Journal of Economic Entomology, XX(XX), 2020, 1–9
doi: 10.1093/jee/toaa133
Research

OXFORD

Horticultural Entomology

Seasonal Occurrence and Abundance of Billbugs (Coleoptera: Curculionidae) in Georgia Sod Farms

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Subject Editor: Tong-Xian Liu

Received 7 April 2020; Editorial decision 24 May 2020

Abstract

The billbug, *Sphenophorus* spp. (Coleoptera: Curculionidae), is an important pest complex in sod farms in Georgia. Larval feeding within stolons and on roots affects spring recovery of slow-growing zoysiagrass and poses a serious challenge to machine harvesting, as the damaged turfgrass rarely holds together. Little is known about major billbug species and their seasonal occurrence and abundance in Georgia sod farms, as most previous research was conducted in golf courses in the region. In 2018 and 2019, adult billbugs were sampled from five zoysiagrass sod field sites in central Georgia. Four linear pitfall traps were used per site from February to December each year, and the traps were checked at weekly intervals. The data show that >98% of the sampled billbugs were the hunting billbug, *Sphenophorus venatus vestitus* Chittenden, whereas the nutgrass billbug, *Sphenophorus cariosus* Olivier; uneven billbug, *Sphenophorus inaequalis* Say; and vegetable weevil, *Listroderes difficilis* Germain were the minor species. Seasonal billbug capture was influenced by turfgrass phenology (e.g., early-growth-stage, late-growth-stage or fully grown turfgrass). The numbers of *Sphenophorus* spp. collected were significantly greater in the fully grown turfgrass than in the early- or late-growth-stage turfgrasses. Significantly greater densities of billbug were found in *Zoysia matrella* (L.) Merrill ('Zeon') and the *Z. matrella* × *Zoysia pacifica* (Goudswaard) M. Hotta & S. Kuroki hybrid ('Emerald') than in the *Zoysia japonica* (Steudel) cultivars 'El Toro' and 'Zenith'. Similar numbers of male and female billbugs were collected from the sod field sites.

Key words: *Sphenophorus* spp., turfgrass, growth stage, zoysiagrass

Turfgrass is an important component in golf courses and general landscapes such as residential and public lawns worldwide and especially in the eastern region of the United States. In Georgia, the turfgrass industry is estimated to be worth $7.8 billion USD (Kane and Wolfe 2012). Sod farms in Georgia span ~11331.2 ha across 61 counties and are valued at $1.12 billion USD (University of Georgia Center for Agribusiness & Economic Development–Farm Gate Value Report 2018). The billbug pest complex, *Sphenophorus* spp. (Coleoptera: Curculionidae), has increased in importance in turfgrass systems throughout the United States in recent years, causing significant losses to sod farms, golf courses, and the landscape care industry, maintaining residential, commercial, and public lawns (Dupuy and Ramirez 2016). Although more than 60 native billbug species occur in the United States (Niemczyk and Shetlar 2000), approximately 10 species threaten the sustainability of turfgrass (Potter and Braman 1991, Vittum et al. 1999, Dupuy and Ramirez 2016). In warm-season grasses, the hunting billbug, *Sphenophorus venatus vestitus* Chittenden, is the most destructive species (Potter and Braman 1991, Huang and Buss 2009).

Previous studies and reports from the Carolinas, Florida and elsewhere have allowed turf scientists and pest managers to develop a picture of the general biology of billbugs (Kelsheimer 1956, Niemczyk 1983, Vittum et al. 1999, Shetlar 2003, Huang 2008, Doskocil and Brandenburg 2012, Reynolds 2014). Adult female billbugs oviposit eggs inside the stolons (stem) of turfgrass. The emerging first instars feed within the internodal space of the stolons. When they molt into second instars, they break out of the stolons because of the inadequate space within the stolons and drop into the soil. Thereafter, they molt through four more instars before becoming pupae. The pupal stage occurs in the soil.

The domestic and international demands for zoysiagrass [*Zoysia matrella* (L.) Merrill and *Zoysia japonica* Steudel] have increased dramatically (Patton 2009). Zoysiagrass was planted on as much as 6593.5 ha on golf courses in the United States in 2006 (Lyman et al. 2007), and the demand is consistently increasing in the southeastern and south-central United States, as more golf courses and residential lawns have been established with or converted to this species (Patton et al. 2017). On sod farms, the damage potential of billbugs on zoysiagrass is magnified because zoysiagrass is slow-growing and does not recover well once adult and larval billbugs have caused damage. Additionally, the damage to turfgrass by billbugs differs between golf turf and sod fields. Whereas billbugs cause patches of dead grass on golf courses, sods infested by billbugs struggle to grow and hold together when machine-harvested, rendering the harvested but broken slabs unsalable. Because the generalized understanding of billbugs was built on information gathered from golf courses planted largely with bermudagrass, this information may not be wholly applicable to turf production, particularly zoysiagrass production. Moreover, the biology and diversity of billbugs clearly differ among turfgrass species (Huang 2008, Chong 2015), and as a result, the information on billbug biology and damage gathered from golf courses cannot be entirely applied to sod farms.

Billbugs can spread to other non-infested regions or around the country through the movement of infested sods (Tashiro 1987). The domestic market is critical for sod producers in Georgia. Additionally, some Georgia growers export sod to other countries. All sods undergo rigorous phytosanitary inspection before shipment to certain European, Middle Eastern, Asian, and South American countries and Australia, which have zero-tolerance policies on billbug larvae-infested sods (M. Evans, GA Department of Agriculture, personal communication). Because hunting billbug eggs are deposited inside stolons (stems), the emerging first instars feed within the stolons and remain undetected until the larvae molt into the second instar and break out of the stolons. The sod leaves the United States with no detectable billbug larvae, but the larvae become visible at the destination, which leads to the rejection of the sod. Rejection has become more common and seriously affects some sod producers in Georgia. Currently, growers sprig their sod and repeatedly treat it with insecticides to control young billbug larvae. This process provides reasonable control but not enough to meet the export standards. Thus, an effective and timely field-level management program is necessary.

