Journal of Integrated Pest Management (*2016*) 7(1): 6; 1–10
doi: 10.1093/jipm/pmw004
Profiles

OXFORD

Biology and Management of Billbugs (Coleoptera: Curculionidae) in Turfgrass

Madeleine M. Dupuy[1] and Ricardo A. Ramirez

Department of Biology, Utah State University, 5305 Old Main Hill, Logan, UT 84322 (madeleine.dupuy@usu.edu; ricardo.ramirez@usu.edu), and [1]Corresponding author, e-mail: madeleine.dupuy@usu.edu

Received 9 October 2015; Accepted 29 January 2016

Abstract

Billbugs (Coleoptera: Curculionidae: *Sphenophorus* spp.) are a complex of weevil pests affecting turfgrass throughout the United States. Billbug larvae cause damage by feeding in stems, on roots, and on the crowns of turf, causing severe discoloration and eventual plant death. Monitoring efforts have focused on nondestructive pitfall sampling of ground-active billbug adults and on destructive sampling using soil cores for larval stages in the soil. Given the cryptic nature of the susceptible larval stages, billbugs are typically managed by preventive applications of long-residual, systemic insecticides, including neonicotinoids and anthranilic diamides. Despite knowledge of effective management practices including pest-resistant turf varieties, irrigation management, and microbial controls that contribute to an IPM approach, billbug management continues to rely heavily on prophylactic synthetic insecticides. This review will summarize the identification and biology of billbugs and strategies for their management.

Key words: *Sphenophorus parvulus*, *Sphenophorus venatus vestitus*, *Sphenophorus cicatristriatus*, pitfall trap, Kentucky bluegrass

Turfgrass covers >164,000 km^2 (63,321 mi^2) of the United States landscape, over three times the land area of any other irrigated crop (Milesi et al. 2005), and includes golf courses, home lawns, sports fields, and sod farms (Gelernter 2012). In 2005, the revenue generated by the turfgrass industry exceeded US$62 billion (Haydu et al. 2008), surpassing the combined value of corn (US$21 billion) and soybeans (US$17 billion) in the same year (NASS 2006). This revenue depends largely on maintenance of turfgrass quality, aspects of which include density, texture, growth habit, smoothness, and color (Beard 1972). Management practices that enhance turfgrass quality, like regular irrigation, fertilization, and mowing, however, encourage many species of turf-feeding arthropods (Held and Potter 2012).

Turf is grown primarily for its utility and appearance, and discoloration of turfgrass can quickly become unacceptable in settings such as golf courses and sod farms, whose revenues depend largely on turf health and quality. Feeding by billbug (Coleoptera: Curculionidae: *Sphenophorus* spp.) larvae in stems and on roots causes spotty patches of yellow and brown turf, which can expand to large areas of dead grass. Thus, billbugs can be a serious pest of turfgrass, but effective management has been historically difficult due to several aspects of billbug biology, which will be discussed in this review.

Billbugs are a complex of weevils native to and widespread throughout the United States (Johnson-Cicalese et al. 1990, Shetlar et al. 2012). The genus *Sphenophorus* contains 71 species, 64 of which occur in North America (Niemczyk and Shetlar 2000). At least 10 species are pests of turfgrass in the United States, including the bluegrass billbug (*Sphenophorus parvulus* Gyllenhal) and hunting billbug (*S. venatus vestitus* Chittenden), which are considered most harmful to cool-season grasses and warm-season grasses, respectively (Potter and Braman 1991, Vittum et al. 1999). Though billbugs have been known to infest other agricultural crops such as corn (*Zea mays* L.), wheat (*Triticum aestivum* L.), and range grasses (Satterthwait 1931a, Asay et al. 1983, Kuhn et al. 2013), they were first recognized as a serious pest of turfgrass when bluegrass billbug began to outbreak in several states in the 1960s (Tashiro and Personius 1970). These outbreaks were thought to be caused by resistance of the bluegrass billbug to pesticides that were heavily used at the time and the resulting reduction in natural enemy populations (Tashiro and Personius 1970). Billbugs continue to be problematic for turfgrass managers throughout the country.

Biology

Distribution

Billbugs are found throughout the continental United States and in Hawaii. Their range extends north to southern Canada and south through Mexico (Reynolds 2013), and they are also pests of turfgrass in Japan (Aoyagi et al. 1990, Georgis et al. 2006). Hunting billbug has also been reported in Puerto Rico, the Bahamas, the

Dominican Republic, and Martinique (Kuhn et al. 2013). Previously, it was thought that bluegrass billbug and hunting billbug were the only species causing damage to turf in the United States; however, Johnson-Cicalese et al. (1990) classified eight species commonly reported in the United States, including a complex of four species damaging turf in New Jersey—bluegrass billbug, hunting billbug, lesser billbug (*S. minimus* Hart), and unequal billbug (*S. inaequalis* Say). Furthermore, it was determined that different species of billbug dominate different parts of the country: hunting billbug in the southeastern United States, bluegrass billbug in the northern half of the country, Phoenix billbug (*S. phoeniciensis* Chittenden) in the southwestern United States, and Rocky Mountain billbug (*S. cicatristriatus* Fabraeus) in the Rocky Mountain region. Three species are prevalent in the wider Intermountain West (in descending order of abundance): bluegrass billbug, hunting billbug, and Rocky Mountain billbug (Fig. 1). This complex is common in the western United States, with the addition of *S. sayi* (Gyllenhal) in northeast Oregon (Walenta et al. 2004) and Phoenix billbug in California (Flint et al. 2009), Idaho (Fritz and Salaiz 2007), and the southwest (Sutherland 2006). Other species found in United States turf include *S. apicalis* (LeConte), *S. coesifrons* (Gyllenhal), the southern corn billbug (*S. callosus* Oliver), and *S. rectus* (Say) (Table 1). Overall, there are at least 10 species of billbug causing damage to turf in the United States (Held and Potter 2012), though detailed biological observations continue to be limited to bluegrass billbug and hunting billbug.

Host Plants

Bluegrass billbug infests mostly cool-season grasses, especially Kentucky bluegrass (*Poa pratensis* L.), but may also inhabit some warm-season grasses and grassy weeds (Vittum et al. 1999; Table 1). Hunting billbug primarily infests warm-season grasses, especially zoysiagrass (*Zoysia* spp.), and is sometimes called the zoysiagrass billbug. Additional hosts include certain cool-season grasses and a variety of grassy weeds (Table 1). For example, yellow nutsedge (*Cyperus esculentus* L.) was previously determined to be the preferred host of hunting billbug (Satterthwait 1931a). Rocky Mountain billbug is most common in Kentucky bluegrass and perennial ryegrass (Niemczyk and Shetlar 2000). Recently, billbugs—including the bluegrass, hunting, and southern corn billbugs—have been recognized as a serious pest of orchardgrass in Virginia (Kuhn et al. 2013). They can also be pests on other range grasses, corn, and wheat (Satterthwait 1931a, Asay et al. 1983). There is little evidence, however, that billbugs are problematic to adjacent ornamental plants within a turf landscape. Relatively little is known about billbug host ranges for other species of billbug beyond the plants in which they have been observed (Table 1).

