UNDERSTANDING THE ABUNDANCE OF BENEFICIAL ARTHROPODS TO REFINE INTEGRATED PEST MANAGEMENT IN TURFGRASS

by

MAHESH GHIMIRE

(Under the Direction of Shimat V. Joseph)

ABSTRACT

Understanding the abundance of beneficial arthropods is important to refine integrated management for pests, such as billbugs, *Sphenophorus* spp. (Coleoptera: Curculionidae) in turfgrass. Two studies were conducted to determine the effects of (1) turfgrass growth cover (0, 50, 100%) and (2) seven commonly used insecticides on the abundance of beneficial arthropods in turfgrass. In the first study, the numbers of carabids, staphylinids, parasitic hymenopterans and Araneae were significantly lower in the 0 or 50% turfgrass cover treatments than in the 100% turfgrass cover treatment. The densities of other hymenopterans and mirids were less abundant in the 100% turfgrass cover treatment than in the 50% cover treatment. In the second study, methoxyfenozide, novaluron, tetraniliprole and chlorantraniliprole were less disruptive to beneficial arthropods, such as carabids, staphylinids, mirids, geocorids, formicids, parasitic hymenopterans and spiders. However, bifenthrin, imidacloprid and acephate + imidacloprid were disruptive to beneficial arthropods in turfgrass.

INDEX WORDS: *Sphenophorus venatus vestitus*, sod farms, zoysiagrass, bermudagrass, pitfall traps, insecticides, beneficial arthropods, predators, parasitoids herbivores, detritivores, integrated pest management

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

The general public use “sod”, “sward” and “turf” interchangeably to refer to turfgrass (Beard 1972). The word “turf” originated from the Sanskrit word “darbha” meaning clump of grass. Turf means vegetative covering that is mowed to give a uniform look and has the upper layer of soil consisting of roots and stems. Sod is a patch of turfgrass with the soil clinging to its roots and used as vegetative propagules for landscaping. The surface of a turf consisting of one or more grass species is referred to as a sward. The trimmed ground covered with fine textured grass is known as a lawn (Beard 1972).

Among 7,500 species (Vittum 2020) of grasses (Poaceae), ~40 species of them are grown as turfgrass. Approximately, 10 grass species are used for turfgrass in the southern USA. The ability of grass to survive under frequent mowing operations is the most notable characteristic that differentiates a turfgrass from other grass species (Duble 2001).

Turfgrass consists of single or multiple species of grasses. Turfgrass is used for various purposes, such as recreational surfaces or just to add aesthetic value. Regardless of where it is used, the six most basic qualities of turfgrass are density, texture, growth habit, smoothness, color, and uniformity (Beard 1972). Climatic conditions determine the type or species of turfgrass that can grow. Cool-season turfgrasses, such as Kentucky bluegrass (*Poa pratensis* L.), tall fescue (*Festuca arundinacea* Schreb), and perennial ryegrass (*Lolium perenne* L.) perform best at 16-24 °C whereas warm-season turfgrasses, such as bermudagrass

(*Cynodon dactylon* [L.] Pers.), zoysiagrass (*Zoysia* spp.) and centipedegrass (*Eremochloa ophiuroides* [Munro.] Hack.) perform well at ~27 °C (Potter 1998).

Turfgrass provides many functional, recreational and aesthetic benefits to humanity and the environment (Beard and Green 1994). The functional benefits include soil erosion control, dust stabilization, improved water recharge and quality of groundwater, biodegradation of synthetic chemical compounds, and the reduction of noise, glare, and visual pollution. Among recreational benefits, turfgrass provides a quality surface for sports activities at a low cost and protects players from getting injured from a fall. As part of aesthetic benefits, turfgrass enhances the value of the landscape and makes it more appealing to people (Beard and Green 1994). Turfgrass contributes to improving the physical and mental well-being of people in urban areas (Duble 2001). Beside this, the turfgrass industry contributes economically to both state and federal governments.

Turfgrass is common in urban and suburban landscapes, such as residential, commercial, and public landscapes in the USA (Jenkins 2015). It is the largest irrigated crop and covers 1.9% of the total surface of the continental USA (Milesi et al. 2005). Maintaining a healthy and attractive turfgrass requires constant care and attention. Regular irrigation, frequent mowing, and timely fertilization, and other management practices, are often necessary to maintain good turfgrass in various landscapes. Turfgrass also creates a favorable environment for many arthropods, including pests (Held and Potter 2012). Turfgrass is grown and maintained for many purposes, such as residential and public lawns, golf courses and athletic grounds. They are commercially produced in sod farms and sold to meet the needs of various sites. Sod is produced in 13,7411 ha and on 1,465 farms throughout the USA. The sod is valued at $1.148 billion USD (USDA NASS 2019). In Georgia, 11,285 ha are planted with sod and the farm gate value is $125.9 million USD (Stubbs 2020). In Georgia, the turfgrass industry contributes $7.8 billion USD to the state's economy (Kane and Wolfe 2012).

Key pests in sod farms

There are many pests that infest turfgrasses. Among them, mole crickets (Orthoptera: Gryllotalpidae), white grubs (Coleoptera: Scarabaeidae), and billbugs (Coleoptera: Curculionidae) feed on roots of the turfgrass (Potter and Braman 1991, Vittum 2020). Sod webworms (Lepidoptera: Crambidae), cutworms and armyworms (Lepidoptera: Noctuidae) feed on leaves and stems. Southern chinch bugs (Hemiptera: Blissidae), spittlebugs (Hemiptera: Cercopidae), and mites (Arachnida: Acari) are the fluid feeders (Potter and Braman 1991, Held and Potter 2012). Because billbugs and fall armyworm, *Spodoptera frugiperda* J.E. Smith (Lepidoptera: Noctuidae) are persistent pests in sod farms (Gireesh and Joseph 2020, 2022), the biology of these pests are briefly discussed.

Billbugs

Billbugs (*Sphenophorus* spp.) (Coleoptera: Curculionidae) are an important turfgrass pest complex throughout the USA (Johnson-Cicalese et al. 1990, Dupuy and Ramirez 2016). About 10 species of billbugs in the genus *Sphenophorus* are the pest of turfgrass in the USA (Held and Potter 2012, Dupuy and Ramirez 2016, Vittum 2020). Among them, the bluegrass billbug, *Sphenophorus parvulus* Gyllenhal infests cool-season turfgrasses, and the hunting billbug, *Sphenophorus venatus vestitus* Chittenden infests warm-season turfgrasses (Potter and Braman 1991, Potter 1998, Dupuy and Ramirez 2016).

Hunting billbugs infest on zoysiagrass and hybrid bermudagrass in the USA and Hawaii. Billbugs are also observed on centipedegrass (*Eremochloa ophiuroides* [Munro.] Hack.), bahiagrass (*Paspalum notatum* Flugge.), and St. Augustinegrass (*Stenotaphrum* *secundatum* [Walt.] Kutze) (Potter 1998). Similarly, the bluegrass billbug is the most common pest on Kentucky bluegrass (*Poa pratensis* L.), perennial ryegrass (*Lolium perenne* L.) and sometimes on tall fescues (*Festuca arundinacea* Schreb.) (Potter 1998) in the USA and southern Canada. Billbug infestation increases from late June to early August, especially when grasses are under high moisture stress (Potter 1998).

Adult billbugs oviposit inside the turfgrass stem. Most species overwinter as adults, whereas others overwinter as late instar larvae (Dupuy and Ramirez 2016). Larvae are the most destructive stage of billbugs (Potter 1998). Larvae cause damage by making tunnels in stem and feeding on the crown, roots and stems. Billbug damage on turfgrass resemble drought stress and diseases, such as dollar spot (*Clarireedia* spp.) symptoms (Potter 1998).

In the spring, adult billbugs emerge from the overwintering sites (Dupuy and Ramirez 2016). They mate and females oviposit 1-3 eggs into the grass stems. They make an opening for oviposition by munching the stem near the crown region (Webster 1892, Satterthwait 1931). The eggs are creamy white, smooth, glossy, oblong-shaped and 1-2 mm long (Kindler and Spomer 1986). Eggs hatch in 6-10 d (Johnson-Cicalese et al. 1990). First instars remain inside the stem, and they feed on the internal tissue of the turfgrass stem. As they molt into second instars, their size increases, and they do not fit inside the stem. They emerge as they eat their way out of the stem, enter into the soil and the later instars feed on the roots and crowns of turfgrass (Johnson-Cicalese et al. 1990, Vittum 2020). They molt through five instars before pupation. The larval stages take 35-55 d to complete for bluegrass billbugs, whereas 21-35 d for hunting billbugs (Watschke et al. 2013). The larvae are creamy, and robust with the tapered abdomen and have a yellowish-brown to reddish-brown head capsule (Dupuy and Ramirez 2016). In the early phases of pupation, the pupa appears as a cream-colored and then undergoes sclerotization to become dark to reddish-brown color during the later phases of pupation (Brandenburg and Villani 1995). The bluegrass and hunting billbug take 8-12 d and 3-7 d to emerge to adults, respectively (Johnson-Cicalese et al. 1990, Watschke et al. 2013).