Knowledge of seasonal occurrence, abundance, and species diversity is critical to developing integrated pest management (IPM) strategies, such as sampling plans or management tactics, for billbugs in sod farms. To date, management approaches have been adopted from previous research on golf courses in North and South Carolina and Florida. Hunting billbugs undergo two generations per year in North Carolina (Doskocil and Brandenburg 2012), whereas there are up to six generations per year in Florida (Huang and Buss 2009). The variability in billbug voltinism underscores the need to understand regional billbug phenology in turfgrass, because the number of generations will dictate the number of insecticide applications needed. Most previous billbug research has been conducted on golf courses. Billbug management approaches on golf courses may not directly apply to sod farms because management options and goals, such as fertilization, irrigation, and plant protection practices, of the two systems vary distinctly. Turfgrass on golf courses is not harvested and sold; it is fully grown, and emphasis is placed on maintenance. Turfgrass in sod farms is harvested and sold, and then the grass is grown from sprigs or rhizomes from the same cut patch within a short time frame. Thus, the major objective of the current study was to determine the occurrence and seasonal abundance of billbugs relative to the growth stages of turfgrass in sod farms.

Materials and methods

Study Site

A survey of adult billbugs was conducted in sod farms in central Georgia in 2018 and 2019. Each year, the sampling was initiated from February to December. The selected sod fields have a history of billbug infestation. The details of the selected fields, such as their locations and grass cultivars, are listed in Table 1. In 2018, sampling was conducted in four sod fields within four distinct sod farms. For the fifth site, sampling was conducted in three fields at the same sod farm in Whitesburg, GA. In 2019, sampling at the Whitesburg site was discontinued, and a new site in Fort Valley, GA, was selected. The turfgrass genotype in all the sod fields was zoysiagrass (*Zoysia* spp.) but the cultivars varied. The zoysiagrass cultivars were 'El Toro', 'Emerald', 'Zenith', and 'Zeon'. The cultivar 'Zeon' is *Z. matrella*, and 'El Toro' and 'Zenith' are *Z. japonica*, while 'Emerald' [*Z. matrella* × *Zoysia pacifica* (Goudswaard) M. Hotta & S. Kuroki] is a hybrid. 'El Toro' and 'Zenith' zoysiagrass are wide-blade cultivars, whereas 'Emerald' and 'Zeon' zoysiagrass are narrow-blade cultivars. At the onset of sampling in 2018 and 2019, all the zoysiagrass in the field sites was fully grown and ready for harvesting.

In 2018, sampling was performed continuously at the five sites from mid-February to mid-December without any interruption (Table 1). In 2019, harvesting at site 1 began in January and was completed by late May, and the site was replanted with a new crop (soybean) instead of turfgrass. Thus, a new field adjacent to site 1, site 1a, was selected for further sampling (Table 1). The newly recruited zoysiagrass site used in 2019 was also fully grown at the onset of sampling. The sampling continued at site 1a from the first week of June to mid-December. In 2019, sampling at site 5 was discontinued because of logistical reasons and upon grower request; thus, a new site, site 6 in Fort Valley, GA, was selected for further sampling (Table 1). All the sites except site 2 received no fungicide or herbicide application. Site 3 was intensively managed by the grower for billbug control, as the maximum label rates of imidacloprid, bifenthrin, and chlorantraniliprole were applied once each during May and June 2018. The rest of the sites received no insecticide applications.

Sampling

Linear pitfall traps as described in Huang and Buss (2009) and Doskocil and Brandenburg (2012) were used to sample adult billbugs. This trap was constructed using white, 2.5-cm-diameter, 0.6-cm thick, polyvinyl chloride (PVC) pipes by cutting a 1-cm-wide linear slit. Four 152.4-cm-long PVC pipes with slits were attached to a five-way PVC adaptor (Fig. 1A). Four PVC stopper caps were attached to the distal ends of the slited PVC pipes. This was done to prevent the movement of the trapped adult billbugs to the distal end of the PVC pipe. The fifth vent of the five-way adaptor was attached to the plastic dome lid of a 236.6 ml disposable Dixie PerfecTouch coffee cup (Fig. 1B). A 2.5-cm hole was drilled in the plastic dome lid to allow it to fit tightly on the fifth vent of the five-way adaptor. This coffee cup served as a collection device. Each linear pitfall trap was created by burying a 7.6-liter plastic pail (24.13 deep × 24.8 cm diameter). Four 2.7-cm-diameter holes were drilled along diagonal lines placed 0.5 cm below the top edge of each plastic pail. Ten 2.5-mm diameter holes were drilled along the bottoms of the pails to drain rainwater. The collection coffee cup inside the pail was supported by placing a 5-cm-tall (5 cm length × 5 cm breadth) brick under the coffee cup. The PVC pipes were installed with the slits facing upward when the pail was deployed in the soil (Fig. 1C). The traps were deployed at the mowing height of the grass. The gaps along the lengthwise edges of the slited PVC pipes were filled with soil so that the adult billbugs could

Table 1. Details of the sod farm sites selected for weekly *Sphenophorus* spp. sampling in central Georgia in 2018 and 2019