Life History

Billbug adults are ground active, and their primary method of locomotion is crawling. Adults have been observed either unsuccessfully attempting flight (Tashiro and Personius 1970, Kindler and Spomer 1986) or flying at very low heights for very short distances when wind conditions increase chances of becoming airborne (Young 2002, Shetlar et al. 2012). Billbug adults are usually found in thicker grasses with a heavy thatch layer that is thought to offer shade and protection (Kindler and Spomer 1986). They prefer grasses with thick, plush stems for oviposition, or simply grasses that are actively growing (Kindler and Spomer 1986, Vittum et al. 1999, Rondon and Walenta 2008). Billbugs overwinter as adults in protected areas, such as thatch, the junction between turf and sidewalk (Niemczyk 1983, Richmond 2015), nearby leaf litter or unmanaged turf areas (Young 2002, Richmond 2015), or buried in the soil head-first at depths of 1 cm or less (Kindler and Spomer 1986). Some species in certain regions may also overwinter as larvae (Doskocil and Brandenburg 2012, Shetlar et al. 2012, Richmond and Duffy 2015). In the southeastern United States, adults of the hunting billbug are nocturnal (Huang and Buss 2009, Reynolds 2013).

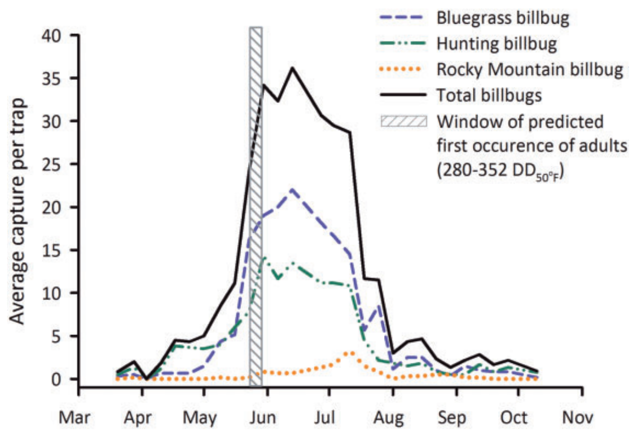

Fig. 1. Adult billbug captures from linear pitfall traps at an infested golf course in the Intermountain West in 2014. The course has six installed linear pitfall traps. Bluegrass billbug is the dominant species, followed by hunting billbug and Rocky Mountain billbug. Degree-days were calculated using a nearby weather station and the available bluegrass billbug model from the east (Watschke et al. 2013). First adult occurrence is apparently earlier in the Intermountain West than is predicted for the eastern United States (280–352 DD50, which fell between May 23 and May 28, as indicated by the gray hatched bar).

Larvae are legless; therefore, feeding by individuals is restricted to a small area (Kindler and Spomer 1986). It is widely accepted that the larval stage is the damaging one, while adults feed minimally on grass blades and cause only superficial damage. In North Carolina, however, adult hunting billbugs appear to be the damaging life stage on warm-season turf while larvae are rarely found in damaged areas (Doskocil and Brandenburg 2012).

Description of Damage

Larval feeding on stems, roots, and crowns causes severe discoloration and can eventually lead to plant death. Feeding damage first appears as yellowing of small patches of turf, which is often mistaken for disease, but quickly expands to larger areas of brown and dying turf under heavy infestation. This more extensive damage is frequently mistaken for drought stress and can be exacerbated under drought conditions (Niemczyk 1983). Heavy larval feeding compromises the root system, and stems of severely damaged turf break and pull away easily from the soil. Often, a sawdust-like frass is present in hollowed-out stems to diagnose billbug feeding (Watschke et al. 2013). Damage by overwintered hunting billbug larvae in spring can appear as delayed green-up in regions where larvae of this species are capable of overwintering (Richmond 2015).

Potential for Economic Damage

Management decisions in the turf industry are largely driven by aesthetics and consumer culture, and traditional metrics of economics used for field crops do not readily translate to the turfgrass system (e.g., yield loss; Held and Potter 2012). The level of acceptable damage varies by the intended use of the turf. On golf courses and sports

Table 1. A summary of billbug species found on turf in the United States, their common host plants, and their geographic distribution, based on reports in the literature

Billbug species	Host plants	Distribution in the contiguous United States	Sources
Bluegrass billbug (*Sphenophorus parvulus*)	**Cool-season turf** (Kentucky bluegrass, ryegrass, fescues, bentgrass) **Warm-season turf** (Zoysiagrass) **Nonturf** (Orchardgrass, corn, timothy, wheat, quackgrass, barley, rye)	**Northeast** (MA, NJ, NY, OH, PA, VA, WI) **Southeast/Gulf** (FL, NC, SC, TX) **Midwest** (KS, NE, SD) **Intermountain West** (ID, UT) **Northwest** (OR, WA) **Anywhere that Kentucky bluegrass is grown,** most likely throughout the contiguous United States	Satterthwait 1931a Tashiro and Personius 1970 Asay et al. 1983 Johnson-Cicalese and Funk 1990 Vittum et al. 1999 Walenta et al. 2004 Huang and Buss 2009 Fry and Cloyd 2011 Kuhn et al. 2013
Hunting billbug (*S. venatus vestitus*)	**Cool-season turf** (Kentucky bluegrass, fescues, perennial ryegrass) **Warm-season turf** (Zoysiagrass, Bermudagrass, St. Augustinegrass, Centipedegrass, Bahiagrass) **Nonturf** (Corn, wheat, sugarcane, yellow nutsedge, orchardgrass, leatherleaf fern, seashore pasalpum)	**Northeast** (NJ, VA) **Southeast/Gulf** (AL, FL, GA, NC, SC, TX) **Midwest** (KS, MO) **Intermountain West** (ID, UT) **Southwest** (CA)	Satterthwait 1931a Johnson-Cicalese and Funk 1990 Vittum et al. 1999 Huang and Buss 2009 Doskocil and Brandenburg 2012 Kuhn et al. 2013 Chong 2015
Rocky Mountain billbug (*S. cicatristriatus*)	**Cool-season turf** (Kentucky bluegrass, perennial ryegrass)	**Midwest** (ND, NE, SD) **Intermountain West** (CO, ID, UT, WY) **Southwest** (NM) **Northwest** (OR)	Vittum et al. 1999 Walenta et al. 2004 Niemczyk and Shetlar 2000
Phoenix billbug (*S. phoeniciensis*)	**Warm-season turf** (Bermudagrass, zoysiagrass, kikuyugrass) **Nonturf** (Johnson grass, oats)	**Intermountain West** (ID) **Southwest** (AZ, CA, NM)	Satterthwait 1931a Vittum et al. 1999 Fritz and Salaiz 2007 Sutherland 2006 Flint et al. 2009
Uneven billbug (*S. inaequalis*)	**Cool-season turf** (Kentucky bluegrass, tall fescue, perennial ryegrass) **Warm-season turf** (Bermudagrass, zoysiagrass)	**Northwest** (NJ) **Southeast** (FL, NC, SC)	Johnson-Cicalese and Funk 1990 Johnson-Cicalese et al. 1990 Vittum et al. 1999 Huang and Buss 2009 Doskocil and Brandenburg 2012 Chong 2015
Lesser billbug (*S. minimus*)	**Cool-season turf** (Kentucky bluegrass, fescues, ryegrass) **Nonturf** (Rice, timothy, wheat, rye)	**Northeast** (NJ, NY, OH, PN) **Southeast** (FL, NC, SC)	Satterthwait 1931a Johnson-Cicalese and Funk 1990 Vittum et al. 1999 Huang and Buss 2009 Chong 2015 Doskocil and Brandenburg 2012

(continued)

Table 1. continued

Billbug species	Host plants	Distribution in the contiguous United States	Sources
Southern corn billbug (*S. callosus*)	**Warm-season turf** (Bermudagrass)	**Southeast** (NC, VA)	Doskocil and Brandenburg 2012
	Nonturf (Corn, yellow nutsedge, orchardgrass)		Kuhn et al. 2013
S. apicalis	**Warm-season turf** (Bermudagrass, zoysiagrass)	**Northeast** (NJ)	Vaurie 1951
		Southeast/Gulf (FL)	Vittum et al. 1999 Huang and Buss 2009
S. coesifrons	**Warm-season turf** (Bahiagrass) **Nonturf** (Nutsedge)	**Southeast** (FL, GA, SC)	Vaurie 1951 Morrill and Suber 1976 Huang and Buss 2009 Chong 2015
S. rectus	**Cool-season turf** (Kentucky bluegrass)	**Southeast** (NC)	Doskocil and Brandenburg 2012
S. cariosus	**Warm-season turf** (Bahiagrass)**Nonturf** (Nutsedge)	**Southeast** (SC)	Chong 2015

fields, for example, the threshold of allowable damage for any insect is very low. Billbugs can not only damage but also can kill extensive areas of turfgrass in a matter of weeks under heavy infestations (Shetlar et al. 2012). Thus, insecticides with long residual activity are often applied preventively against billbugs on an annual basis regardless of whether or not they will become damaging.

