaluated visually on a 1 to 9 scale, where 1 = poor and 9 = excellent.

		2018									
Source of variance	**df**	**14 May**	**23 May**	**31 May**	**22 Jun.**	**22 Jul.**	**24 Aug.**	**27 Aug.**	**21 Sep.**	**30 Oct.**	**30 Nov.**
		Probability of significant F test									
Paclobutrazol rate	3	*	***	***	***	*	NS	NS	NS	NS	NS
Insecticide program	2	NS†	***	***	***	***	***	**	NS	NS	NS
Insecticide program × paclobutrazol rate	6	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
		2019									
Source of variance	**df**	**1 May**	**15 May**	**20 May**	**29 May**	**3 Jun.**	**9 Jul.**	**16 Aug.**	**10 Sep.**	**22 Oct.**	**21 Nov.**
		Probability of significant F test									
Paclobutrazol rate	3	**	**	**	NS	NS	NS	NS	NS	NS	NS
Insecticide program	2	NS	*	*	**	**	NS	NS	NS	NS	NS
Insecticide program × paclobutrazol rate	6	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

† NS, non-significant; *, **, ***, significant when $\alpha \leq 0.05$, 0.01 and 0.001, respectively

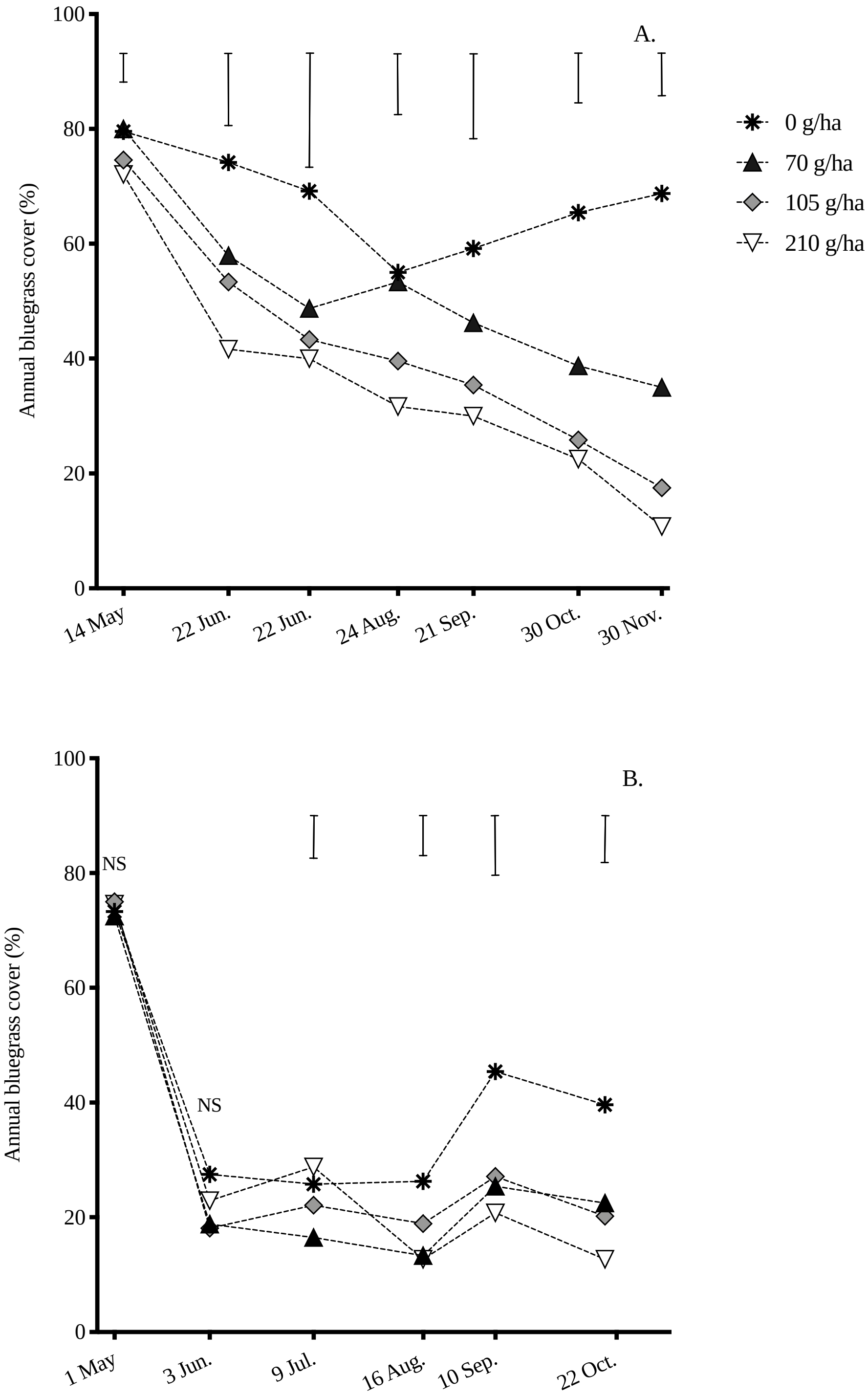

Figure 3.1 Main effect of paclobutrazol rate (0, 70, 105, or 210 g ha^{-1}, applied monthly) on visual annual bluegrass cover in 2018 (A) and 2019 (B). Experiments were located adjacently in a simulated creeping bentgrass fairway at Hort Farm 2 (North Brunswick, NJ). Means averaged across insecticide programs. Bars represent Fishers' Protected LSD (α = 0.05), NS = not significant.