The billbugs infestation can cause severe losses to sod farms, golf courses, residential, commercial and public lawns (Dupuy and Ramirez 2016). Hunting billbug is the most common and serious pest infesting the turfgrass particularly zoysiagrass cultivars in the sod farms in Georgia (Gireesh and Joseph 2020). Adults billbugs were observed on all stages of zoysiagrass green cover (Gireesh and Joseph 2020). Similarly, adult hunting billbugs movement in and out of harvested and nonharvested sides of sod fields have been reported (Gireesh and Joseph 2021).

Fall armyworm

The fall armyworm, *Spodoptera frugiperda* (Smith, 1797) (Lepidoptera: Noctuidae) is a serious polyphagous pest of turfgrass. It is native to the western hemisphere from southern North America to Argentina in South America. It continuously develops in tropical regions of the USA, such as southern Florida and southern Texas (Luginbill 1928).

The fall armyworm adults are nocturnal and are often found near host plants that provides food and oviposition and mating substrates (Sparks 1979). During the night time, virgin females mate with males that quickly respond to sex pheromones as mating calls produced by females. In turfgrass, females oviposit on man-made structures near turfgrass, such as barns, patios, fences, houses, trees, irrigation systems, etc. Females oviposit eggs in masses ranging from 50-200 eggs each and cover them with white fussy scales. The eggs hatch in 2-3 d at 21- 27 ˚C. The larvae undergo six instars before they turn into pupae in soil. The adult moths emerge from those pupae in 8-30 d. In the summer of the southeastern USA and the Gulf coast states, including Georgia, the fall armyworm completes from egg to adult in four weeks (Sparks 1979).

The larvae of fall armyworms prefer grasses (Poaceae), including corn, sorghum, bermudagrass, etc (Luginbill 1928). About 353 plant species in 76 plant families are infested. The members from families, mostly Poaceae, Asteraceae and Fabaceae, have been recorded as larval hosts of fall armyworms (Montezano et al. 2018). Two important strains of fall armyworm have been reported based on their association with the hosts. They are"corn-strain", having a host preference for large grasses, such as corn, *Zea mays* L., and sorghum, *Sorghum bicolor* (L.) Moench, and "rice-strain", having a host preference for smaller grasses, such as rice, *Oryza sativa* L., and bermudagrass (Nagoshi and Meagher 2008). Depending upon the host strains, fall armyworm shows variation in development and physiology (Whiteford et al. 1988) and host preferences (Juárez et al. 2012).

Beneficial arthropods in turfgrass system

Numerous groups of arthropods and microorganisms dwell in turfgrass (Potter et al. 1985, Potter and Braman 1991). Many studies have reported a diverse group of arthropods, including beneficial arthropods, such as predators (Braman et al. 2002, 2003, Joseph and Braman 2012), parasitoids (Braman et al. 2004, Joseph and Braman 2011) and pollinators (Del Toro and Ribbons 2020, Joseph et al. 2020). Other arthropods were also reported, such as herbivores (Potter and Braman 1991, Eickhoff et al. 2006, Nair et al. 2021) and detritivores (Joseph and Braman 2009a). Previously, the seasonal abundance of arthropods has been documented, such as collembollens (Rochefort et al. 2006a), billbugs (Gireesh and Joseph 2020) and carabids (Rochefort et al. 2006b) in various turfgrass systems. Arthropods belonging to various taxa, such as Anthocoridae, Geocoridae, Miridae, Blissidae, Cicadellidae, Delphacidae, Aphididae, Cercopidae, Diptera, Formicidae, Collembola, etc. inhabit residential warm-season turfgrass (Joseph and Braman 2009a) and their abundance and diversity were affected by the turfgrass genotype and turfgrass height and density. Similarly, various taxa of hymenopteran wasps were also reported from residential turfgrass, such as Mymaridae, Platygastridae, Scelionidae, Braconidae, Trichogrammatidae, Chalcididae, Brachonidae, etc. (Joseph and Braman 2011). These parasitic wasps can play an important role in pest management; thus, it is important to conserve them. Insect predators also contribute to managing pest species, particularly Carabidae, which were collected from turfgrass (Khan and Joseph 2021).

Parasitic wasps can play an important role in managing key pests in turfgrass. A braconid wasp, *Aleiodes laphygmae* Viereck reduced survival of fall armyworm larvae when larvae were infested on warm-season turfgrass, seashore paspalum (*Paspalum vaginatum* Swartz) (Braman et al. 2004). *Cotesia marginiventris* Cresson and *Meteorus sp.* (both Hymenoptera: Braconidae) were recovered from larvae of fall armyworm infesting turfgrasses (Braman et al. 2004). Similarly, predatory heteropterans, such as *Geocoris puncitpes* (Say), *G. uliginosus* (Say) (both Hemiptera: Geocoridae), and *Orius insidiosus* (Say) (Hemiptera: Anthocoridae) have been found to reduce densities of fall armyworm larvae in seashore paspalum and bermudagrass (Braman et al. 2003). This suggests that natural enemies can be utilized to manage fall armyworms in susceptible turfgrass genotypes (Joseph and Braman 2009b). Generalist predators, such as ground beetles (Coleoptera: Carabidae) and spiders (Araneae: Lycosidae) play an important role in the predation of billbug larvae (Dupuy and Ramirez 2019). Presence of predators affect the activity of billbugs, such as mating and movement behaviors (Dupuy and Ramirez 2019).

Diverse groups of ground beetles have been reported from turfgrass. These ground beetles feed mostly on insects, such as lepidopteran pests. Some others, such as *Harpalus* spp. and *Amara* spp. consume weed seeds (Kromp 1999). Blubaugh et al. (2011) showed that greater densities of ground beetle, *Cyclotrachelus sodalis* LeConte (Coleoptera: Carabidae) were collected from the turfgrass system. *Amara impuncticollis* (Say) and staphylinid, *Philonthus* spp. Actively consume all larval stages of black cutworm, *Agrotis ipsilon* (Hufnagel) (Lepidoptera: Noctuidae) on golf courses (Frank and Shrewsbury 2004). Incidence of predation by indigenous ants, *Lasius neoniger* Emer, *Formica pallidifulva nitiventris* Emery, *F. subsericea* Say (Hymenoptera: Formicidae) on eggs and larvae of *A. ipsilon*, and eggs of Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae) were observed on golf courses and lawns (López and Potter 2000) These studies suggest that beneficial arthropods can be utilized to manage key pests in turfgrass. Additionally, many ground beetles and rove beetles effectively consumed eggs and grubs of *Ataenius spretulus* (Haldeman) (Coleoptera: Scarabaeidae) on golf courses (Jo and Smitley 2003).

Use of insecticides on turfgrass

In the USA, pest management in turfgrass mostly involves using insecticides with a long residual activity (Blaine et al. 2012, Held and Potter 2012). Insecticides in various classes are used to manage pests in turfgrass (IRAC 2023). Many of them are reported to have negative effects on natural enemies. Substantial reduction in ant numbers and whitegrubs egg predation was observed when isofenphos and diazinon were sprayed during the growing season in turfgrass (Zenger and Gibb 2001). Chlorpyrifos reduced predation on sod webworms, *Crambus* spp. And *Pediasia* spp. (Lepidoptera: Crambidae) eggs for at least three weeks after exposure to Kentucky bluegrass (Cockfield and Potter 1984). Similarly, chlorpyrifos and isofenphos reduced the activity of predators, such as mites, spiders and rove beetles, for up to six weeks after application (Cockfield and Potter 1983). Another study showed that neonicotinoid, a combination of a neonicotinoid and a pyrethroid, and anthranilic diamide had negative effects on *Harpalus pennsylvanicus* DeGeer (Coleoptera: Carabidae), *Tiphia vernalis* Rohwer (Hymenoptera: Tiphiidae), *Copidosoma bakeri* Howard (Hymenoptera: Encyrtidae), and *Bombus impatiens* Cresson (Hymenoptera: Apidae) (Larson et al. 2014). These studies suggest that more studies are warranted to determine the effects of commonly used insecticides in turfgrass on nontarget pests. Clay models mimicking caterpillar larvae were used to study predatory activity in turfgrass (Khan and Joseph 2021). More impressions were observed on clay models when deployed in residential lawns than in sod farms (Khan and Joseph 2022). Clearly, these studies show that predators can play a major role in pest management in turfgrass systems.