Insecticides for all turf insects account for 31 and 19% of annual chemical expenditures for lawn care companies and golf courses, respectively (Held and Potter 2012). In 2006, lawn and garden products accounted for 16% of all conventional insecticides used in the United States (Grube et al. 2011). The cost of insecticides for pest control can account for millions of dollars of the multibillion-dollar turf industry (Haydu et al. 2008). In 2006 for the Georgia turf industry alone, not including golf courses, billbugs contributed to US$2,835,000 worth of damage caused by miscellaneous turf pests (including non-fire ants, billbugs, leafhoppers, bermudagrass mites, and stunt mites; Oetting et al. 2006). The cost of insecticides for preventive billbug management in the Intermountain West can range from US$12 per acre to US$114 per acre for treatments of imidacloprid and clothianidin, respectively (P. Stokes, personal communication). Unfortunately, there are no published figures on economic losses in turfgrass caused specifically by billbugs nationwide.

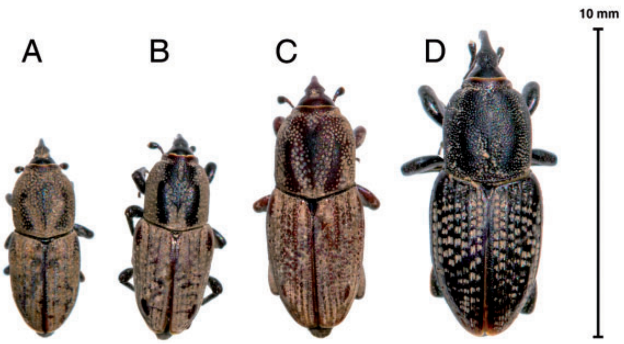

Fig. 2. Commonly occurring species of billbug adults in the western United States can be easily distinguished by markings on the elytra and thorax and relative sizes. (**A**) Bluegrass billbug (*Sphenophorus parvulus*) has even dimples covering the thorax and is ~5–7 mm (0.20–0.28 in) in length. (**B**) Phoenix billbug (*S. phoeniciensis*) has a raised, smooth M-shape on the thorax and is ~6–8 mm (0.24–0.31 in) in length. (**C**) Hunting billbug (*S. venatus vestitus*) has a raised, smooth marking resembling a "Y" in parentheses on the thorax and is ~7–9 mm (0.28–0.35 in) in length. (**D**) Rocky Mountain billbug (*S. cicatristriatus*) has small, even dimples on the thorax and deep, heart-shaped or hoof-shaped punctures on the elytra and is ~10–12 mm (0.40–0.47 in) in length. Photo credit: James Bradford.

Life Stages and Phenology

Description and Life Cycle

Adult billbugs have hard wing covers and a long beak-like snout with chewing mouthparts at the distal end, typical of weevils (Fig. 2A–D). They have clubbed, elbowed antennae with a long scape inserted at the proximal end of the snout. Depending on the species, adults are black or dull red/brown in color (Reynolds 2013), but when coated in soil can appear lighter in color (Niemczyk and Shetlar 2000, Richmond 2015). Billbug species can be differentiated from one another using pronotal patterns and markings on the elytra, color, and relative size (Shetlar et al. 2012; Fig. 2A–D). *Sphenophorus* is distinguished from other related genera by the shape of the antennal club, the relative separation of the coxae, the shape of the mesoepimeron, metaepimeron, and intercoxal processes, the claw segment, and the amount and arrangement of hairs on the underside of the third tarsal segment (Vaurie 1951).

Bluegrass and hunting billbugs are univoltine in multiple parts of the country (Johnson-Cicalese et al. 1990, Rondon and Walenta 2008, Kindler and Spomer 1986). Adults emerge from protected overwintering sites with warming temperatures in the spring and mate (April-May). Adult females chew holes in turf stems near the crown and deposit one to three eggs in each opening (Webster 1892, Satterthwait 1931a). Johnson-Cicalese et al. (1990) observed egg laying through August in New Jersey. Billbug eggs are oblong, creamy white, smooth and glossy, and 1–2 mm (0.04–0.08 in) in length (Fig. 3; Kindler and Spomer 1986). The egg stage generally lasts 6–10 d (Johnson-Cicalese et al. 1990, Rondon and Walenta 2008) before first-instars emerge.

Fig. 3. Adult female billbugs chew notches in grass stems and lay one to three eggs in the chamber. Photo credit: Madeleine Dupuy, Utah State University.

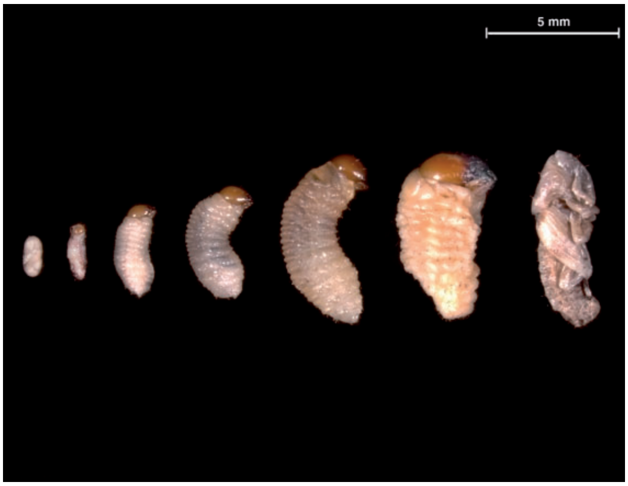

Fig. 4. Billbugs have an egg stage (left), five larval stages (middle), and a pupal stage (right) before maturing as adults. Photo credit: Madeleine Dupuy, Utah State University.

The larval stage has five instars that are cream-colored and robust, with a slightly tapered abdomen and a yellowish-brown to reddish-brown head capsule (Fig. 4). Billbug larvae are legless, which distinguishes them from white grubs (Coleoptera: Scarabaeidae), to which they may otherwise appear similar in initial stages. First instars are typically around 1.3 mm (0.01 in) long and feed in grass stems after egg hatch. They then drop 2–8 cm (0.79–3.15 in) into the soil and continue feeding on the roots and crown of the plant (June–August; Johnson-Cicalese et al. 1990, Vittum et al. 1999). These later instars range from 6–10 mm (0.24–0.39 in) in length (Shetlar et al. 2012). Currently, no external characters have been identified that can be used to distinguish larval species from one another, but DNA-based larval identification tools have been examined (Richmond et al. 2011). The larval stage generally lasts 35–55 d for bluegrass billbug and 21–35 d for hunting billbug before pupation (Watschke et al. 2013).

Pupae are initially cream colored, then sclerotize and darken to reddish brown. The appendages and wing pads of these exarate pupae are held close to the body, and the characteristic curculionid snout is evident (Fig. 4; Shetlar et al. 2012). Pupae of different billbug species can be distinguished from one another, using characters such as setae, length of beak, and the width of the pronotum (Satterthwait 1931a). The pupal stage lasts 8–12 d for bluegrass billbug or 3–7 d for hunting billbug before adults emerge in the fall and return to overwintering sites (Johnson-Cicalese et al. 1990, Watschke et al 2013).