Site	Year	Location	Zoysiagrass cultivar	Field coordinates of trap location	Components of surrounding landscape	Field size (ha)
1	2018, 2019 (up to May 2019)	Marshallville, GA	'Emerald'	1) 32.4286, –84.0022 2) 32.4285, –84.0032 3) 32.4284, –84.0051 4) 32.4296, –85.0051	Wood line, open fields	14.02
1a	2019	Marshallville, GA	'Zenith'	1) 32.4287, –83.9943 2) 32.4287, –83.9940 3) 32.4292, –83.9945 4) 32.4316, –83.9952	Open fields	27.55
2	2018, 2019	Marshallville, GA	'Zenith'	1) 32.3864, –83.9920 2) 32.3843, –83.9918 3) 32.3814, –83.9934 4) 32.3800, –83.9974	Wood line, open fields	66.33
3	2018, 2019	Fort Valley, GA	'El Toro'	1) 32.5193, –83.9463 2) 32.5206, –83.9459 3) 32.5215, –83.9448 4) 32.5196, –83.9437	Pecan orchard, wood line, open fields	7.89
4	2018, 2019	Marshallville, GA	'Zeon'	1) 32.4241, –83.8880 2) 32.4237, –83.8902 3) 32.4276, –83.8928 4) 32.4293, –83.8927	Wood line, open fields	31.12
5	2018	Whitesburg, GA	'El Toro'	1) 33.4918, –84.8604 2) 33.4964, –84.8639 3) 33.4989, –84.8544 4) 33.5516, –84.8512	Wood line, creek, open fields	Traps 1 and 2: 4.66 Trap 3: 4.44 Trap 4: 1.82
6	2019	Fort Valley, GA	'El Toro'	1) 32.5075, –83.9412 2) 32.5059, –83.9406 3) 32.5070, –83.9393 4) 32.5804, –83.9398	Pecan orchard, woods	9.66

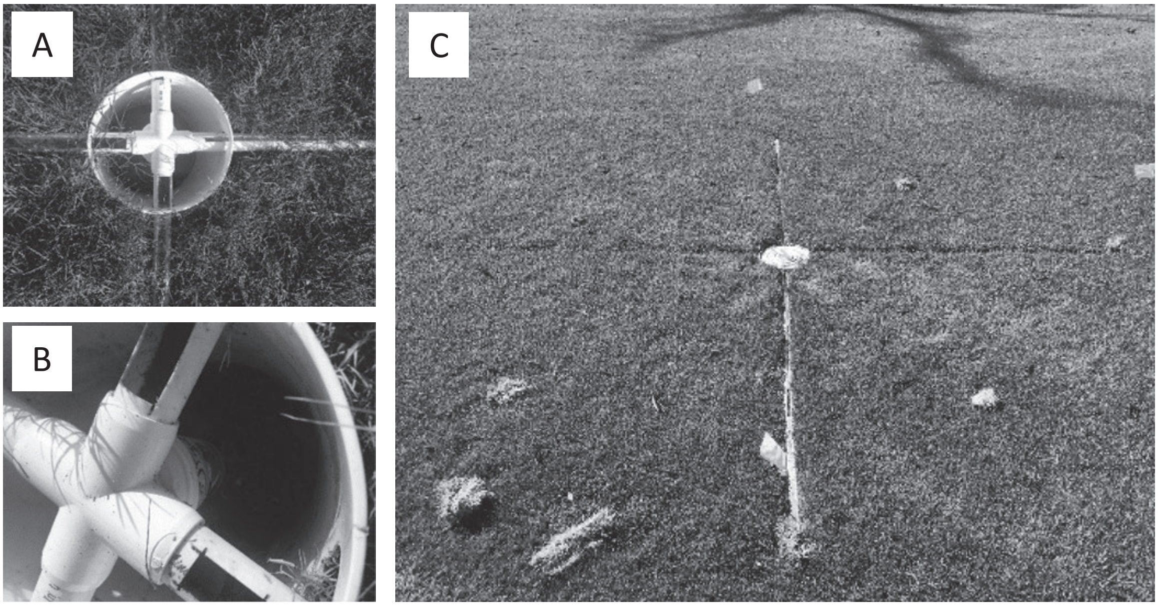

Fig. 1. A four-pipe linear pitfall trap with (A) four slited PVC pipes connected to a central five-way adaptor; (B) the five-way adaptor empties into a coffee cup in a plastic pail; (C) the fully deployed linear pitfall trap on the turfgrass.

walk over the pipe, fall into the slit, and become trapped in the coffee cup. Because stoppers were placed at the distal ends of the PVC pipes and the other end emptied into a collection container, the billbugs were ultimately forced to move in one direction and become trapped in the collection device. The curved edges of the slits along the PVC pipe prevented the escape of the adult billbugs that fell into the trap. Four linear pitfall traps were placed in each site. In site 5, however, two linear pitfall traps were deployed in one field, and one trap was placed in each of the other two fields.

One-third of the collection container was filled with ethylene glycol as a preservative agent. These traps were serviced at weekly intervals, and the billbugs were recovered by pouring the content through a copper strainer. Then, the strainer was emptied into plastic bags in the field. The billbugs were transported to the entomology laboratory, University of Georgia, Griffin, GA, for further identification. The billbugs were preserved in 70% ethyl alcohol.

Evaluation

The adult billbugs were identified to species based on the morphological characters described by Vaurie (1951) and Johnson-Cicalese et al. (1990). The males and females were distinguished by the presence of a groove or depression on the metasternum and the first two abdominal sterna (Johnson-Cicalese et al. 1990). The growth stages of the turfgrass in the sod farms were recorded quarterly. The turfgrass was considered to be in an early growing stage when the turfgrass surrounding the trap had been harvested and <50% of the soil was covered by grass. The grass was considered to be in the late growing stage when >50% of the soil was under grass cover. The grass was classified as fully grown when it was at least ~5 cm tall (measured from the soil) and ready to harvest. The data were organized by turfgrass growth stage and season. The seasons were as follows: spring (February to May), summer (June to August), and fall (September to December).