Pitfall trap

Pitfall trap was first developed by Hertz (1927) and used by Barber (1931) to capture cave dwelling insects. Pitfall traps are considered one of the most popular, versatile, and widely used sampling techniques for epigeal invertebrates in various habitats (Woodcock 2005). Pitfall traps was used as a sampling technique in every terrestrial habitat from forests to deserts (Woodcock 2005). Pitfall trap estimates the abundance and activity of individual species in various habitats (Brown and Matthews 2016). Not all invertebrates species on the ground are captured by pitfall traps. Captures of many invertebrates are directly related to their activity (Curtis 1980). The rate of capture of arthropods in pitfall traps is dependent on abundance and activity in the specific habitat (Woodcock 2005). The ground beetles (Coleoptera: Carabidae), rove beetles (Coleoptera: Staphylinidae), ants (Hymenoptera: Formicidae), and ground dwelling spiders (Araneae: Lycosidae) are mostly sampled using pitfall traps (Baars 1979, Woodcock 2005, Skvarla et al. 2014, Montgomery et al. 2021).

Pitfall traps effectively sampled nocturnal arthropods that are missing in other trapping methods (Huusela-Veistola 1996, Skvarla et al. 2014). There are many factors affecting the captures of arthropods by pitfall traps. The color of the pitfall traps, their numbers and deployment strategy, duration of deployment, the diameter of traps (Abensperg-Traun and Steven 1995), and the fluid inside the traps (Skvarla et al. 2014) influence arthropods capture (Woodcock 2005, Brown and Matthews 2016, Hohbein and Conway 2018). Some reports are shown to affect the diversity of arthropods captured (Baars 1979) whereas some others are reported of not having any effects on insect community by the pitfall traps cover use (Buchholz and Hannig 2009). Similarly, surrounding vegetation near pitfall traps also affect the arthropod captures (Melbourne 1999). Due to low cost, easy availability, and good preservative and killing properties ethylene glycol is popularly used as a preservative in pitfall trap than water (Woodcock 2005). Due to the high toxicity of ethylene glycol to birds and mammals, less toxic propylene glycol has also been recommended for use as preservative in pitfall traps (Hall 1991). Digging in effects, which is defined as a temporary increase in the capture rate of pitfall traps due to the physical disturbance during the trap deployment, can also affect the sampling process and to avoid this discarding of the first week pitfall trap's capture after deployment is suggested (Woodcock 2005). Digging-in effects can also be avoided by placing pitfall traps upside down for a week before using them as traps after laying out in the ground (Greenslade 1973, Schirmel et al. 2010, Skvarla et al. 2014). Digging-in effects have been reported for Collembola (Joosse and Kapteijn 1968), ants (Greenslade 1973), carabids (Digweed 1995, Schirmel et al. 2010) and other Coleoptera (Schirmel et al. 2010). One of the reason for digging-in effects is assumed to be increase level of CO_2, that attracts collembolans, followed immediately after disturbing the soil while laying out the pitfall traps (Joosse and Kapteijn 1968). Similarly, species that uses pheromones to locate conspecifics and show aggregation behaviour might lead to more capture in traps as the first individual that get trapped in pitfall traps might lead others of same species to the same traps (Skvarla et al. 2014).

Research objectives

Objective 1: To determine the abundance of beneficial arthropods on turfgrass growing at various stages of development in sod farms.

Billbugs (*Sphenophorus* spp.) (Coleoptera: Curculionidae) are an important turfgrass pest complex throughout the USA (Johnson-Cicalese et al. 1990, Dupuy and Ramirez 2016). Recent research showed that they are active in all stages of sod development (Gireesh and Joseph 2020). Management sprays for billbugs are typically conducted when the sod is fully grown and ready for harvest (Gireesh and Joseph 2020). Diverse groups of arthropods dwell in sod when it is fully grown in sod farms (Singh and Joseph 2022). Management sprays could be administered when the sod is at the early stages of development, but it is unclear whether beneficial arthropods are abundant during that time. If the beneficial arthropods are not abundant during the early stages of sod development, insecticide application at the early stages of sod should do minimal harm to beneficial arthropods. This information could be incorporated into integrated pest management programs in sod farms. Thus, this study aimed to determine the abundance of beneficial arthropods at various stages of turfgrass development in sod farms. The null hypothesis was there is no difference among beneficial arthropods captured from various turfgrass cover in sod farms, whereas the alternative hypothesis is that some beneficial arthropods are captured more in certain pitfall traps for at least one of the turfgrass cover in sod farms.

Objective 2: To determine the nontarget effects of common insecticides on beneficial arthropods in turfgrass.

Many insecticides are used in various turfgrass systems, such as residential, public and commercial lawns, athletic fields, golf courses, and sod farms (UGA Extension 2022). Previous studies showed that some older insecticides could harm beneficial arthropods. Recently, many new insecticides entered the turfgrass market, and managers are using them to manage many insect pests. It is unclear if the commonly used insecticides negatively affect their abundance. Thus, this study aimed to determine the effects of commonly used insecticides on the abundance of beneficial arthropods in turfgrass. The null hypothesis was that there is no difference among beneficial arthropods captured across the various insecticide treatments applied to the plots in turfgrass. The alternative hypothesis is that there is difference among the beneficial arthropods captured for at least one of the insecticide treatments.

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CHAPTER 2

INFLUENCE OF TURFGRASS COVER ON ABUNDANCE OF BENEFICIAL ARTHROPODS IN SOD FARMS

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Abstract

Hunting billbug, *Sphenophorus venatus vestitus* Chittenden (Coleoptera: Curculionidae) is a serious pest in sod farms, which reduces the turf quality due to larval feeding. High densities of billbugs occur at various stages of turfgrass in sod farms. To develop an effective integrated pest management (IPM) strategy for *S. venatus vestitus*, it is critical to understand the relative abundance of beneficial arthropods at various stages of turfgrass growth in sod farms. Therefore, the objective of this study was to determine the abundance of beneficial arthropods under various stages of turfgrass growth in sod farms. In 2021 and 2022, zoysiagrass (*Zoysia* spp.) sod fields with 0%, 50%, and 100% turfgrass cover were selected in sod farms, and arthropod abundance was documented using pitfall traps. The numbers of carabids, staphylinids and parasitic hymenopterans in 2021, and the parasitic hymenopterans in 2022 were significantly lower for the 0 and/or 50% turfgrass cover treatments than for the 100% turfgrass cover treatment. However, captures of dermapterans were significantly lower in the 100% than in the 0% and 50% turfgrass cover treatments in 2021, whereas in the 0% turfgrass cover treatment than for the 50% turfgrass cover treatment in 2022. The densities of other hymenopterans in 2021 and mirids in 2022 were significantly less abundant in the 100% turfgrass cover treatment than in the 50% turfgrass cover treatment. Both years, Araneae numbers were significantly lower in the 0% turfgrass cover treatment than in other treatments. Thus, beneficial arthropods were abundant at all stages of turfgrass cover, but tended to be lower when turfgrass cover was < 100%. The implications of the results on IPM of *S. venatus vestitus* and conservation of beneficial arthropods in sod farms are discussed.

Key words Zoysiagrass, billbugs, *Sphenophorus* spp., ground beetles, pitfall traps

Among 7,500 (Vittum 2020) species of grasses known, approximately 40 species are recognized as major turfgrasses worldwide (Duble 2001). The major characteristics of turfgrass are that it forms a uniform, low-height ground cover and is tolerant to regular mowing and foot traffic (Turgeon 1980, Duble 2001). In the southeastern USA, turfgrass is an important component of urban and suburban landscapes (Beard 1972, Monteiro 2017). Turfgrass provides many ecosystem services (Monteiro 2017), such as cooling effects to the surrounding environment, aiding carbon sequestration, reducing water runoff, improving water infiltration, preventing soil erosion, reducing noise pollution, providing wildlife habitat, and helping to prevent fire outbreaks (Beard 1972, Beard and Green 1994, Monteiro 2017). In addition, turfgrass adds economic, aesthetic, and recreational value to ornamental landscapes (Beard and Green 1994, Monteiro 2017). Turfgrass is commercially produced in sod farms on extensive land areas. In 2017, there were 1,465 sod farms covering 1,37,411.4 ha in the USA, and total sales were valued at $1.15 billion USD (USDA NASS 2019). In Georgia, there were approximately 53 counties growing sod on 10,337.3 ha, with an annual farm gate value of $126 million USD from turfgrass, which is 10.2% of total farm gate value contributed by ornamental horticulture in 2021 (UGA CAED 2022). These suggest that sod production is an important enterprise for economies of USA and Georgia.