Differences in Phenology Throughout the United States

In northeast Oregon, Rocky Mountain billbug is also univoltine, but adults and larvae are present year-round (Rondon and Walenta 2008). Larvae of the hunting and Rocky Mountain billbugs in New Jersey and northeast Oregon, respectively, have also been observed during the winter months, suggesting that a partial second generation occurs for these species in particular regions (Johnson-Cicalese et al. 1990, Rondon and Walenta 2008). In Indiana and North Carolina, the hunting billbug produces two overlapping generations per year and is capable of overwintering both as an adult or larva (Doskocil and Brandenburg 2012, Richmond and Duffy 2015). In Florida, Huang and Buss (2009) observed up to six overlapping generations of hunting billbug per year in greenhouse experiments at 25.8–27°C (78.4–80.6°F), with total development from egg to adult taking only 8–9 wk on warm-season turfgrasses. Under field conditions, such as those reported in New Jersey where average spring and summer temperatures range from 10°C to 24°C (50–75.2°F) (Robinson 2013), univoltine billbugs develop from egg to adult through the months of April–September. In the Intermountain West, where billbugs also appear to be univoltine, the window of development is extended from March through October (Fig. 1).

Monitoring

Adult Activity

Billbug activity can be monitored with pitfall traps because billbug adults are primarily ground active. Pitfall traps can be as simple as a plastic cup placed in the ground so that the lip of the cup is flush with the ground surface, or they can be more complex. Linear pitfall traps use PVC pipe or similar material to capture ground-active insects from a wider area in a single collection cup (Fig. 5A–C). Adults captured in the traps should be counted at least once per week to inform pest management decision-making (Potter 1998). Nocturnal hunting billbug adults may also be monitored easily by searching on greens and fairways at night with a strong light (Reynolds 2013).

An early treatment threshold suggests management is necessary when 15–25 adults can be collected by one person from pavement over a 5-min period (Tashiro and Personius 1970). However, this does not specify the area of pavement to be covered, time of day collection is to be done, or other important parameters. Unfortunately, more useful treatment thresholds have not been developed, but information from pitfall traps on first occurrence and increases in activity can be paired with other monitoring techniques to time management strategically.

Larval Activity

Billbug larvae are stem- and soil-dwelling, and thus, more difficult to monitor. Stems in areas of suspected billbug feeding can be inspected using the "tug test." Stems that have been fed on by larvae will break away easily when tugged on, particularly under heavy infestation (Fig. 6A–B). These stems are often hollow or filled with a sawdust-like frass. Later instars can be sampled by taking a soil core (e.g., using a cup cutter) in areas where larval feeding is suspected and inspecting the crown and root zone. In North Carolina, a standard cup cutter may not be an effective sampling tool because hunting billbug larvae

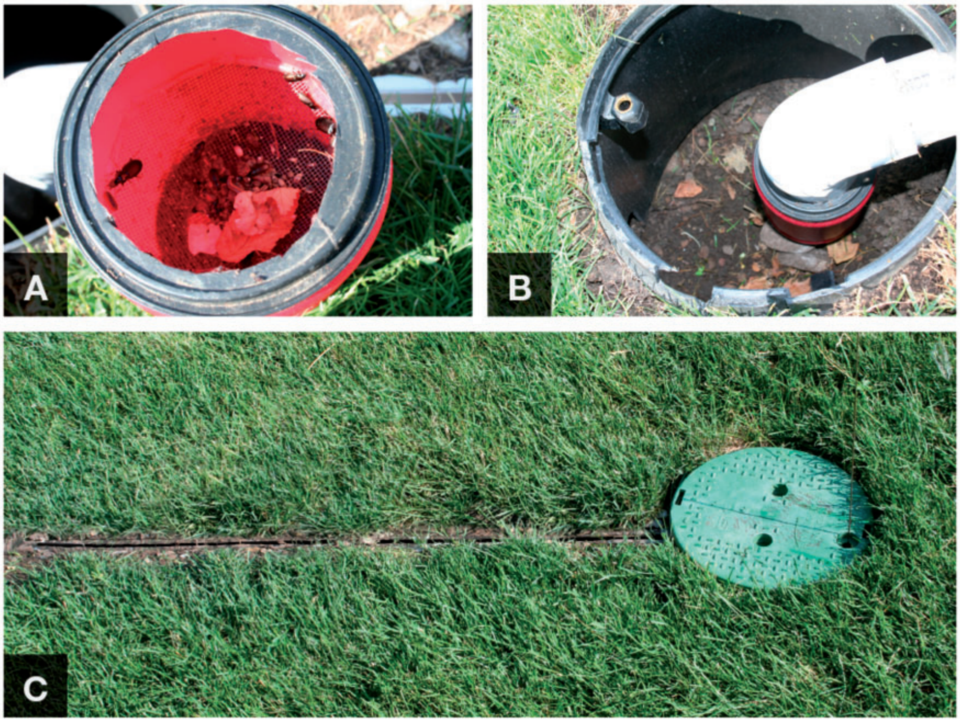

Fig. 5. A linear pitfall trap (similar to Lawrence 1982) is a useful tool for monitoring ground-active adult billbugs. The trap consists of (**A**) a collection vessel, here made from a recycled coffee container, with a hole cut in the lid for attachment to the end of the PVC pipe. Modifications to the collection vessel can be made including drilling small holes into the bottom for drainage and attaching mesh midway with adhesive to reduce moisture contact with captured insects. (**B**) The collection vessel attaches to an elbowed end of the pitfall PVC pipe and is housed within an irrigation box. The entire trap (**C**) consists of a 5.08-cm (2 in)-diameter, 1-m (3.28 ft)-long PVC pipe with a 1-cm (0.393 in) slit running the length of the pipe. The pipe is dug into the ground with the slit facing upward so that the slit is flush with the surface of the ground. The other end of the PVC pipe is capped. Photo credits: Madeleine Dupuy, Utah State University.

Fig. 6. Stems of turfgrass in a heavily billbug-damaged area have broken away easily during a "tug test" (**A**) to reveal later instars that have dropped into the soil to feed on the roots and crown of the turfgrass (**B**). Photo credits: Lori Spears, Utah State University

are often found beyond the cup cutter's sampling range, up to 23 cm (9.05 in) beneath the soil surface (Reynolds and Brandenburg 2015). Larvae can also be found by cutting three sides of a square foot in the turf with a sturdy knife. The turf can then be peeled back to check for the presence of larvae in the root zone and can be easily replaced with minimal damage afterwards (Vittum et al. 1999).

Degree-day Model

Predictive degree-day models may be paired with the monitoring tools previously described and have been implemented effectively in many systems, including turfgrass for the annual bluegrass weevil (*Listronotus maculicolis* Dietz; Syngenta®, Greencast®, Weevil Trak^{TM}). The degree-day approach assumes that insect development is directly related to ambient temperature and that higher temperatures result in increased growth rate, to a certain threshold (Higley et al. 1986). Heat units based on daily high and low temperatures (degree-days) accumulate from a biofix, or starting date, every day the average temperature is above a predetermined lower development threshold (a temperature below which the insect does not develop) for a particular species (Higley et al. 1986). A degree-day model for bluegrass billbug was developed in Ohio using the average method of calculation, a March 1 biofix, and a lower development threshold of 10°C (50°F). This model predicts first adult activity at 155–195 $DD_{10^\circ C}$ (280–352$DD_{50^\circ F}$), larval emergence from stems at 513–575 $DD_{10^\circ C}$ (925–1,035 $DD_{50^\circ F}$), and apparent visual damage at 739–825 $DD_{10^\circ C}$ (1,330–1,485 $DD_{50^\circ F}$; Watschke et al. 2013). However, this model does not appear to be robust, as preliminary calculations do not accurately predict activity in other regions of the country (Fig. 1). Adjustments to the model may need to be considered for different regions, including the western United States.