Statistical Analyses

All the analyses were conducted using SAS software (SAS Institute 2012). To determine the incidence and abundance of billbugs from February to December 2018 and 2019, the number of billbugs captured in the four traps at each site were averaged by sampling date. The average billbug data were subjected to one-way analysis of variance (ANOVA) using the general linear model procedure (PROC GLM) in SAS after log transformation (ln[x +1]), where the sample date and sites served as the treatment and replication, respectively. Because the growth stages of turfgrass were not uniform across the sampling dates, the billbug trap captures from all the sites were organized by turfgrass growth stage and season. Two-way ANOVA was performed on these data using the general linear model procedure (PROC GLM) in SAS after log transformation (ln[x +1]), where the effects of turfgrass growth stage and season were analyzed with interaction. The means and SEs of the variables were calculated using the PROC MEANS procedure in SAS.

For each field, the billbug data were subjected to one-way ANOVA using the general linear model procedure (PROC GLIMMIX) in SAS with a log link function and a negative binomial distribution. The turfgrass growth stage had a fixed effect and replication (pitfall trap) had a random effect in the model. The least squares means were back transformed and separated for a pairwise t-test (P < 0.05). The billbug data from sites 1, 1a, 5, and 6 were combined when the analysis was performed. For the combined data from sites 5 and 6, billbug data were obtained from only two traps in late-growth-stage turfgrass; thus, the data from the late growth stages were not included in the analysis. A one-way ANOVA was performed using the general linear model procedure (PROC GLM) after log transformation (ln[x +1]) to determine the effect of zoysiagrass genotypes on billbug captures. For this analysis, billbug capture data only from February to June 2018 were used, as all the turfgrass was fully grown during this period. The means were analyzed using the Tukey HSD method (α = 0.05). To determine the effect of gender, male and female billbug data for 2 yr were combined by trap for each site, and a paired Student's t-test was performed on the data using the PROC TTEST procedure in SAS after log transformation (ln[x +1]). When reporting the statistics, the 'pooled' data were used. The means and SEs of the variables were calculated using the PROC MEANS procedure in SAS.

Results

Billbug Species

From mid-February 2018 to mid-December 2019, 3,320 adult billbugs were collected from five different sod fields in central Georgia using linear pitfall traps. Four different species of billbugs were captured: the hunting billbug, *S. venatus vestitus*; nutgrass billbug, *Sphenophorus cariosus* Olivier; uneven billbug, *Sphenophorus inaequalis* Say; and vegetable weevil, *Listroderes difficilis* Germain. *Sphenophorus venatus vestitus* accounted for 98.3% of the total adult captures for 2 yr, whereas 1.3% of the total captures were *S. cariosis*. Similarly, *S. inaequalis* and *L. difficilis* accounted for 0.3 and 0.1% of the total adult captures, respectively.

Overall Seasonal Abundance of Billbugs and the Influence of Turfgrass Phenology

A total of 2,695 adult billbugs were captured in 2018, whereas 625 adults were captured in 2019. In 2018, billbugs were significantly more abundant in most sampling dates in the early part of the year, from mid-February to late May, than in October and November (F = 6.4; df = 42, 168; P < 0.001; Fig. 2A). More than 86% of the total billbugs captured in 2018 were collected from mid-February to late June. However, the number of billbugs captured during the mid-season period (June to September) was not significantly different from the number of billbugs captured during the early season period (mid-February to late May). When the total number of billbugs captured in 2018 and 2019 were combined, only approximately 19% of the billbugs were captured in 2019. In 2019, the number of billbugs captured was significantly greater on a few sampling dates, especially during late February, late March, late September, and early October, than during the rest of the sampling period (F = 2.3; df = 45, 185; P < 0.001; Fig. 2B).

When the traps from all the sites were analyzed by turfgrass phenology and season, the number of billbugs captured was significantly greater in fully grown turfgrass than in early- or late-growth-stage turfgrass (F = 9.2; df = 2, 81; P < 0.001; Fig. 3). The number of billbugs captured was not significantly different by season, i.e., spring, summer and fall (F = 2.5; df = 2, 81; P = 0.092). Similarly, the interaction effects between turfgrass phenology and season were not significantly different (F = 0.1; df = 4, 81; P = 0.991).

Site-by-Site Assessment of Billbug Captures Relative to Turfgrass Phenology

To understand the seasonal incidence and abundance pattern of billbugs at the individual site level, billbug captures were assessed in relation to the turfgrass growth stages at each site. At site 1, only fully grown and late-growth-stage turfgrass was present during 2018 and 2019. The number of billbugs captured per trap was not significantly different between the fully grown and late-growth-stage grasses (F = 5.4; df = 1, 7; P = 0.053; Fig. 4A). In 2018, the number of billbugs captured in the traps gradually decreased throughout the season until late fall, when the turfgrass was ready to harvest (Fig. 5A). In 2019, the number of billbugs captured was low during the spring when the turfgrass was in the harvesting phase (Fig. 5A).