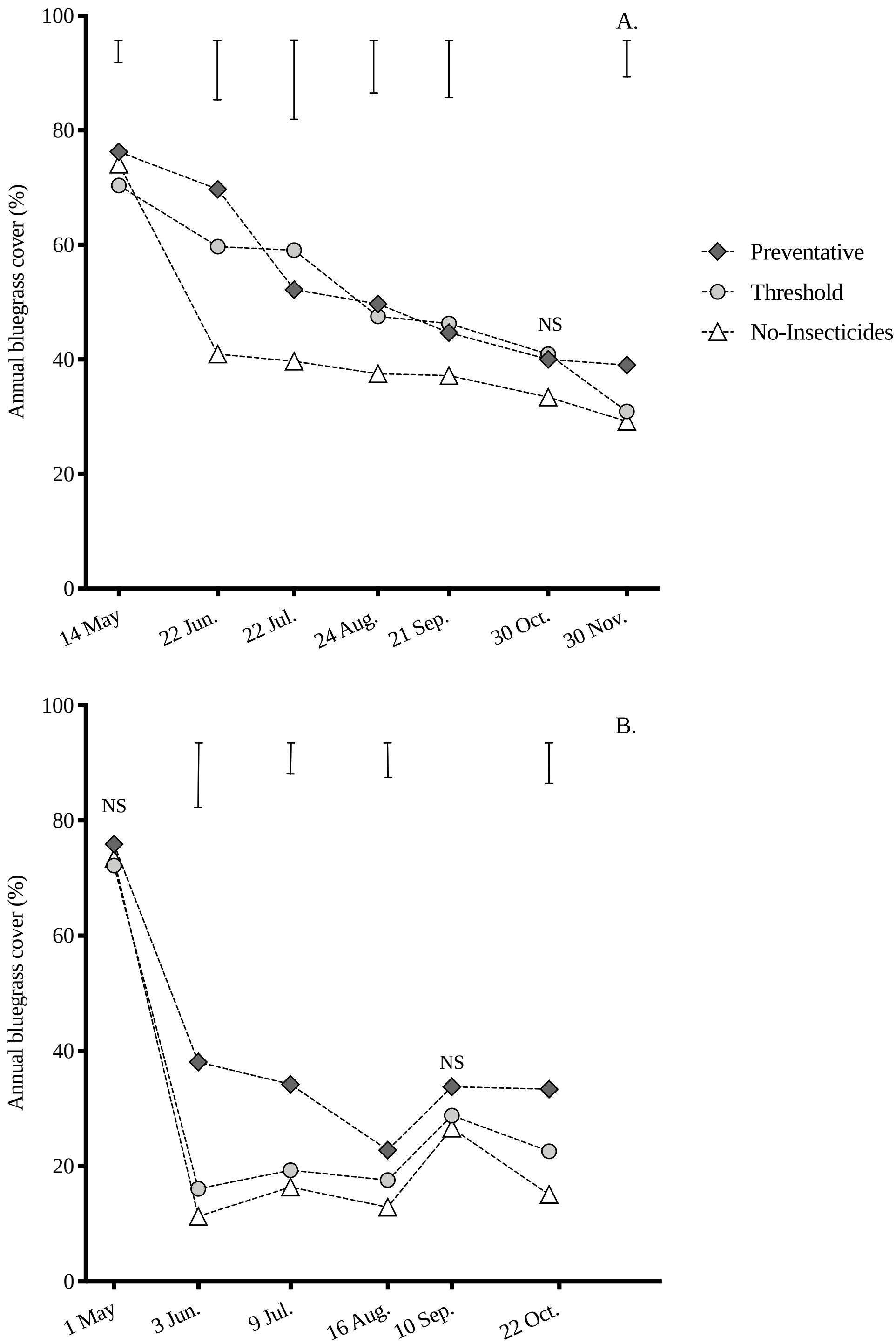

Figure 3.2 Main effect of insecticide program (preventative, threshold, and no insecticide) on visual annual bluegrass cover in 2018 (A) and 2019 (B). Experiments were located adjacently in a simulated creeping bentgrass fairway at Hort Farm 2 (North Brunswick, NJ). Means averaged across paclobutrazol rate. Bars represent Fishers' Protected LSD ($\alpha = 0.05$), NS = not significant.