Management Options

Billbugs are particularly difficult to manage effectively because of differences in susceptibility of life stages to management methods and the soil- and stem-dwelling nature of larval stages versus the surface-dwelling adult stage. For optimal management, turf managers must first have a sound understanding of billbug seasonal activity and biology.

Cultural Control

Resistant turfgrass varieties provide a nonchemical and economic method of long-term billbug management that can be paired with other IPM strategies. Additionally, turfgrass that has already been killed by billbugs can be overseeded with a resistant variety (Shetlar 1991). Many varieties and cultivars of Kentucky bluegrass have been shown to be resistant to feeding by bluegrass billbug, including Park, Arista, NuDwarf, Delta, Kenblue, and South Dakota Certified (Watschke et al. 2013). These varieties have fine stems and leaves and tougher plant tissue, which offer more resistance to feeding and are less preferred for oviposition than nonresistant varieties with thicker stems and leaves (Bruneau et al. 1987, Johnson-Cicalese et al. 1989). Varieties of Kentucky bluegrass with more aggressive growth habits also displayed faster recovery from billbug feeding (Johnson-Cicalese 1989). Several varieties of warm-season grasses resistant to feeding by hunting billbug have also been identified, including the *Zoysia matrello* (L.) cultivars Diamond, Zorro, Cavalier, and Royal (Reinert et al. 2011), and TifEagle bermudagrass (Huang and Buss 2013). *Acremonium* endophytic fungi grow symbiotically with many species of grasses, causing them to produce higher concentrations of plant allelochemicals that deter feeding by many insect herbivores (Breen 1994). Endophyte-enhanced ryegrasses and fescues are highly resistant to feeding by billbugs and have been shown to be optimally resistant when they comprise 35–40% of the stand (Johnson-Cicalese and White 1990, Richmond et al. 2000, Watschke et al. 2013).

Billbug damage is most evident in stressed turf (i.e., under drought conditions or inadequate fertility; Shetlar et al. 2012). Under light to moderate billbug infestation, damage can often be masked with adequate irrigation and fertilization (Watschke et al. 2013). Irrigation should be applied regularly to cool-season grasses when they are preparing for summer dormancy or while billbug larvae are emerging from grass stems to feed at the crown (Shetlar 1991, Shetlar et al. 2012).

Transportation of infested sod is a major cause of the spread of billbugs, especially with hunting billbug on bermudagrass and zoysiagrass sod farms (Watschke et al. 2013). Billbugs from unmanaged sites may also infest nearby managed sites (Watschke et al. 2013).

Biological Control

Entomopathogenic nematodes are a potential biological control agent for billbug larvae (Georgis et al. 2006). In the United States, *Steinernema carpocapsae* ((Weiser) Wouts, Mracek, Gerdin & Bedding), *Steinernema feltiae* ((Filipjev) Wouts, Mracek, Gerdin & Bedding), and *Heterorhabditis bacteriophora* (Poinar) have all been reported to control billbugs at rates comparable to commonly used insecticides in both field and lab trials (Niemczyk 1988, Georgis and Poinar 1994, Niemczyk and Shetlar 2000). The turfgrass system is ideal for use of nematodes because of ease of application and the soil-dwelling nature of many turfgrass pests. Despite promising efficacy results (74–78% mortality of bluegrass billbug; Georgis and Poinar 1994) and availability in commercial preparations, use of entomopathogenic nematodes for billbug management is limited because of the high availability of insecticides that are less expensive, have longer shelf lives, are regarded as more reliable, and require less consideration of application conditions (e.g., UV exposure, pre- and postapplication irrigation). In Japan, *Steinernema carpocapsae* was the primary means of control for hunting billbug because of the lack of available effective insecticides and favorable environmental conditions. Since the registration of imidacloprid for use in Japan, however, sales of *Steinernema carpocapsae* have significantly declined (Georgis et al. 2006).

Grandevo and Venerate are two microbial products (active ingredients: *Chromobacterium subtsugae* strain PRAA4-1 and spent fermentation media and heat-killed *Burkholderia* spp. strain A396 cells and spent fermentation media, respectively) that have been assessed for use against bluegrass billbug in Kentucky bluegrass. Grandevo reduced numbers by 79.3% at 25.51 g/92.9 m^2 (0.90 oz/1,000 ft^2), and Venerate reduced numbers of larvae and pupae by 93.1% at 177.44 ml/92.9 m^2 (6 fl oz/1,000 ft^2; Stamm et al. 2014). These rates of control are comparable to many commonly used chemical insecticides; thus, these microbial products deserve further consideration.

Billbug adults and larvae are also susceptible to the entomopathogenic fungi *Beauveria* spp. and *Metarhizium* spp. Naturally existing complexes of these fungi rarely kill enough billbugs to have an effect on damage levels, and though commercial preparations of both fungi are available, they are expensive and field trials do not show consistent control (Watschke et al. 2013).

Additionally, there are a few known natural enemies of billbugs. *Zavipio (Vipio) belfragei* (Cresson) is a hymenopteran (Braconidae) parasitoid that has been reared from billbug larvae; however, no studies have been done on percent parasitism or potential impact (Young 2002). *Anaphes (Anaphoidea) calendrae* (Gahan) (Hymenoptera: Myrmaridae) has been reported as a parasitoid of eggs of bluegrass billbug, lesser billbug, and southern corn billbug (Satterthwait 1931b). This parasitoid is distributed throughout the eastern half of the United States and reportedly results in relatively high percentages of parasitism; thus, it may deserve further study (Young 2002).

There is a diverse predatory arthropod fauna inhabiting turfgrass, including spiders (Arachnida: Araneae), ground beetles (Coleoptera: Carabidae), rove beetles (Coleoptera: Staphylinidae), and ants (Hymenoptera: Formicidae) (Bixby-Brosi and Potter 2012). Several studies have documented factors impacting predatory arthropod communities and the impact of these predators on certain turf pests (Cockfield and Potter 1984, 1985; Arnold and Potter 1987; Terry et al. 1993; Kunkel et al. 1999; Lopez and Potter 2000; Zenger and Gibb 2003; Peck 2009; Dobbs and Potter 2014). For instance, commonly used turf insecticides have adverse effects on nontarget predatory arthropods and their natural pest suppression (Terry et al. 1993, Kunkel et al. 2001), while conservation biocontrol practices (e.g., cultivation of flowering plants and predator refugia) have positive effects (Braman et al. 2002). In a study by Frank and Shrewsbury (2004), not only did “conservation strips” (strips of bunch grass and flowering plants) increase predator abundance, but instances of predation on black cutworm (*Agrostis ipsilon* Hufnagel) were more frequent on golf course fairways adjacent to strips. In our work, we have observed evidence of spider-feeding on billbug adults in pitfall traps. Predators may also have indirect effects on pest populations by changing behavior of pests which can lead to fitness costs. For example, billbugs feign death in response to disturbance, which is thought to be an antipredator defense (Kindler and Spomer 1986). Further responses to and impacts of predatory arthropods on billbugs have not been documented, but as demand for sustainable turfgrass management increases, conservation biocontrol should be considered.

American toad (*Anaxyrus americanus* Holbrook) and several bird species are also reported billbug predators (Young 2002). Often larger predators like birds become pests themselves as they damage turf while foraging for larvae in the soil. Therefore, predatory arthropods offer better opportunities for pest suppression while maintaining the aesthetics of turf.