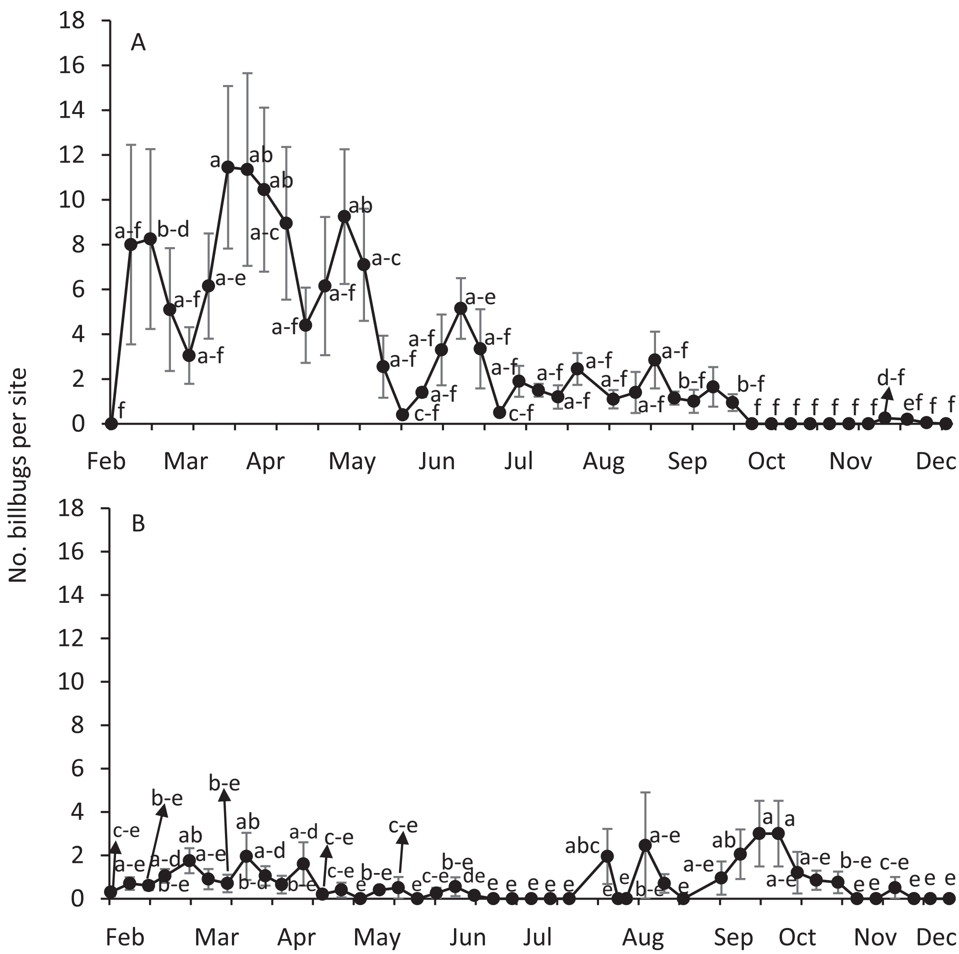

Fig. 2. Mean (±SE) (A) number of *Sphenophorus* spp. captured from February to December in the linear pitfall traps in (A) 2018 and (B) 2019. The average billbugs captured across the sampling dates with the same letters are not significantly different (Tukey's HSD test, $P < 0.05$).

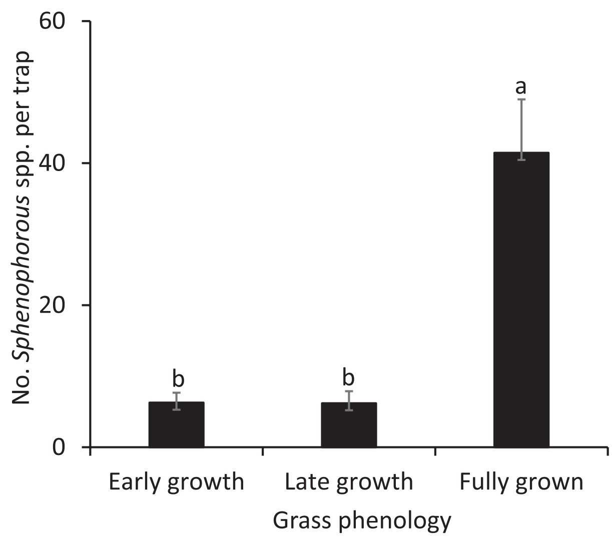

Fig. 3. Mean (±SE) number of *Sphenophorus* spp. captured per trap by turfgrass development stages when all the traps at all the sites were combined. The bars with the same letters are not significantly different (Tukey's HSD test, $P < 0.05$).

On the new, adjacent site with fully grown turfgrass, the number of billbugs captured increased in August and September. At site 2, there was no significant difference in the number of billbugs captured between the fully grown and early-growth-stage turfgrasses ($F = 3.7$; df = 1, 4; $P = 0.128$; Fig. 4B). The turfgrass was fully grown and ready to harvest, and it was not harvested until September 2019 (Fig. 5B). Captures of billbugs spiked in spring 2018, and thereafter, the number of billbug captures remained low (Fig. 5B). At site 3, there was not a significant difference between the fully grown, early-growth-stage and late-growth-stage turfgrasses ($F = 5.4$; df = 2, 6; $P = 0.654$; Fig. 4C). The number of billbugs collected from this site was generally low, with some spikes in captures during June and October (Fig. 5C). At site 4, the number of billbugs captured was significantly greater in fully grown turfgrass than in early- or late-growth-stage turfgrass ($F = 10.1$; df = 2, 6; $P = 0.012$; Fig. 4D). Billbug captures were relatively high during spring and summer of 2018 and fall of 2019 (Fig. 5D). When sites 5 and 6 were combined, the number of billbugs collected was significantly greater in the fully grown turfgrass than in the early-growth-stage turfgrass ($F = 22.4$; df = 1, 9; $P = 0.001$; Fig. 4E). The largest number of billbugs were captured on fully grown turfgrass in spring of 2018 (Fig. 5E).