On sod farms, many beneficial arthropod taxa, such as predators (Anthocoridae, Geocoridae, Miridae, Araneae, etc.) have been collected (Singh and Joseph 2022) and found actively interacting with fall armyworm, *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae) larvae or larval models (Khan and Joseph 2022). Similarly, predators were reported to play a critical role in reducing pests from other turfgrass systems. *Geocoris uliginosus* (Say) (Hemiptera: Georcoridae) nymphs were effective in reducing *S. frugiperda* larval densities on various turfgrass genotypes (Braman et al. 2003). Predaceous ant, *Pheidole tysoni* Forel (Hymenoptera: Formicidae), and a mite, *Macrocheles* spp. (Mesostigmata: Macrochelidae) effectively consumed eggs of sod webworm, *Crambus* spp., and *Pediasia* spp., (Lepidoptera: Pyralidae) on turfgrass (Cockfield and Potter 1984). *Amara impuncticollis* (Say) (Coleoptera: Carabidae) and *Philonthus* sp. (Coleoptera: Staphylinidae) reduced black cutworm, *Agrotis ipsilon* (Hufnagel) (Lepidoptera: Noctuidae) larvae on golf courses (Frank and Shrewsbury 2004a). Similarly, predaceous beetle, *Tetracha floridensis* (Leng & Mutchler) (Coleoptera: Carabidae) and predatory ant, *Solenopsis invicta* (Hymenoptera: Formicidae), have been found to attack sentinel black cutworm larvae, *A. ipsilon* (Hufnagel) in creeping bentgrass, *Agrostis stolonifera* L. (Hong et al. 2011). In the presence of generalist predators, such as Carabidae, dispersal and reproduction of hunting billbug, *Sphenophorus venatus vestitus* Chittenden (Coleoptera: Curculionidae) were reduced (Dupuy and Ramirez 2019). Similarly, parasitic wasps, such as Mymaridae, Platygastridae, Scelionidae, Braconidae and Trichogrammatidae were collected from turfgrass (Joseph and Braman 2011) and can potentially parasitize arthropods in sod farms. These suggest that predators and parasitoids are integral components of turfgrass systems providing essential management services. Thus, IPM programs should be developed with minimal disruption to these naturally occurring beneficial arthropods on sod farms.

Among turfgrass pests, *S. venatus vestitus* is a serious pest on sod farms (Dupuy and Ramirez 2016), and their densities were high on fully grown sod (Gireesh and Joseph 2020). A similar densities of *S. venatus vestitus* were found on fully grown and recently harvested sod (Gireesh and Joseph 2021). *Sphenophorus venatus vestitus* is managed using insecticides, such as neonicotinoids when high densities of adults were detected on sod farms. A recent study showed that beneficial arthropods were abundant on fully grown sod (Singh and Joseph 2022). One strategy to minimize disruptive effects on beneficial arthropods is schedule management sprays when beneficial arthropods are at the lowest densities. One such window is applying management sprays when the turfgrass is at early growth stages. Because *S. venatus vestitus* adults can colonize on the newly developing sod after sod harvest, it could be an effective strategy to schedule the insecticide applications when *S. venatus vestitus* are at the early growth stages. Before evaluating the effects of insecticide applications at early growth stages on *S. venatus vestitus* adults or larvae, it is important to understand the abundance of beneficial arthropods at the early stages of sod. However, little is known about the relative abundance of beneficial arthropods especially at early growth stages of sod. This information will be valuable to optimize the timing of pest management decisions and can be developed as a risk aversion strategy for beneficial arthropod communities. Therefore, the major objective of this study was to determine the abundance of arthropods, especially beneficials at various growth stages or percentage turfgrass cover of sod after harvest on sod farms.

Materials and Methods

Study sites. In 2021 and 2022, the study was conducted in the sod farms of central Georgia. In 2021, the sod farms in Marshallville and Fort Valley, Georgia were selected and sampled in June and July. In 2022, sod farms in Marshallville, Fort Valley and Whitesburg, Georgia were sampled in July, whereas in September, farms in Marshallville, and Fort Valley were sampled. Entirely different sod fields were selected during each monthfor both years. The sites selected in sod farms also differed between years. The sites were selected based on the availability of suitable sod fields that fits the criteria (indicated in the experimental design section) during the sampling periods. All the selected sites had either 'Zeon' and 'Zenith' zoysiagrass because *S.*

venatus vestitus problem was mostly observed on zoysiagrass (Gireesh and Joseph 2020), although high densities of *S. venatus vestitus* were found on all warm-season turfgrass genotypes (Huang and Buss 2013, Chong 2015, Dupuy and Ramirez 2016). The details of the sites, such as location and cultivar, are listed in Table 2.1. The sites were intensively managed under routine irrigation, herbicide, and fertilizer regime. The fungicides and insecticides were spot applied as needed and were not applied to the entire field. Chlorantraniliprole and fipronil were applied along the edges of the sod fields for *S. frugiperda* and ant management. The edges and those areas of the field with insecticide application were not selected in the study. The sod fields were irrigated at least once in every day using the central pivot system unless rained within 48 h. The sod fields were regularly mowed at least two to three times a week. The nitrogen-based fertilizers were routinely used in the sod farms.

Experimental design. The treatments of this study were the area of grass cover expressed as percentage in selected sod field sites, and they were: (1) 0, (2) 50, and (3) 100% turfgrass cover. The treatments were replicated four times and one set of all three grass cover treatments were within a same sod farm. Thus, the replicates were sod farm sites. The treatments were organized in a randomized complete block design. The percentage turfgrass cover was determined based on the visual inspection. The sod sites for 0% turfgrass cover treatment were bare ground with minimal turfgrass cover. The sod from these sites was harvested within four weeks before start of the study. Some sites had ribbons of zoysiagrass left behind after previous harvest. For 50% grass cover treatment, half of the sod field sites were covered with scattered patches of turfgrass, and the other half was devoid of turfgrass cover with visible bare soil surface. For 100% grass cover treatment, the sod field sites were completely covered with turfgrass with no visible patches of bare ground area. The turfgrass in this treatment was ready for harvesting. The three treatments were about 100 m apart in the sod farm and were included in a block. The area of each site varied from one another (Table 2.1) but met the criteria of percentage turfgrass cover. Each site was at least 74,869.8 m^2.

Sampling. Sampling was conducted twice a year. In 2021, arthropod sampling was conducted in June-July, and August, whereas in 2022, it was conducted in July and September. Arthropod sampling was conducted using pitfall traps and they were deployed in all selected sod field sites. Three 11.6 × 8.9 × 7.6 cm (top diameter × base diameter × height), 473 mL solo plastic cups (Pro-Kal™ Polypropylene Clear Deli Containers, Fabri-Kal Corp, Kalamazoo, MI, USA) were used for pitfall traps. These three solo cups were deployed in the ground after digging three holes using a cup cutter. These three traps were deployed 1 m apart in a triangular pattern at each site. The solo cups were filled with 100 mL of ethylene glycol (NAPA Green Antifreeze and Coolant, Old World Industries, LLC, Northbrook, IL, USA). Ethylene glycol preserves the trapped arthropods and does not evaporate between sampling dates. Pitfall traps were covered with disposable plastic plates, supported by metal wire to prevent direct sunlight. Pitfall traps were emptied and replenished with 100 mL ethylene glycol at 7 d intervals for two weeks. Thus, sampling was conducted for 14 d during June-July and August 2021 and July and September 2022. In 2021, pitfall traps were first deployed on June 17 and July 30. Whereas in 2022, pitfall traps were first deployed on July 8, and later on September 2. The arthropods captured from three pitfall traps deployed at each site were combined. The sampled arthropods from the solo cups of pitfall traps were emptied into plastic bags and transported to the entomology laboratory. The arthropods in bags were sorted, cleaned, and stored in 100 mL of 70% ethanol in plastic cups (PP, SARSTEDT AG and Co. KG, Numbrecht, Germany).