Chemical Control

Billbugs have historically been managed through use of contact insecticides, such as pyrethroids (e.g., bifenthrin), targeting spring adults emerging from overwintering sites (Watschke et al. 2013). More recently, billbugs have been managed through prophylactic applications of long-residual, systemic insecticides targeting early-instars, against which they are most effective. These preventive insecticides include the neonicotinoids (e.g., clothianidin and imidacloprid) and the anthranilic diamides (e.g., chlorantraniliprole and cyantraniliprole), and are ideally applied approximately a month (neonicotinoids) or more (anthranilic diamides, which are less water soluble) before egg hatch to allow them to be translocated throughout the turf plant before stem-dwelling larvae begin feeding (Potter 1998, Reynolds and Brandenburg 2015). Neonicotinoids also have activity against adults—either by ingestion or contact during foraging and oviposition—and can be applied curatively against adults (Shetlar and Andon 2012).

The existing degree-day model for bluegrass billbug suggests that the latest a contact insecticide against billbug adults is effective is 311–347 $DD_{10°C}$ (560–624 $DD_{50°F}$), or at ~30% of total adult emergence. Systemic insecticides applied against larvae should be effective from 513–825 $DD_{10°C}$ (925–1,485 $DD_{50°F}$; Watschke et al. 2013). Note again that this model may not be applicable to regions beyond the eastern United States or to species other than the bluegrass billbug (see billbug captures in the Intermountain West, Fig. 1).

Most work assessing insecticide efficacy against billbugs has been done in cool-season turfgrass with bluegrass billbug and hunting billbug. In field trials, products containing chlorantraniliprole applied preventively against hunting and bluegrass billbugs resulted in 93–100% suppression of larvae and pupae, while bifenthrin provided 82.7% suppression, and imidacloprid provided 62.1–79.4% suppression when compared with controls (Heller et al. 2008a). Furthermore, the preventive application of a combination of bifenthrin+clothianidin against bluegrass and hunting billbugs yielded varied results depending on the rate of application (50.2–83.4% suppression of larvae and pupae when compared with controls; Heller et al. 2008b). In contrast, Reynolds and Brandenburg (2015) have recently assessed common insecticides against hunting billbug larvae and adults in warm-season turf in greenhouse trials. Bifenthrin, clothianidin, cyantraniliprole, and a combination of bifenthrin + clothianidin all had > 80% efficacy against adults while imidacloprid had the greatest efficacy against larvae with just 33.6% mortality. The authors attribute low efficacy of the tested chemicals against larvae to observations that hunting billbug larvae are sometimes found very deep in the soil profile, perhaps beyond the reach of soil insecticides.

Insecticide Resistance

The current reliance on prophylactic insecticide applications may be short-lived if insecticide resistance management practices (i.e., IPM and chemical rotations) are not implemented in billbug management plans. Many turfgrass insect pests have evolved resistance to commonly used pyrethroids, including chinch bugs (Hemiptera: Blissidae), fall armyworm (*Spodoptera frugiperda* J.E. Smith), and the annual bluegrass weevil (Silcox and Vittum 2012). Other insect pests have become resistant to the relatively new classes of insecticides that are commonly used against billbugs, including resistance to neonicotinoids in whiteflies (Hemiptera: Alyrodidae), aphids (Hemiptera: Aphididae), houseflies (*Musca domestica* L.), Colorado potato beetle (*Leptinotarsa decemlineata* Say), and codling moth (*Cydia pomonella* L.) (Bass et al. 2015). A substantial portion of resistance issues with neonicotinoids involve imidacloprid (Bass et al. 2015), one of the most widely used active ingredients for billbugs. Additionally, the diamondback moth (*Plutella xylostella* L.) has shown high levels of resistance to chlorantraniliprole, part of the relatively newer class of anthranilic diamides (Teixeira and Andaloro 2013). Although insecticide resistance has not been observed in billbugs since the 70s (bluegrass billbug resistance to the cyclodiene dieldrin; Niemczyk and Frost 1978), it is important to be aware of the potential for resistance because of the limited classes of insecticides available for use in turfgrass and the current reliance on preventive insecticide applications.

In addition to insecticide loss through resistance, neonicotinoids have faced mounting public scrutiny over nontarget effects, particularly those on pollinators, and have been recently banned in the European Union (Gross 2013). There have been localized bans elsewhere, including the United States, where the Environmental Protection Agency is currently assessing the risk of imidacloprid to pollinators to support the review of the registered uses of imidacloprid in the United States (Housenger et al. 2016). In turfgrass, flowering weeds can provide a path for neonicotinoid exposure to pollinators (Larson et. al. 2013). Larson et al. (2013) found that mowed clover reduced the effect of neonicotinoids on pollinators compared to unmowed clover, and the authors also found that the anthranilic diamide chlorantraniliprole did not appear to harm pollinators. It is not clear how the availability of neonicotinoids in turfgrass will be affected, but it may become necessary to consider alternative management strategies.

In conclusion, billbugs remain one of the primary pests of turfgrass in the United States. Chemical control methods for billbugs continue to advance, but as concerns with insecticide resistance and the negative impact of pesticides on the environment, people, and other nontarget organisms grow, the demand for alternative management strategies is increasing. Future billbug research should be focused on a path to sustainable management methods, including the development of more robust predictive models, assessment of the effects of existing populations of predatory arthropods, and integration of cultural and biological controls into an IPM approach to billbug management. More broadly, the body of knowledge on billbug biology and management should be expanded from the eastern United States to the western United States, where comparatively little research has been conducted.

Acknowledgments

Thanks to Samantha LeBaron for assistance with billbug collections and sample processing and to James Bradford for imaging support. Special thanks to Paul Stokes of Logan Golf and Country Club for making the course available for sampling. Thanks also to Lori Spears, Alice Ruckert, and three anonymous reviewers for reviewing earlier versions of this manuscript. Funding was provided by the United States Department of Agriculture National Institute of Food and Agriculture Western Region Integrated Pest Management grant 2012-03313.

References Cited

Aoyagi, M., M. Ishii, T. Hirowatari and T. Yasuda. 1990. Record of the zoysiagrass billbug, *Sphenophorus venatus vestitus* Chittenden, from the bank of the Yamato River in Osaka and Nara Prefectures. Japanese Journal of Applied Entomology and Zoology 34: 253–254.

Arnold, T.B. and D.A. Potter. 1987. Impact of a high-maintenance lawn-care program on nontarget invertebrates in Kentucky bluegrass turf. Environmental Entomology 16: 100–105.

Asay, K.H., J.D. Hansen, B.A. Haws and P.O. Currie. 1983. Genetic differences in resistance of range grasses to the bluegrass billbug, *Sphenophorus parvulus* (Coleoptera: Curculionidae). Journal of Range Management 36: 771–772.

Bass, C., I. Denholm, M.S. Williamson and R. Nauen. 2015. The global status of insect resistance to neonicotinoid insecticides. Pesticide Biochemistry and Physiology 121: 78–87.

Beard, J.B. 1972. Turfgrass: Science and Culture, Prentice-Hall, Englewood Cliffs, NJ.

Bixby-Brosi, A. and D.A. Potter. 2012. Beneficial and innocuous invertebrates in turf, pp. 87–93. *In* R.L. Brandenburg and C.P. Freeman (eds.), Handbook of Turfgrass Insects, 2nd ed. The Entomological Society of America, St. Paul, MN.

Braman, S.K., A.F. Pendley and W. Corley. 2002. Influence of Commercially Available Wildflower Mixes on Beneficial Arthropod Abundance and Predation in Turfgrass. Environmental Entomology 31: 564–572.

Breen, J.P. 1994. *Acremonium* endophyte interactions with enhanced plant resistance to insects. Annual Review of Entomology 39: 401–423.