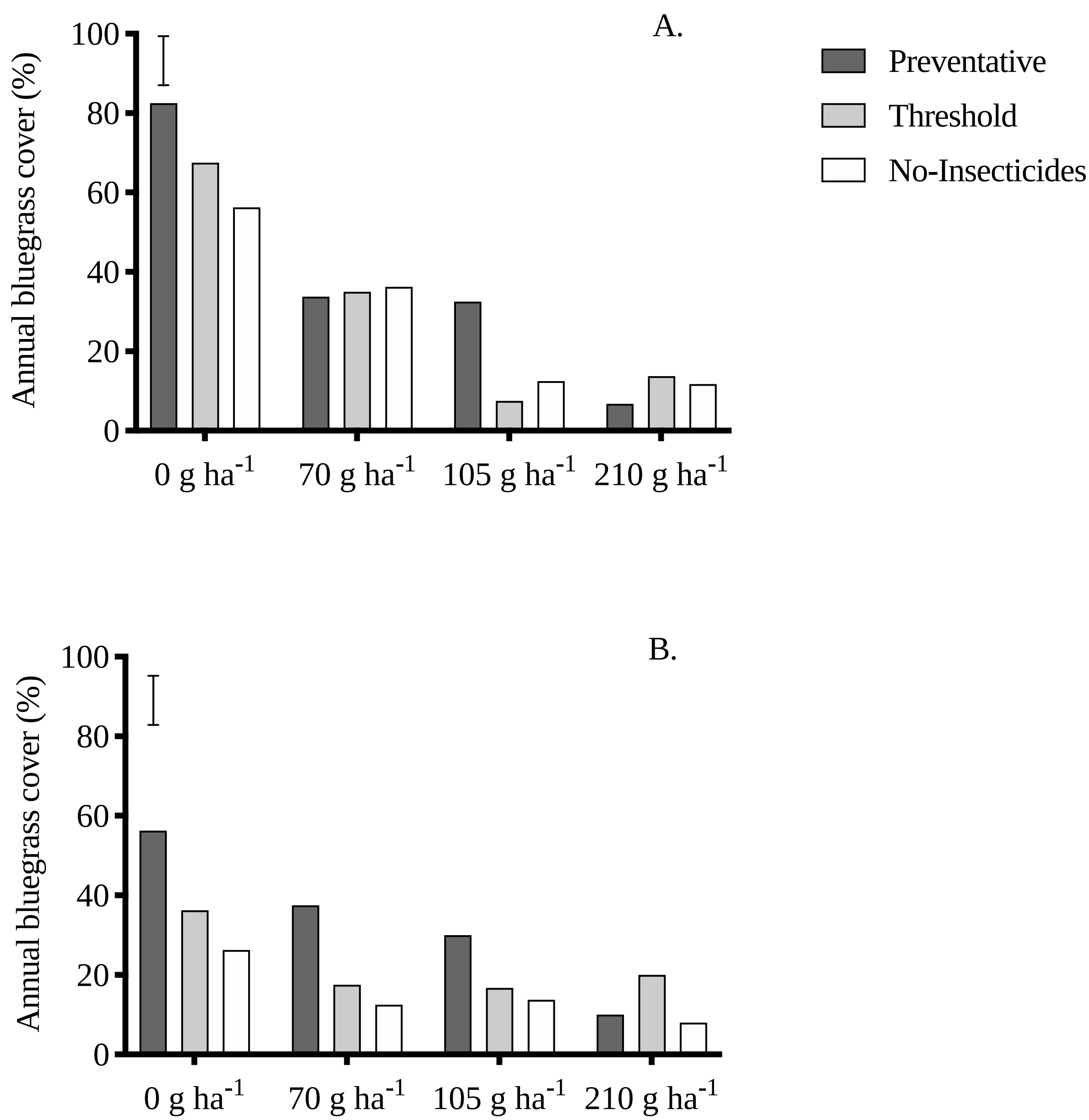

Figure 3.3 Annual bluegrass cover as observed on 30 November 2018 and 18 October 2019 as affected by paclobutrazol rate (0, 70, 105, and 210 g ha-1) and insecticide program (preventative, threshold, and no insecticide). Sites located adjacently in a simulated creeping bentgrass fairway at Hort Farm 2 (North Brunswick, NJ). Bars represent Fishers' Protected LSD (α = 0.05), NS = not significant.