Effect of Grass Genotype and Gender

A significantly higher number of billbugs was collected in the traps in *Z. matrella* ('Zeon') and the hybrid 'Emerald' than in the *Z. japonica* cultivars 'El Toro' and 'Zenith' ($F = 32.7$; df = 2, 6; $P = 0.002$; Fig. 6). There was no significant difference between the number of male and female billbugs collected from any site (site 1: $t = -0.4$,

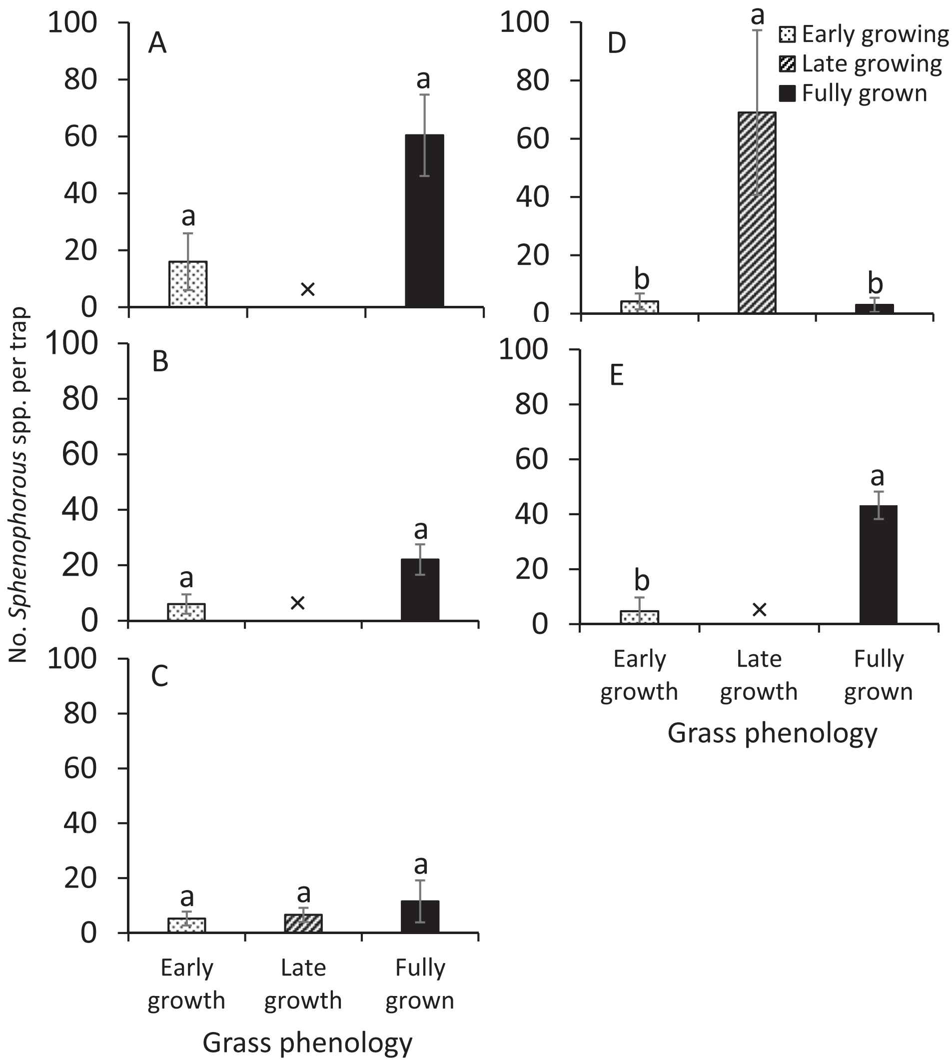

Fig. 4. Mean (±SE) number of *Sphenophorus* spp. captured per trap by turfgrass development stage at (A) sites 1 and 1a, (B) site 2, (C) site 3, (D) site 4, and (E) sites 5 and 6. The symbol '×' indicates that a specific turfgrass stage was not present. The bars with the same letters are not significantly different (pairwise *t*-test, $P < 0.05$).

df = 6, P = 0.672; site 2: t = 0.1, df = 6, P = 0.909; site 3: t = −0.1, df = 6, P = 0.990; site 4: t = −0.7, df = 6, P = 0.537; site 5: t = −0.3, df = 6, P = 0.804; Fig. 7).

Discussion

The results show that the hunting billbug, *S. venatus vestitus*, is the most common billbug species collected from sod farms in Georgia. This result is consistent with billbug captures in the Carolinas (Johnson-Cicalese et al. 1990, Doskocil and Brandenburg 2012) and Florida (Huang and Buss 2009), where *S. venatus vestitus* was also the most abundant species in warm-season turfgrass. Other minor species captured in the current study include *S. inaequalis* and *S. cariosis*, which were also found on golf courses in Florida and South Carolina (Huang and Buss 2009, Chong 2015), although *S. cariosis* was not reported from golf courses in North Carolina (Doskocil and Brandenburg 2012). However, other *Sphenophorus* spp. such as the bluegrass billbug, *Sphenophorus parvulus* Gyllenhal, and *Sphenophorus minimus* Hart found on golf courses in Florida and the Carolinas were not found on sod farms in Georgia (Huang and Buss 2009, Doskocil and Brandenburg 2012, Chong 2015). Billbugs such as *Sphenophorus apicalis* (LeConte), *Sphenophorus deficiens* Chittenden, *Sphenophorus cubensis* Buchanan, *Sphenophorus necydaloides* Dunedin, and *Sphenophorus pontederiae* Chittenden found in Florida (Huang and Buss 2009); *Sphenophorus rectus* Say and *Sphenophorus callosus* Olivier found in North Carolina (Doskocil and Brandenburg 2012); and *Sphenophorus coesifrons* Gyllenhal found in South Carolina (Chong 2015) were not found on sod farms in Georgia in the current study. Few vegetable weevils, *L. difficilis* were collected from sod farms in central Georgia; previous studies did not find this species on golf courses in neighboring states.