Bruneau, A.H., A.M. Parkhurst and R.C. Shearman. 1987. Discriminate analysis for Kentucky bluegrass billbug resistance ratings. Journal of the American Society for Horticultural Science 112: 978–980.

Chong, J.-H. 2015. Species richness and seasonal abundance of billbugs, *Sphenophorus* spp. from South Carolina golf courses. Journal of Agricultural and Urban Entomology 31: 20–28.

Cockfield, S.D. and D.A. Potter. 1984. Predatory insects and spiders from suburban lawns in Lexington, Kentucky. The Great Lakes Entomologist 17: 179–184.

Cockfield, S.D. and D.A. Potter. 1985. Predatory arthropods in high- and low-maintenance turfgrass. The Canadian Entomologist 117: 423–429.

Dobbs, E. and D.A. Potter. 2014. Conservation biological control and pest performance in lawn turf: Does mowing height matter?. Environmental Management 53: 648–659.

Doskocil, J.P. and R.L. Brandenberg. 2012. Hunting billbug (Coleoptera: Curculionidae) life cycle and damaging life stage in North Carolina, with notes on other billbug species abundance. Journal of Economic Entomology 105: 2045–2051.

Flint, M.L., M.A. Harivandi and H.K. Kaya. 2009. UC IPM pest management guidelines: Turfgrass: Billbugs.

Frank, S.D. and P.M. Shrewsbury. 2004. Effect of conservation strips on the abundance and distribution of natural enemies and predation of *Agrostis ipsilon* (Lepidoptera: Noctuidae) on golf course fairways. Environmental Entomology 33: 1662–1672.

Fritz, M. and T. Salaiz. 2007. Idaho's four billbug species are lying in wait this spring, Ag Weekly. University of Idaho, ID.

Fry, J.D. and R.A. Cloyd. 2011. Zoysiagrass genotypes differ in susceptibility to the bluegrass billbug, *Sphenophorus parvulus*. Horticultural Science 46: 1314–1316.

Gelernter, W. 2012. Insect pests of turfgrass: management challenges in a changing environment, pp. 2–8. *In* R.L. Brandenburg and C.P. Freeman (eds.), Handbook of Turfgrass Insects, 2nd ed. The Entomological Society of America, St. Paul, MN.

Georgis, R. and G. Poinar Jr. 1994. Nematodes as bioinsecticides in turf and ornamentals, pp. 477–489. *In* A.R. Leslie (ed.), Integrated pest management for turfgrass and ornamentals. CRC, Boca Raton, FL.

Georgis, R., A.M. Koppenhofer, L.A. Lacey, G. Belair, L.W. Duncan, P.S. Grewal, M. Samish, L. Tan, P. Torr and R.W.H.M. van Tol. 2006. Successes and failures in the use of parasitic nematodes for pest control. Biological Control 38: 103–123.

Gross, M. 2013. EU ban puts spotlight on complex effects of neonicotinoids. Current Biology 23: R462–R464.

Grube, A., D. Donaldson, T. Kiely and L. Wu. 2011. Pesticides industry sales and usage: 2006 and 2007 market estimates. *In* U.S.E.P. Agency (ed.), Biological and economic analysis division, office of pesticide programs. Office of Chemical Safety and Pollution Prevention, Washington, DC.

Haydu, J.J., A.W. Hodges and C.R. Hall. 2008. Estimating the economic impact of the U.S. golf course industry: Challenges and solutions. Horticultural Science 43: 759–763.

Held, D.W. and D.A. Potter. 2012. Prospects for managing turfgrass pests with reduced chemical inputs. Annual Review of Entomology 57: 329–354.

Heller, P.R., D. Kline and A. Houseman. 2008a. Preventive application of Acelepryn, Grub-Ex, Merit, and Talstar formulations to suppress hunting and bluegrass billbugs, 2007. Arthropod Management Tests 33.

Heller, P.R., D. Kline and A. Houseman. 2008b. Preventive application of Aloft and Merit formulations to suppress hunting and bluegrass billbugs, 2007. Arthropod Management Tests 33.

Higley, L.G., L.P. Pedigo and K.R. Ostlie. 1986. DEGDAY: A program for calculating degree-days and assumptions behind the degree-day approach. Environmental Entomology 15: 999–1016.

Housenger, J., K.G. Sappington, M.A. Ruhman, S. Bireley, J., Richard D., Trolano and Alder. 2016. Preliminary pollinator assessment to support the registration review of imidacloprid, pp. 1–305. United States Environmental Protection Agency: Office of Chemical Safety and Pollution Prevention, Washington, DC.

Huang, T.-I. and E.A. Buss. 2009. Billbug (Coleoptera: Curculionidae) species composition, abundance, seasonal activity, and developmental time in Florida. Journal of Economic Entomology 102: 309–314.

Huang, T.-I. and E.A. Buss. 2013. *Sphenophorus venatus vestitus* (Coleoptera: Curculionidae) preference for bermudagrass cultivars and endophytic perennial ryegrass overseed. The Florida Entomologist 96: 1628–1630.

Johnson-Cicalese, J.M. and C.R. Funk. 1990. Additional host plants of four species of billbug found on New Jersey turfgrasses. Journal of the American Society for Horticultural Science 115: 608–611.

Johnson-Cicalese, J.M. and R.H. White. 1990. Effect of *Acremonium* endophytes on four species of billbug found on New Jersey turfgrasses. Journals of the American Society for Horticultural Science 115: 602–604.

Johnson-Cicalese, J.M., R.H. Hurley, G.W. RWolfe and C.R. Funk. 1989. Developing turfgrasses with improved resistance to billbugs, The 6th International Turfgrass Research Conference, Tokyo, Japan.

Johnson-Cicalese, J.M., G.W. Wolfe and C.R. Funk. 1990. Biology, distribution, and taxonomy of billbug turf pests (Coleoptera: Curculionidae). Environmental Entomology 19: 1037–1036.

Kindler, S.D. and S.M. Spomer. 1986. Observations on the biology of the bluegrass billbug, *Sphenophorus parvulus* Gyllenhal (Coleoptera: Curculionidae), in an eastern Nebraska sod field. Journal of the Kansas Entomological Society 59: 26–31.

Kuhn, W.R., R.R. Youngman, S. Wu and C.A. Laub. 2013. Ecology, taxonomy, and pest management of billbugs (Coleoptera: Curculionidae) in orchardgrass of Virginia. Journal of Integrated Pest Management 4.

Kunkel, B.A., D.W. Held and D.A. Potter. 1999. Impact of halofenozide, imidacloprid, and bendiocarb on beneficial invertebrates and predatory activity in turfgrass. Journal of Economic Entomology 92: 922–930.

Kunkel, B.A., D.W. Held and D.A. Potter. 2001. Lethal and sublethal effects of bendiocarb, halofenozide, and imidacloprid on *Harpalus pennsylvanicus* (Coleoptera: Carabidae) following different modes of exposure in turfgrass. Journal of Economic Entomology 94: 60–67.

Larson, J.L., C.T. Redmond and D.A. Potter. 2013. Assessing insecticide hazard to bumble bees foraging on flowering weeds in treated lawns. PLoS ONE 8: 1–7.

Lawrence, K.O. 1982. A linear pitfall trap for mole crickets and other soil arthropods. Florida Entomologist 65: 376–377.

Lopez, R. and D.A. Potter. 2000. Ant Predation on eggs and larvae of the black cutworm and Japanese beetle in turfgrass. Environmental Entomology 29: 116–125.

Milesi, C., S.W. Running, C.D. Elvidge, J.B. Dietz, B.T. Tuttle and R.R. Nemani. 2005. Mapping and modeling the biogeochemical cycling of turfgrasses in the United States. Environmental Management 36: 426–438.