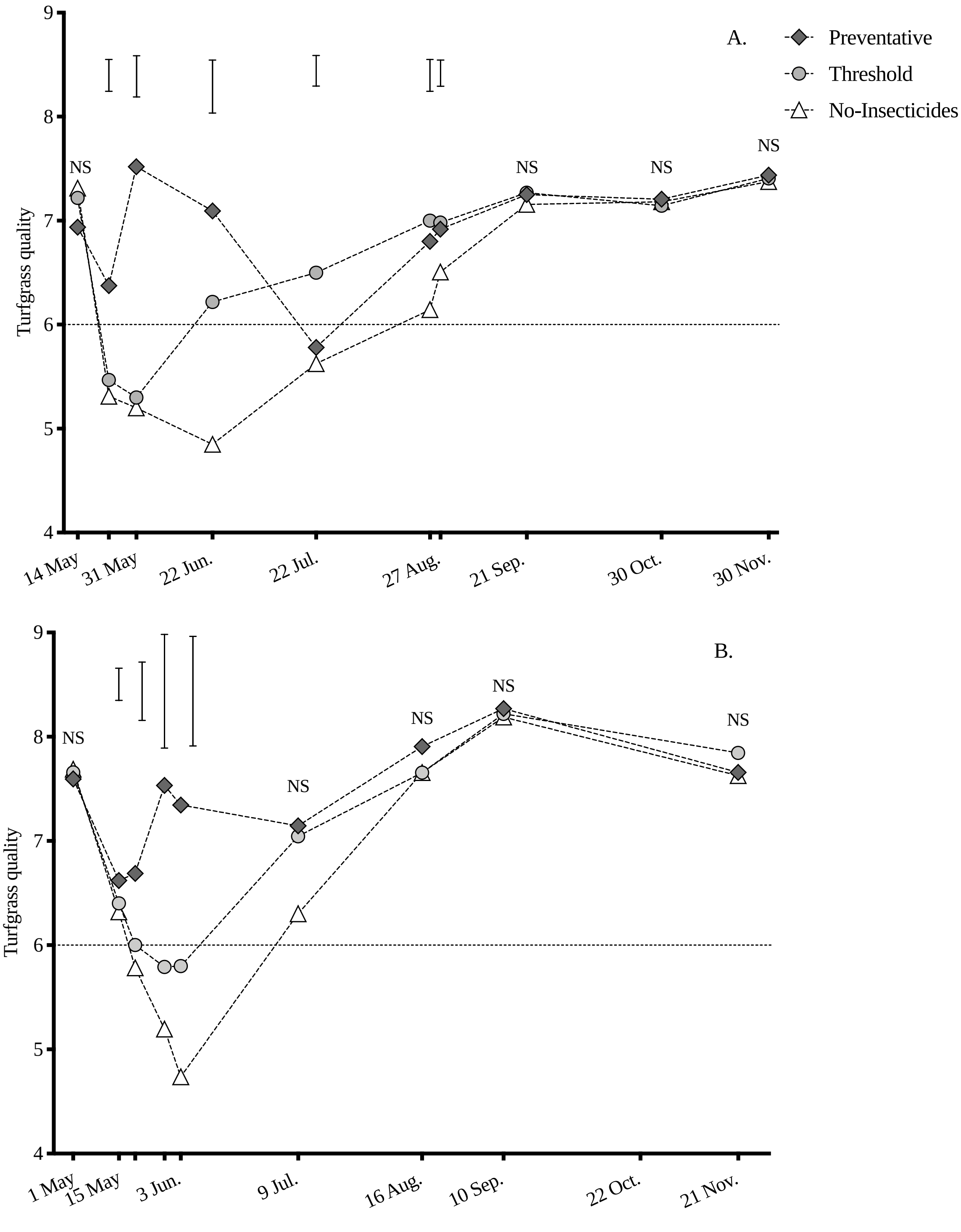

Figure 3.4 Main effect of insecticide program on turfgrass quality from 2018 (A) to 2019 (B). Sites were located adjacently in a simulated creeping bentgrass fairway at Hort Farm 2 (North Brunswick, NJ). Quality was ranked on a 1 to 9 scale, poor to excellent; 6 = acceptable. Means averaged across insecticide programs. Bars represent Fishers' Protected LSD ($\alpha = 0.05$), NS = not significant.