The data show that billbugs were abundant in sod farms when the turfgrass was fully grown or ready to harvest. Unlike in golf courses or residential or public lawns, turfgrass in sod farms is continuously grown, cut, and sold throughout the year. Within a sod farm, sod producers maintain turfgrass at various stages in several fields so that they can meet the demand year round. Hunting billbugs undergo two generations per year in North Carolina (Doskocil and Brandenburg 2012) and up to six generations per year in Florida (Huang and Buss 2009). The number of hunting billbug generations in Georgia can vary between two and six, as sod is produced in approximately 61 counties across the state. This also suggests that the longer the turfgrass stays in the ground, the more vulnerable

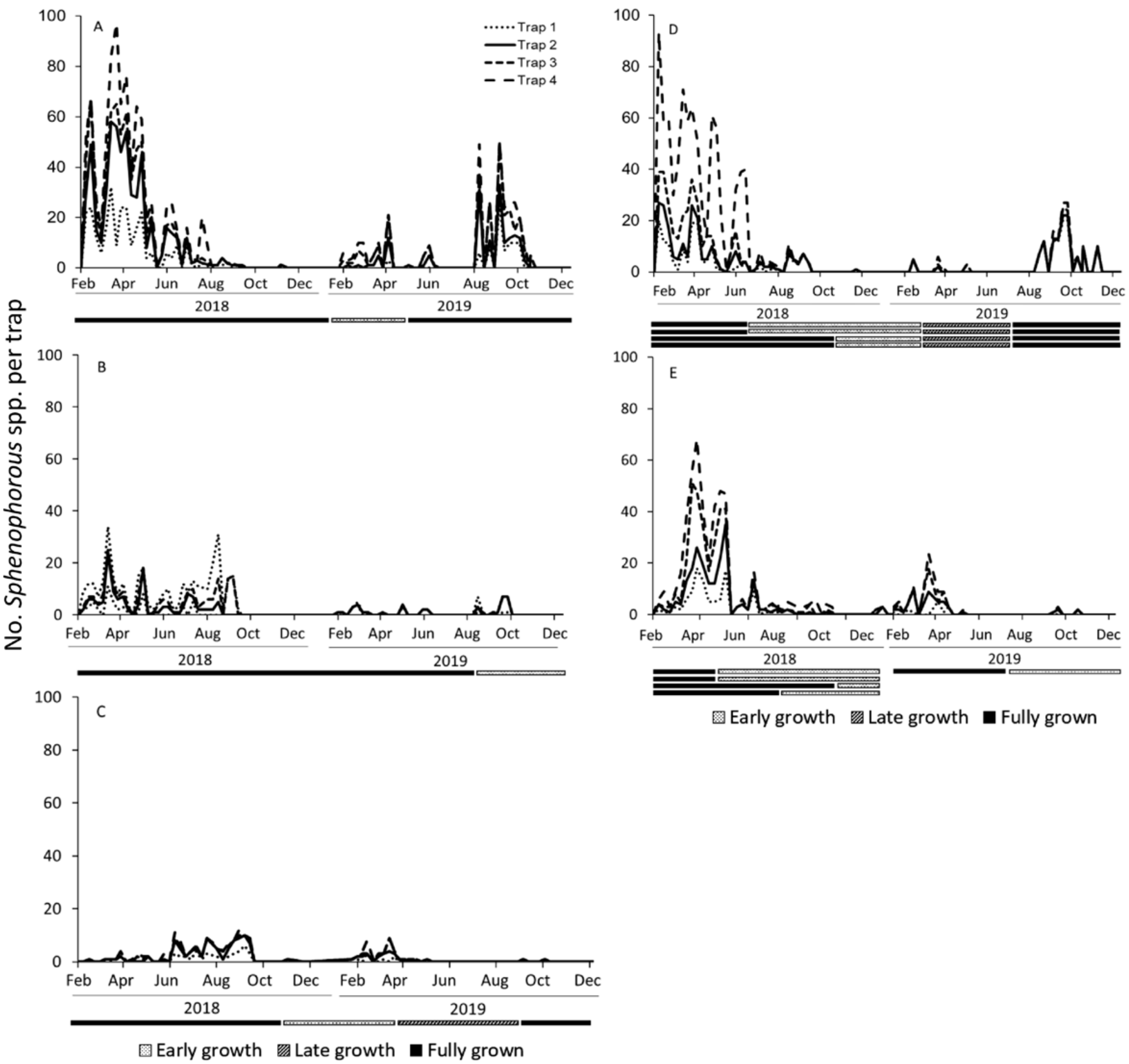

Fig. 5. The number of *Sphenophorus* spp. captured per trap stage from February to December in 2018 and 2019 at (A) sites 1 and 1a, (B) site 2, (C) site 3, (D) site 4, and (E) sites 5 and 6. The horizontal bars with various patterns represent the grass phenology status corresponding to the sampling dates. A single horizontal bar represents a single grass phenology status around all four traps, and four stacked horizontal bars represent the different grass phenology stages around four traps, from 1 to 4.

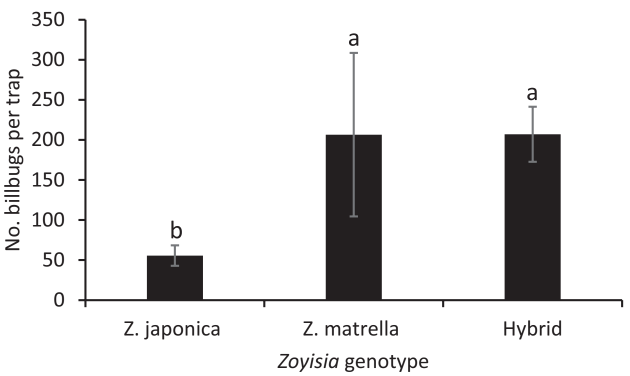

Fig. 6. Mean (±SE) number of *Sphenophorus* spp. captured by turfgrass genotype. The bars with the same letters are not significantly different (Tukey's HSD test, $P < 0.05$).

it is to the constant influx and colonization of billbugs, resulting in a high population buildup. Although billbugs are found on both zoysiagrass and bermudagrass, zoysiagrass is slow growing and takes approximately 6 more months to be ready for harvest in central Georgia. This longer time frame not only exposes zoysiagrass to within-field accumulation and invasion of several overlapping generations of billbugs but also magnifies the damage potential of billbugs to zoysiagrass because this species does not recover well once damaged by adult and larval billbugs. This was evident in the data, as the number of billbugs captured was higher in the fully grown turfgrass than in grass in the early or late developmental stages.