Evaluation. The numbers of arthropods in the samples were identified and quantified to various taxa under stereo microscope at 10× magnification (Nikon SMZ745T, Nikon Corporation, Minato-ku, Tokyo Japan). Dichotomous keys in Johnson and Triplehorn (2004) were used for the identification of the arthropods. The beetle specimens were identified using the guide Beetles of Eastern North America (Evans 2014). All spider specimens were placed under Order Araneae, and all mites were placed under the Sub Class Acari. The tiny parasitic wasps were grouped into "parasitic hymenopterans". Adults and immatures of earwig's specimens were placed under Order Dermaptera. Besides these, the most abundantly encountered insects in the samples were identified to the Family. The beneficial arthropods irrespective of their densities caught were grouped by Family or combined under specific taxon. Those arthropods that were collected in low densities and challenging to identify to Family were placed under "other" category of that particular taxon. For example, "Other Coleoptera" group consisted of Nitidulidae, Ptilidae, Tenebrionidae, Mordellidae, and all other unidentified beetle specimens found in the samples. Similarly, Rhyparocromidae, Coreidae, Cydnidae, Delphacidae and all other unidentified hemipterans were placed under "Other Hemiptera". The nymphs of hemipterans that were not identified to a Family level were also grouped in "Other Hemiptera" group, whereas those that we identified were combined with adults and placed under specific families. The taxon group, "Other Hymenoptera" includes all adults Pompilidae, Scoliidae, Mutilidae, Halictidae, Apidae and other unidentified nonparasitic hymenopterans caught in the pitfall traps. Myriapoda consisted of arthropods belonging to Class Chilopoda and Diplopoda. All the collected arthropods were presented under broader groups, such as predators, herbivores and detritivores based on their ecology and feeding habit.

Statistical analyses. All statistical analyses were performed using Statistical Analysis Software (SAS Institute 2016). The data were log-transformed (ln[x+2]) after checking the normality of residuals using PROC UNIVARIATE procedure in SAS. To determine the effects of turfgrass cover, sampling date, and their interactions for specific densities of arthropod taxa, a two-way analysis of variance (ANOVA) was conducted using the PROC MIXED procedure in SAS. The turfgrass cover and sampling month were the fixed effects and sod field sites were the random effects. Means and standard errors of arthropod taxa by turfgrass cover and sampling month was calculated using the PROC MEANS procedure in SAS. The least square means for turfgrass cover and sampling months were separated by using the Tukey-Kramer ($P < 0.05$) test in SAS. Some families of arthropods were only captured in either one of the experimental years. For example, densities of Heteroceridae and Gryllotalpidae were not captured in 2021, and hence not indicated in tables.

Results

In 2021, a total number of 15,933, 22,252, and 1,27,044 arthropods were collected from 0%, 50%, and 100% turfgrass cover, while in 2022, the numbers were 9,205, 18,831, and 70,487 arthropods collected from turfgrass cover treatments, respectively. A total number of 6,363 and 5,141 beneficial arthropods were collected in 2021 and 2022, respectively. Carabids, staphylinids, coccinellids, lampyrids, mirids, geocorids, phlaeothripids, formicids, hymenopterans, dermapterans and Araneae were the major predatory beneficial arthropod taxa captured in this study. Similarly, curculionids, scarabaeids, chrysomelids, elaterids, silvanids, cicadellids, aphidids, dipterans, acridids, gryllids, lepidopterans, Acari, collembolans, psocopterans, and myriapods were other herbivorous and detritivorous arthropod taxa collected from turfgrass cover treatments in pitfall traps.

Effects of percentage turfgrass cover

Beneficial arthropods

In 2021, among the coleopteran predators, the numbers of carabids and staphylinids collected in pitfall traps were significantly lower for the 0% and 50% turfgrass cover treatments than for the 100% turfgrass cover treatment (Table 2.2; Fig. 2.1A and B). The numbers of other predators, such as coccinellids, and lampyrids were not significantly different among percentage turfgrass cover treatments (Table 2.2; Fig. 2.1C and D). The densities of mirids, geocorids, other predatory heteropterans, phlaeothripids, and formicids were not significantly different among turfgrass covers (Table 2; Fig. 1E-I). A significantly lower number of parasitic hymenopterans was collected for the 0% turfgrass cover treatment than the 50% turfgrass cover treatment followed by the 100% turfgrass cover treatment (Table 2.2; Fig. 2.1J). However, the numbers of other hymenopterans were significantly lower for the 0% and 100% turfgrass cover treatments than for the 50% turfgrass cover treatment (Table 2.2; Fig. 2.1K). A significantly greater number of dermapterans were collected for the 0% and 50% turfgrass cover treatments than for the 100% turfgrass cover treatment in sod farms (Table 2.2; Fig. 2.1L). The numbers of Araneae collected were significantly lower for the 0% turfgrass cover treatment than for the 50% and 100% turfgrass cover treatments (Table 2.2; Fig. 2.1M).

In 2022, turfgrass cover treatments did not significantly affect the numbers of carabids, staphylinids, coccinellids, and lampyrids (Table 2.2; Fig. 2.2A-D). The densities of mirids and geocorids were significantly lower for the 100% turfgrass cover treatment than for the 50% turfgrass cover treatment (Table 2.2; Fig. 2.2E and F). The numbers of mirids were not significantly different between 0% and 50% turfgrass cover treatments, whereas significantly lower numbers of geocorids were collected for the 0% turfgrass cover treatment than 50% and

100% turfgrass cover treatments. There were no significant differences among turfgrass cover treatments for the numbers of other predatory heteropterans, phlaeothripids and formicids (Table 2.2; Figs. 2.2G-I). The densities of parasitic hymenopterans were significantly lower for the 0% turfgrass cover treatment followed by 50% turfgrass cover treatment than for the 100% turfgrass cover treatment (Table 2.2; Fig. 2.2J). There was no significant difference among treatments for densities of other hymenopterans (Table 2.2; Fig. 2.2K). The numbers of dermapterans were significantly lower for the 100% turfgrass cover treatment than for the 50% turfgrass cover treatment (Table 2.2; Fig.2. 2L), whereas for Araneae, significantly lower densities were collected for the 0% turfgrass cover treatment than for the 50% and 100% turfgrass cover treatments (Table 2.2; Fig. 2.2M).

Herbivorous and detritivorous arthropods

In 2021, the numbers of *Sphenophorus* spp. were significantly lower for the 0% and 50% turfgrass cover treatments than for the 100% turfgrass cover treatment (Tables 2.3 and 2.4). The densities of silvanids, anthicids, Acari, and Collembola were significantly lower for the 0% and 50% turfgrass cover treatments than for the 100% turfgrass cover treatment (Tables 2.3 and 2.4). Significantly lower numbers of elaterids, and dipterans were captured in the 0% turfgrass cover treatment than in the 50% and 100% turfgrass cover treatments (Tables 2.3 and 2.4). The numbers of cicadellids were significantly lower for the 100% turfgrass cover treatment than for the 0% and 50% turfgrass cover treatments (Tables 2.3 and 2.4). The adult lepidopterans densities were significantly lower for the 50% turfgrass cover treatment than for the 0% turfgrass cover treatment (Tables 2.3 and 2.4). There were no significant differences among treatments for the remaining arthropod taxa (Tables 2.3 and 2.4).

In 2022, the numbers of *Sphenophorus* spp. were significantly lower for the 0% turfgrass cover treatment than for the 100% turfgrass cover treatment (Tables 2.3 and 2.4). The numbers of silvanid, other coleopterans, and Acari were significantly lower 0% and 50% turfgrass cover treatments than for the 100% turfgrass cover treatment (Tables 2.3 and 2.4). The numbers of elaterids were significantly lower for the 0% turfgrass cover treatment than for the 50% turfgrass cover treatment. A significantly lower number of cicadellids was collected in the 0% and 100% turfgrass cover treatments than in the 50% turfgrass cover treatment (Tables 2.3 and 2.4). The numbers of dipterans were significantly lower for the 0% turfgrass cover treatment than for the 50% and 100% turfgrass cover treatments (Tables 2.3 and 2.4). The number of adult lepidopterans was significantly lower in the 100% turfgrass cover treatment than in the 0% turfgrass cover treatment. For the remaining arthropods, there were no significant differences among treatments.

Effects of sampling time

Beneficial arthropods

In general, majority of the predatory arthropods captured in the pitfall traps were not significantly different between the two sampling periods each year. In 2021, significantly greater numbers of carabids, dermapterans, and Araneae were collected in the August samples than in the June-July samples (Tables 2.2 and 2.5). In 2022, significantly more numbers of parasitic hymenopterans were collected in the September samples than in the June samples (Tables 2.2 and 2.5).

In both years, the interaction between turfgrass cover and sampling time was not significantly different for majority of the arthropod population captured. In 2021, in the June-July sampling, a significantly greater number of Araneae was collected for the 100% turfgrass cover treatment than for the 0%turfgrass cover treatments. In contrast, in the August sample, the Araneae densities were not significantly affected by the turfgrass cover treatments (Table 2.2). In 2022, no significant interaction between turfgrass cover and sampling time treatments was observed.