Morrill, W.F. and E.F. Suber. 1976. Biology and control of *Sphenophorus coesifrons* (Gyllenhal) (Coleoptera: Curculionidae) in bahiagrass. Journal of the Georgia Entomological Society 11: 283–288.

National Agricultural Statistics Service. 2006. Agricultural Statistics 2006. *In* U. S. D. O. Agriculture. United States Government Printing Office, Washington DC.

Niemczyk, H.D. 1983. The bluegrass billbug: a frequent misdiagnosed pest of turfgrass. American Lawn Applicator 4.

Niemczyk, H.D. 1988. Cool season insect control. Landscape Management 27: 25–30.

Niemczyk, H.D. and C. Frost. 1978. Insecticide resistance found in Ohio bluegrass billbug. Ohio Report 62: 22–23.

Niemczyk, H.D. and D.J. Shetlar. 2000. Destructive Turf Insects, 2 ed. H.D.N. Books, Wooster, OH.

Oetting, R., W.G. Hudson and S.K. Braman. 2006. Ornamental, Lawn, and Turf Insects. *In* P. Guillebeau, N. Hinkle and P. Roberts (eds.), Summary of Losses from Insect Damage and Cost of Control in Georgia 2006. Department of Entomology Special Committee on Insect Survey and Losses for 2006.

Peck, D.C. 2009. Long-term effects of imidacloprid on the abundance of surface- and soil-active nontarget fauna in turf. Agricultural and Forest Entomology 11: 405–419.

Potter, D.A. 1998. Understanding halofenozide (Mach 2) and imidacloprid (Merit) soil insecticides, pp. 6–7, TURFAX.

Potter, D.A. and S.K. Braman. 1991. Ecology and management of turfgrass insects. Annual Review of Entomology 36: 383–406.

Reinert, J.A., M.C. Engelke and J.J. Heitholt. 2011. Hunting billbug (Coleoptera: Curculionidae) resistance among zoysiagrass (*Zoysia* spp.) cultivars. The Florida Entomologist 94: 613–621.

Reynolds, D.S. 2013. Ecology and behavior of the hunting billbug *Sphenophorus venatus vestitus* in warm-season turfgrass. Doctor of Philosophy Dissertation, North Carolina State Raleigh, NC.

Reynolds, D.S. and R.L. Brandenburg. 2015. Hunting billbug (*Sphenophorus venatus vestitus*) response to insecticide application in warm-season turfgrass and implications for management. Crop, Forage, and Turfgrass Management 1: 1–7.

Richmond, D.S. 2015. Managing Billbugs in Turfgrass. Turfgrass Insects. Purdue Extension, (http://extension.entm.purdue.edu/publications/E-266.pdf)

Richmond, D.S. and A. Duffy. 2015. Hunting Billbug Larvae Overwintering in Indiana, Purdue Turf Tips. Purdue Extension (http://purdueturftips.blogspot.com/2015/04/hunting-billbug-larvae-overwintering-in.html)

Richmond, D.S., H.D. Niemczyk and D.R. Shetlar. 2000. Overseeding endophytic perennial ryegrass into stands of Kentucky bluegrass to manage bluegrass billbug (Coleoptera: Curculionidae). Journal of Economic Entomology 93: 1662–1668.

Richmond, D.S., B.J. Schermerhorn and M.G. Abdelwahab. 2011. Developing a DNA-based larval identification tool for billbugs. USGA Turfgrass and Environmental Research Online 10: 1–7.

Robinson, David. 2013. Monthly mean temperatures in New Jersey from 1895–2013. Rutgers University, http://climate.rutgers.edu/stateclim_v1/data/index.html, last accessed 26 February 2016.

Rondon, S.I. and D.I. Walenta. 2008. Elucidating the biology of the bluegrass and Denver billbugs in NE Oregon.

Satterthwait, A.F. 1931a. Key to known pupae of the genus *Calendra*, with host-plant and distribution notes. Annals of the Entomological Society of America 24: 143–172.

Satterthwait, A.F. 1931b. *Anaphoidea calendrae* (Gahan), a myrmarid parasite of eggs of weevils of the genus *Calendra*. Journal of the New York Entomological Society 39: 171–190.

Shetlar, D.J. 1991. Billbugs in Turfgrass. *In* T.O.S. University (ed.). The Ohio State University Extension, Columbus, Ohio. (ohioline.osu.edu/hyg-fact/2000/2502.html)

Shetlar, D.J. and J.E. Andon. 2012. Billbugs in Turfgrass. *In* T.O.S. University (ed.), ohioline.osu.edu. The Ohio State University Extension, Columbus, Ohio.

Shetlar, D.J., D. Silcox and T.J. Gibb. 2012. Billbugs, pp. 16–18. *In* R.L. Brandenburg and C.P. Freeman (eds.), Handbook of Turfgrass Insects, 2 ed. The Entomological Society of America, St. Paul, MN.

Silcox, C.A. and P.J. Vittum. 2012. Turf Insecticide Resistance Management. *In* R.L. Brandenberg and C.P. Freeman (eds.), Handbook of Turfgrass Insects, 2 ed. The Entomological Society of America, St. Paul, MN.

Stamm, M.D., K.M. O'Brien, K.M. Armitage and F.P. Baxendale. 2014. Efficacy of GRANDEVO and Venerate for Control of Bluegrass Billbugs, 2013. Arthropod Management Tests 39.

Sutherland, C.A. 2006. Billbugs. N. M. S. University. Cooperative Extension Service, Las Cruces, NM.

Tashiro, H. and K.E. Personius. 1970. Current status of the bluegrass billbug in its control in western New York home lawns. Journal of Economic Entomology 63: 23–29.

Teixeira, L.A. and J.T. Andaloro. 2013. Diamide insecticides: Global efforts to address insect resistance stewardship challenges. Pesticide Biochemistry and Physiology 106: 76–78.

Terry, L.A., D.A. Potter and P.G. Spicer. 1993. Insecticides affect predatory arthropods and predation on Japanese beetle (Coleoptera: Scarabaeidae) eggs and fall armyworm (Lepidoptera: Noctuidae) pupae in turfgrass. Journal of Economic Entomology 86: 871–878.

Vaurie, P. 1951. Revision of the genus *Calendra* (formerly *Sphenophorus*) in the United States and Mexico (Coleoptera: Curculionidae). Bulletin of the American Museum of Natural History 93: 382–395.

Vittum, P.J., M.G. Villani and H. Tashiro. 1999. Turfgrass Insects of the United States and Canada, 2 ed. Cornell University Press, Ithaca, NY.

Walenta, D.L., S. Rao, C.R. McNeal, B.M. Quebbman and G.C. Fisher. 2004. *Sphenophorus* spp., a complex billbug community infesting Kentucky bluegrass seed fields in the Grande Ronde Valley of Northeastern Oregon, pp. 53–56. Department of Crop and Soil Science Extension, Seed Production Research at Oregon State University.

Watschke, T.L., P.H. Dernoeden and D.J. Shetlar. 2013. Managing Turfgrass Pests, 2 ed. CRC Press, Boca Raton, FL.

Webster, F.M. 1892. Insects which burrow in the stems of wheat. Bulletin of the Ohio Agricultural Experiment Station 5: 72–73.

Young, F.B. 2002. Seasonal activity and biology of the hunting billbug, *Sphenophorus venatus vestitus* (Coleoptera: Curculionidae), in northwest Arkansas. Master of Science Thesis, University of Arkansas Fayetteville, AR.

Zenger, J. and T.J. Gibb. 2001. Identification and impact of egg predators of *Cyclocephala lurida* and *Popillia japonica* (Coleoptera: Scarabaeidae) in turfgrass. Environmental Entomology 30: 425–443.