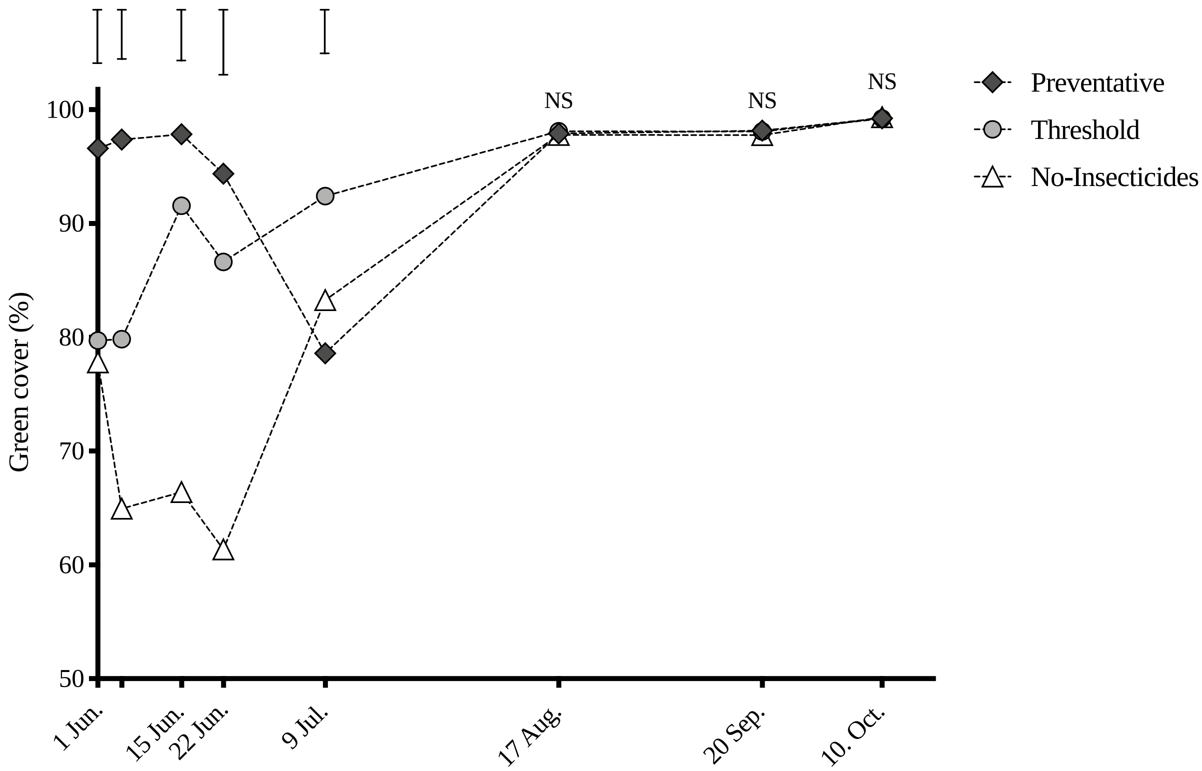

Figure 3. 5 Main effect of insecticide program on percent green cover estimated from lightbox photos subjected to digital analysis (Turf Analyzer Software) in 2018. Site was a simulated creeping bentgrass fairway at Hort Farm 2 (North Brunswick, NJ). Means averaged across insecticide programs. Bars represent Fishers' Protected LSD (α = 0.05), NS = not significant.