Herbivorous and detritivorous arthropods

In 2021, the numbers of *Sphenophorus* spp., cicadellids, dipterans, and lepidopteran larvae were significantly greater in the August samples than in the June-July samples (Tables 2.3 and 2.5). However, the densities of aphidids were significantly more abundant in the June-July samples than in the August samples (Tables 2.3 and 2.5). There were no significant differences in sampling time on the densities of other herbivores and detritivores (Tables 2.3 and 2.5). In 2022, the numbers of *Sphenophorus* spp., scarabaeids, thripids, dipterans, Acari and psocopterans were significantly greater in the September samples than in the July samples (Tables 2.3 and 2.5).

In 2021, the interaction between turfgrass cover and sampling time was observed for the numbers of Acari collected (Table 2.3). In contrast, in 2022, the interaction was observed for other hemipterans, thripids, dipterans, and lepidopteran larvae. No significant interaction between turfgrass cover and sampling date treatments was observed for the remaining taxa.

Discussion

The results show that beneficial arthropods, herbivorous and detritivorous were present across the maximum range of turfgrass cover in sod farms. Because *Sphenophorus* spp. adults were active even at 0% turfgrass cover, pest management tactics can be applied at early growth stages of turfgrass in sod farms. At the early stages of turfgrass establishment when soil coverage ranges from 0% to < 100% when the abundance of certian beneficial arthropods was lower relative to later stages of turfgrass cover, applying management tactics during the early stage could be less disruptive to these beneficial arthropods. This strategy may reduce early colonization of *Sphenophorus* spp. population on the developing sod without significantly impacting key beneficial arthropods. The data show that later stages of turfgrass cover have more abundance of beneficial arthropods, and early intervention could reduce the impact on beneficial arthropod communities in sod farms. Occurrence and increased abundance of beneficial arthropods may avoid the need for additional applications of pest management tactics at the fully grown stage of turfgrass. Previously, Dupuy and Ramirez (2019) showed the presence of generalist predators could induce nonconsumptive effects where the growth and development of *Sphenophorus* spp. were altered as the normal mating, oviposition, and dispersal behavior were affected. Thus, the results from the current study can be used to refine pest management strategies by adjusting the application timing, especially at the early stages of establishment of turfgrass in sod farms after the previous harvesting of turfgrass.

For many beneficial arthropods, their occurrence and abundance were not affected by the percentage of turfgrass cover. Some specific examples were phlaeothripids and formicids. This suggests that the abundance of these arthropods is independent of turfgrass growth and development. It is possible that these arthropods do not use turfgrass as a means of refugia on sod farms and may have minimal influence on their abundance. In some cases, the pattern of increase or decrease of arthropods with an increase in turfgrass cover was inconsistent between years. Some specific examples of this pattern were carabids, staphylinids, mirids, and geocorids. Perhaps, the biotic factors, such as the availability of specific prey arthropods (Fok et al. 2014, Snyder 2019) or nonpest arthropods (Robertson et al. 1994, Settle et al. 1996, Symondson et al. 2002, Frank and Shrewsbury 2004a) and abiotic factors, such as moisture (Braman et al. 2000, Frampton et al. 2000, Frank and Shrewsbury 2004b) and temperature (Uhler et al. 2021) variations between those two years might have affected their abundance. In addition, this suggests that factors related to turfgrass cover, such as refugia, do not consistently influence arthropod abundance. Braman et al. (2002) reported the presence of refugia in turfgrass did not influence abundance of most of the beneficial arthropods, including formicids. Availability of refugia also doesn't mean high predation, as they reported disparity in predation rates on *S. frugiperda* eggs and larvae as well as Japanese beetle eggs regardless of the refugia, such as either wildflower mixes or mulches. More research is warranted in sod farms to improve the conservation of beneficial arthropods by exploring alternative options that can be easily incorporated into sod production.

In the current study, the densities of spiders and parasitic hymenopterans increased with an increase in area of turfgrass cover in both years. Joseph and Braman (2011) demonstrated that a diverse community of parasitic hymenopterans, such as mymarids, platygastrids, scelionids, and braconids were abundant in residential turfgrasses. The current and past studies suggest that the dynamics of parasitic hymenopterans and spiders may be related to increased prey densities. For example, females of *Aphhelinus asychis* (Hymenoptera: Aphelinidae) responded by increased oviposition to increasing aphid densities (Bai and Mackauer 1990). However, parasitic hymenopteran consumption of hosts and oviposition rates can vary by varying host densities (Yang et al. 2012). Most of the spider species found in forests and grasslands habitat are important predators of insects and also serve as important sources of food for predators and parasitoids (Nyffeler and Birkhofer 2017). Some hymenopterans are parasites on spider eggs. For example, *Melleus* (Masner and Denis 1996), *Baeus* spp. (Stevens and Austin 2007), *Ceratobaeus* spp. (Austin 1984) (all Hymenoptera: Scelionidae) and *Aprostocetus* spp. (Hymenoptera: Eulophidae) (LaSalle 1994) parasitize spider eggs. In addition, prey consumption increases with the increase in prey populations (Mansour and Heimbach 1993) or varies by host densities (Vucic-Pestic et al. 2010). The activities of parasitic wasps and spiders in sod farms should be effectively enhanced for pest suppression.

In contrast, there were cases where beneficial arthropods were more abundant in the low turfgrass cover than in the 100% turfgrass cover on sod farms. Some specific examples showcasing this pattern in the current study was the abundance of dermapterans. The dermapteran densities decreased with an increase in the percentage of turfgrass cover. The dermapteran might be utilizing the bare ground or limited turfgrass surface habitat for nesting and other predatory activities. This could be because fully covered turfgrass obstruct the movement of predators than bare or early stages of grass cover of sod farm. The frequent management practices, such as pesticide application (Malagnoux et al. 2015) on fully grown turfgrass, can cause increase in dermapterans inhabiting low turfgrass covers with reduced human interventions. Dermapterans are mobile in bare ground and low vegetation fields (Collard et al. 2022). They hide from light under debris during the day (Caussanel 1970) and their pheromones directed aggregation behavior (Sauphanor and Sureau 1993, Walker et al. 1993, Hehar et al. 2008) and tendency to use shelters previously visited by their conspecifics (Sauphanor and Sureau 1993) might have led to high dermapterans capture in pitfall traps.

Most of the arthropods captured from sod farms in the current study were consistent with those collected by Joseph and Braman (2009) and Singh and Joseph (2022) from residential turfgrass and sod farms, respectively. Previous studies collected beneficial arthropods, such as staphylinids, mirids, geocorids, spiders and parasitic hymenopterans from zoysiagrass (Joseph and Braman 2009, Singh and Joseph 2022). In addition, the predatory activities of those arthropods on *S. frugiperda* were recorded from sod farms (Khan and Joseph 2022).

In summary, the current study indicated that beneficial arthropods, herbivores, and detritivores inhabit all stages of turfgrass cover in sod farms. For certain beneficial arthropods, their densities were especially lower during the early stages of turfgrass cover than during the later stages, suggesting that the early intervention of using management sprays for *Sphenophorus* spp. is a viable possibility that warrants further investigation. In addition, this information can be incorporated into the IPM program as a strategy to conserve beneficial arthropods. More research is warranted to understand how these arthropods interact among tropic levels within and outside the turfgrass in sod farms.

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Table 2.1. Details of sod farm sites selected for sampling in central Georgia in 2021 and 2022.

Month	Sites	Location in GA	*Zoysia* cultivar	Site coordinates	Components of surrounding landscape
2021					
June/July	1	Fort Valley	Zeon	32.518410, -83.940293	Wood lines, open fields
June/July	2	Marshallville	Zeon	32.424803, -83.889649	Wood lines, open fields
June/July	3	Marshallville	Zeon	32.431232, -83.885915	Wood lines, open fields
June/July	4	Marshallville	Zenith	32.429238, -83.998138	Open fields
August	1	Marshallville	Zeon	32.424295, -83.887181	Wood lines, open fields
August	2	Marshallville	Zeon	32.428754,-83.885380	Open fields
August	3	Marshallville	Zeon	32.424489,-83.885716	Wood lines, open fields
August	4	Marshallville	Zeon	32.423979,-83.893865	Wood lines, open fields
2022					
June	1	Fort Valley	Zeon	32.516444,-83.945090	Open fields, pecan groove
June	2	Marshallville	Zeon	32.429322,-83.882066	Open fields
June	3	Whitesburg	Zeon	33.494511,-84.863666	Open fields
June	4	Marshallville	Zenith	32.421812,-83.991997	Open fields, pecan groove
September	1	Fort Valley	Zeon	32.509282,-83.944521	Open fields
September	2	Fort Valley	Zeon	32.516720,-83.943705	Open fields
September	3	Marshallville	Zeon	32.430936,-83.891576	Open fields, tree lines
September	4	Marshallville	Zenith	32.417674,-83.996567	Open fields, tree lines

Table 2.2. The effects of turfgrass cover, sampling time and their interactions on beneficial arthropods collected in pitfall traps from sod farms in 2021 and 2022.