Understanding synchronous billbug voltinism can help determine the incidence of the most vulnerable life stage. In turn, this helps determine the insecticide types, such as contact or systemic, and the number and timing of applications needed as part of IPM methods. Degree-day models have been used to predict the synchronous

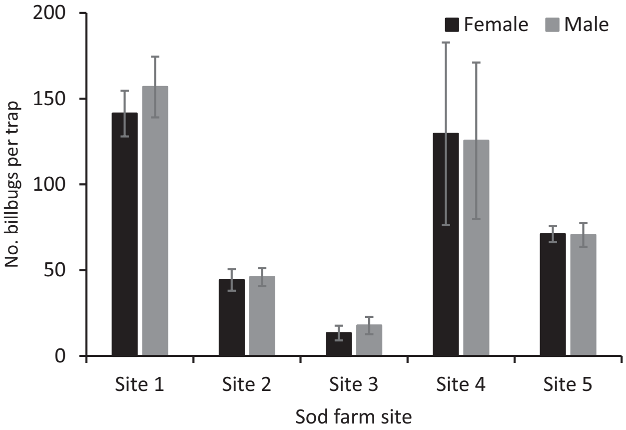

Fig. 7. Mean (±SE) numbers of male and female *Sphenophorus* spp. captured by site from February to June 2018. The bars (paired by site) without symbols are not significantly different at $\alpha = 0.05$ (Student's *t*-test).

emergence of adult billbugs (Dupuy et al. 2017, Duffy et al. 2018) for the best use of control measures, such as insecticides. Based on the data from the current study, it is not clear how useful degree-day models are for predicting the emergence of adult billbugs for management decisions, as billbug populations vary by turfgrass growth stage. Thus, this approach may not be generally useful for determining billbug emergence in sod farms unless fully grown sod is maintained for a long time period and grown through the winter months into the spring months in the following year or beyond. At a given time, turfgrass can be found at various stages in a sod field. The key strategy in any pest management approach is to tackle the pest before the population size grows beyond a certain threshold. If this holds true for billbug management in sod farms in Georgia, it is critical that management is administered when turfgrass is still growing. More studies are warranted to determine the best insecticide application timing, as the data from the current study suggest that the size of the billbug population could be influenced by the time of the previous sod harvest and indicate the length of time that exposes sods to multiple overlapping generations of billbugs.

We resorted to sampling adult billbug populations rather than billbug larvae, although developing larval stages are more destructive and cause more economic damage than adults (Doskocil and Brandenburg 2012). It is challenging to determine the phenology of billbugs by sampling larvae. There are potential overlapping generations during the growing seasons, and early larval stages develop inside stems, while the later stages develop in the soil while consuming roots (Huang and Buss 2009). Moreover, the distribution pattern of billbugs on zoysiagrass is still not known, although this information could help determine how many samples are required from an area as well as the optimal spatiotemporal sampling plan. Lack of specific biological data on larval behavior and infestation pattern in the soil, it is difficult to determine a reliable sampling plan to determine larval phenology. The current sampling method (using cup cutters) is very time consuming and laborious (Doskocil and Brandenburg 2012) and is less likely to yield reliable data for determining billbug phenology in sod farms.

Billbug density was greater on the *Z. matrella* cultivar 'Zeon' and hybrid 'Emerald' than on the *Z. japonica* cultivars 'El Toro' and 'Zenith'. Previous studies show that zoysiagrass cultivars such as 'Emerald', 'Royal', 'Zeon', and 'Zorro' are resistant to the hunting billbug, whereas 'Zenith' and 'El Toro' are susceptible to this pest (Reinert and Engelke 2001, Huang et al. 2014). The exact reason for this is not clear. Previous data also showed that *Z. matrella* cultivars were less susceptible to hunting billbug damage than are *Z. japonica* cultivars (Reinert and Engelke 2001, Reinert et al. 2011, Huang et al. 2014). In the current study, the sex ratio of male to female hunting billbugs from all five sod farm sites was approximately the same, which was consistent with a previous study (Huang and Buss 2009).

In summary, the results show that *S. venatus vestitus* is the dominant billbug species in Georgian sod farms. Other minor species of billbugs found in the traps included *S. inaequalis* and *S. cariosis*. The data showed that billbugs were abundant when the turfgrass was fully grown or ready to harvest. This suggests that the management of billbugs in sod farms should not be based on billbug phenology data described from golf courses in neighboring southern states (where sequential spikes of billbug abundance were observed), which are used to time insecticide application for specific life stages of billbugs. The data suggest that a field-by-field management strategy needs to be developed to reduce population surges in slow-growing zoysiagrass. More studies are necessary to understand the risk of incidence and abundance of billbugs in a given sod field; factors such as when turfgrass was previously harvested, the turfgrass growth stage and the temporal exposure windows to billbug populations within and adjacent to turfgrass fields in sod farms should be studied. Clearly, current IPM plans, including the use of insecticides, timing of applications, stage of the turfgrass, and time of the harvest, need to be revisited to improve billbug control in sod farms.

Acknowledgments

We thank C. Julian for assistance in the construction and deployment of linear pitfall traps and the regular maintenance of those traps at the grower sites in Fort Valley, Marshallville, and Whitesburg, GA. We appreciate M. Hayden, L. Pool, A. Monterrosa, and D. Westburry for billbug sample collection. We thanks C. Waltz for site selection and sod producers for providing sites for the study. We also thank E. R. Hoebeke at the Natural History Museum of the University of Georgia, Athens, GA, for help with the identification of a few representative samples and the Hatch Project for funding this project.

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