Taxa	Turfgrass cover$^{\alpha}$						Sampling time$^{\beta}$						Turfgrass cover × Sampling time					
	2021			2022			2021			2022			2021			2022		
	F	df	*P*	*F*	df	*P*	*F*	df	*P*	*F*	df	*P*	*F*	df	*P*	*F*	df	*P*
Carabidae	8.1	2,12	0.006	2.1	2,12	0.170	18.8	1,12	0.001	0.0	1,12	0.934	1.9	2,12	0.196	0.3	2,12	0.783
Staphylinidae	5.2	2,12	0.024	0.6	2,12	0.587	1.9	1,12	0.194	4.8	1,12	0.050	0.9	2,12	0.450	5.8	2,12	0.018
Coccinellidae	0.5	2,12	0.619	2.0	2,12	0.178	0.0	1,12	1.000	0.0	1,12	1.000	1.5	2,12	0.262	0.0	2,12	1.000
Lampyridae	4.1	2,12	0.044	1.0	2,12	0.395	0.1	1,12	0.825	0.0	1,12	0.939	0.1	2,12	0.950	0.4	2,12	0.698
Miridae	2.3	2,12	0.144	9.8	2,12	0.003	1.1	1,12	0.323	1.1	1,12	0.317	3.1	2,12	0.081	1.3	2,12	0.304
Geocoridae	0.6	2,12	0.569	26.4	2,12	<0.001	1.1	1,12	0.310	0.4	1,12	0.553	1.3	2,12	0.309	1.7	2,12	0.234
Other predatory Heteroptera$^{\gamma}$	0.1	2,12	0.937	1.5	2,12	0.266	3.8	1,12	0.074	0.7	1,12	0.405	0.3	2,12	0.723	1.0	2,12	0.405
Phlaeothripidae	1.8	2,12	0.207	1.8	2,12	0.213	2.5	1,12	0.143	0.1	1,12	0.787	1.8	2,12	0.207	0.2	2,12	0.815
Formicidae	0.4	2,12	0.657	0.0	2,12	0.981	0.3	1,12	0.618	1.6	1,12	0.227	0.8	2,12	0.477	0.8	2,12	0.473
Parasitic Hymenoptera	31.8	2,12	<0.001	9.9	2,12	0.003	1.4	1,12	0.264	5.7	1,12	0.034	2.3	2,12	0.146	2.6	2,12	0.117
Other Hymenoptera†	8.1	2,12	0.006	2.2	2,12	0.152	1.3	1,12	0.282	2.5	1,12	0.139	0.7	2,12	0.489	0.2	2,12	0.858
Dermaptera	4.9	2,12	0.028	6.0	2,12	0.016	29.3	1,12	<0.001	0.4	1,12	0.565	2.1	2,12	0.162	0.4	2,12	0.670
Araneae	19.3	2,12	<0.001	27.4	2,12	<0.001	12.5	1,12	0.004	0.0	1,12	0.959	4.9	2,12	0.027	2.2	2,12	0.159

$^{\alpha}$0%, 50%, and 100% turfgrass cover in sod field site; $^{\beta}$Represents the two sampling months when combined 14 d samples were collected from sod farms during each month. Combined 14 d samples at a week interval were collected in June/July and August 2021, and July and September 2022; $^{\gamma}$Saldidae and Reduviidae in 2021, and Reduviidae and Nabidae in2022 were combined; and †Scoliidae, Pompilidae, Mutilidae, Halictidae, Apidae and other unidentified nonparasitic hymenopterans were combined.

Table 2.3. The effects of turfgrass cover, sampling time and their interaction on herbivorous and detritivorous arthropods collected in pitfall traps from the sod farms in 2021 and 2022.

Taxa	Turfgrass cover[α]						Sampling time[β]						Turfgrass cover * Sampling time					
	2021			2022			2021			2022			2021			2022		
	F	df	*P*	*F*	df	*P*	*F*	df	*P*	*F*	df	*P*	*F*	df	*P*	*F*	df	*P*
Sphenophorus spp.	20.7	2,12	<0.001	4.3	2,12	0.038	7.0	1,12	0.021	17.7	1,12	0.001	0.7	2,12	0.516	0.0	2,12	0.980
Scarabaeidae	0.1	2,12	0.980	0.9	2,12	0.425	3.3	1,12	0.094	8.3	1,12	0.014	0.1	2,12	0.893	0.8	2,12	0.484
Chrysomelidae	2.6	2,12	0.116	2.2	2,12	0.158	1.4	1,12	0.268	0.0	1,12	0.871	0.3	2,12	0.765	0.6	2,12	0.580
Elateridae	5.2	2,12	0.024	7.5	2,12	0.008	0.4	1,12	0.526	1.7	1,12	0.222	0.4	2,12	0.710	0.4	2,12	0.712
Silvanidae	28.7	2,12	<0.001	6.4	2,12	0.013	0.6	1,12	0.444	2.2	1,12	0.168	2.1	2,12	0.163	0.4	2,12	0.708
Anthicidae	5.4	2,12	0.021	1.3	2,12	0.301	2.0	1,12	0.183	1.4	1,12	0.263	1.6	2,12	0.246	0.3	2,12	0.755
Heteroceridae	-	-	-	1.3	2,12	0.315	-	-	-	0.3	1,12	0.611	-	-	-	0.3	2,12	0.749
Other Coleoptera[γ]	3.6	2,12	0.058	8.2	2,12	0.006	0.6	1,12	0.461	0.2	1,12	0.664	0.5	2,12	0.627	0.6	2,12	0.543
Coleoptera larvae[£]	1.4	2,12	0.275	2.3	2,12	0.144	1.6	1,12	0.237	3.3	1,12	0.095	0.5	2,12	0.603	1.4	2,12	0.290
Cicadellidae	14.5	2,12	<0.001	13.4	2,12	0.001	12.1	1,12	0.005	0.3	1,12	0.571	1.7	2,12	0.218	0.4	2,12	0.653
Aphididae	0.4	2,12	0.672	3.2	2,12	0.079	15.0	1,12	0.002	0.2	1,12	0.681	1.0	2,12	0.408	1.6	2,12	0.249
Other Hemiptera[€]	1.9	2,12	0.198	2.5	2,12	0.126	0.5	1,12	0.509	2.0	1,12	0.186	0.1	2,12	0.949	5.5	2,12	0.020
Thripidae	0.7	2,12	0.510	4.4	2,12	0.037	0.6	1,12	0.456	5.1	1,12	0.043	0.6	2,12	0.568	4.6	2,12	0.034
Diptera	6.5	2,12	0.012	11.3	2,12	0.002	7.6	1,12	0.018	17.6	1,12	0.001	1.2	2,12	0.350	5.8	2,12	0.018
Acrididae	0.1	2,12	0.929	0.5	2,12	0.619	0.1	1,12	0.828	0.0	1,12	1.000	0.1	2,12	0.929	1.5	2,12	0.262
Gryllidae	0.4	2,12	0.684	0.8	2,12	0.482	0.2	1,12	0.673	0.2	1,12	0.667	0.2	2,12	0.817	0.4	2,12	0.680
Gryllotalpidae	-[†]	-	-	3.0	2,12	0.088	-	-	-	3.0	1,12	0.109	-	-	-	3.0	2,12	0.088
Lepidoptera[¥]	4.9	2,12	0.028	7.6	2,12	0.007	4.5	1,12	0.055	0.1	1,12	0.731	3.7	2,12	0.056	2.3	2,12	0.141

Lepidoptera larvae	2.3	2,12	0.139	0.1	2,12	0.879	4.8	1,12	0.050	1.9	1,12	0.199	0.7	2,12	0.508	5.5	2,12	0.020
Acari	17.8	2,12	<0.001	16.9	2,12	<0.001	0.0	1,12	0.956	10.5	1,12	0.007	6.1	2,12	0.015	2.7	2,12	0.107
Collembola	8.7	2,12	0.005	3.9	2,12	0.050	1.3	1,12	0.279	0.0	1,12	0.997	1.1	2,12	0.361	1.1	2,12	0.360
Psocoptera	2.1	2,12	0.171	3.0	2,12	0.088	3.0	1,12	0.112	6.4	1,12	0.026	1.3	2,12	0.305	2.0	2,12	0.181
Myriapoda	1.0	2,12	0.397	1.0	2,12	0.397	1.0	1,12	0.337	1.0	1,12	0.337	1.0	2,12	0.397	1.0	2,12	0.397

[α]0%, 50%, and 100% turfgrass cover in sod field site; [β]Represents the two sampling months when combined 14 d samples were collected from sod farms during each month. Combined 14 d samples at a week interval were collected in June/July and August 2021, and July and September 2022; [γ]Nitidulidae, Ptiliidae, Tenebrionidae, Mordellidae and all other unidentified beetles were combined; [£]All unidentified beetle larvae; [€]Ryparochromidae, Coreidae, Cydnidae, Delphacidae and all other unidentified hemipterans (adults and nymphs) were combined; [¥]All adult lepidopterans were combined; and [†]No statistical analysis was done.

Table 2.4. Mean (± SE) numbers of herbivorous and detritivorous arthropods collected in pitfall traps deployed on three turfgrass cover treatments in sod farms in 2021 and 2022.

Taxa	Turfgrass cover[α] (%)					
	2021			2022		
	0%	50%	100%	0%	50%	100%
Sphenophorus spp.	6.5 ± 1.5b	25.1 ± 10.6b	103.0 ± 29.5a	14.1 ± 5.2b	25.3 ± 10.1ab	61.8 ± 21.1a
Scarabaeidae	77.4 ± 52.6	311.3 ± 295.7	194.6 ± 176.8	309.3 ± 287.8	23.3 ± 9.7	105 ± 66.6
Chrysomelidae	6.1 ± 4.2	15.6 ± 7.8	2.3 ± 1.2	3.5 ± 2.0	26.5 ± 21.3	2.0 ± 1.5
Elateridae	1.0 ± 0.3b	7.0 ± 2.7a	8.4 ± 2.9a	0.1 ± 0.1b	6.8 ± 2.3a	2.9 ± 1ab
Silvanidae	0.0 ± 0.0b	0.3 ± 0.3b	8.3 ± 2.3a	0.3 ± 0.2b	0.5 ± 0.3b	5.0 ± 1.9a
Anthicidae	0.0 ± 0.0b	0.1 ± 0.1b	19.3 ± 16.6a	1.1 ± 0.5	1.8 ± 0.9	7.6 ± 4.8
Heteroceridae	-	-	-	1.4 ± 0.8	2.6 ± 1.7	0.3 ± 0.2
Other Coleoptera[γ]	1.4 ± 1.0	2.1 ± 0.7	5.0 ± 1.1	0.8 ± 0.6b	1.3 ± 0.7b	5.4 ± 2.1a
Coleoptera larvae[£]	3.0 ± 2.5	0.8 ± 0.7	2.5 ± 1.1	0.9 ± 0.6	7.3 ± 6.1	0.4 ± 0.2
Cicadellidae	41.3 ± 14.2a	76.3 ± 17.5a	8.9 ± 2.8b	17.9 ± 5.9b	125.8 ± 33.5a	20.1 ± 9.1b
Aphididae	2.5 ± 1.1	2.0 ± 1.1	2.9 ± 1.1	2.0 ± 0.8	3.0 ± 1.3	0.8 ± 0.5
Other Hemiptera[€]	0.4 ± 0.3	0.9 ± 0.4	6.1 ± 4.5	6.9 ± 4.2	17 ± 8.2	6.4 ± 2.1
Thripidae	0.0 ± 0.0	0.3 ± 0.3	0.3 ± 0.2	2.6 ± 2.1b	7.3 ± 5.7a	0.3 ± 0.2b
Diptera	105.0 ± 76.9b	136.4 ± 58.2a	145.6 ± 43.4a	53.3 ± 20.8b	130.8 ± 45.2a	88.4 ± 19.8a
Acrididae	0.3 ± 0.2	0.4 ± 0.3	0.3 ± 0.2	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0
Gryllidae	1.0 ± 0.5	0.5 ± 0.3	0.9 ± 0.4	0.9 ± 0.4	1.6 ± 0.6	1.5 ± 0.5
Gryllotalpidae	-[†]	-	-	0.0 ± 0.0	0.3 ± 0.2	0.0 ± 0.0
Lepidoptera[¥]	2.4 ± 0.9a	0.6 ± 0.2b	1.0 ± 0.3ab	5.4 ± 1.6a	1.6 ± 0.4ab	0.9 ± 0.7b
Lepidoptera larvae	3.1 ± 2.5	2.5 ± 1.4	8.0 ± 4.4	8.9 ± 6.9	3.0 ± 1.2	7.0 ± 5.1
Acari	6.8 ± 2.2b	7.4 ± 1.8b	122.6 ± 42.7a	35.8 ± 22.2b	29.4 ± 17.8b	168.6 ± 28.3a
Collembola	1577.8 ± 1145.6b	1953.0 ± 1281.0b	14840.8 ± 6962.4a	587.8 ± 336.6	1681.4 ± 959.1	8033.1 ± 5316.5
Psocoptera	0.0 ± 0.0	0.6 ± 0.3	0.6 ± 0.4	0.4 ± 0.3	0.6 ± 0.4	5.4 ± 3.7

Myriapoda	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0

Within a year, arthropod taxa means followed by same letters among turfgrass cover treatments within rows are not significantly different (Tukey – Kramer test, $\alpha = 0.05$); Where no letters are provided for taxa, no significant difference among treatments at $\alpha = 0.05$; [α]0%, 50%, and 100% turfgrass cover in sod field site was observed; [β]Represents the two sampling months when combined 14 d samples were collected during each month from sod farms. Combined 14 d samples at a week interval were collected in June/July and August 2021 and July and September 2022; [γ]Nitidulidae, Ptiliidae, Tenebrionidae, Mordellidae and all other unidentified beetles were combined; [£]All unidentified beetle larvae. [€]Ryparochromidae, Coreidae, Cydnidae, Delphacidae and all other unidentified hemipterans (adults and nymphs) were combined; [¥]All adult lepidopterans were combined; and [†]No statistical analysis was done.

Table 2.5. Mean (± SE) numbers of arthropods collected during sampling periodsin pitfall traps deployed in sod farms in 2021 and 2022.

Taxa	Sampling time[α]			
	2021		2022	
	June/July	August	June	September
Beneficial arthropods				
Carabidae	16.9 ± 4.4b	40.8 ± 6.7a	25.1 ± 9.4	16.5 ± 4.6
Staphylinidae	37.5 ± 10.6	17.1 ± 4.2	9.6 ± 4.2	14.1 ± 2.7
Coccinellidae	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Lampyridae	0.4 ± 0.3	0.8 ± 0.7	0.5 ± 0.4	0.3 ± 0.2
Miridae	9.3 ± 2.5	8.0 ± 2.9	11.5 ± 5	4.8 ± 1.7
Geocoridae	1.3 ± 0.5	4.8 ± 2.2	1.4 ± 0.5	1.8 ± 0.6
Other predatory Heteroptera[β]	0.2 ± 0.1	1.4 ± 0.7	13.5 ± 13	0.7 ± 0.3
Phlaeothripidae	0.3 ± 0.1	0.0 ± 0.0	0.3 ± 0.2	0.3 ± 0.1
Formicidae	40.5 ± 35.2	7.5 ± 2.4	36.1 ± 10.7	18.8 ± 7.5
Parasitic Hymenoptera	49.6 ± 20.4	52.0 ± 14.4	31.3 ± 13.9b	33.8 ± 5.7a
Other Hymenoptera[‡]	1.6 ± 0.6	2.7 ± 0.8	0.2 ± 0.1	0.8 ± 0.3
Dermaptera	13.2 ± 6.6b	79.9 ± 16.9a	75.3 ± 38.2	43.5 ± 9.7
Araneae	52.9 ± 17.6b	91.7 ± 16.4a	49.2 ± 12.8	38.9 ± 8.2
Herbivorous and detritivorous arthropods				
Sphenophorus spp.	20.3 ± 6.1b	69.5 ± 24.3a	15.6 ± 8.3b	51.8 ± 13.8a
Scarabaeidae	14.9 ± 3.3	373.9 ± 217.5	16.3 ± 6.5b	275.4 ± 191.3a
Chrysomelidae	5.1 ± 3.0	10.9 ± 5.4	16.9 ± 14.4	4.4 ± 1.8
Elateridae	6.8 ± 2.6	4.2 ± 1.4	4.3 ± 1.6	2.3 ± 1.2
Silvanidae	3.7 ± 1.9	2.0 ± 1.1	1.2 ± 0.9	2.7 ± 1.2
Anthicidae	12.2 ± 11.2	0.8 ± 0.7	2.1 ± 1.3	4.9 ± 3.1
Heteroceridae	-[†]	-	0.9 ± 0.6	1.9 ± 1.2
Other Coleoptera[γ]	2.6 ± 1.0	3.1 ± 0.9	1.8 ± 0.9	3.2 ± 1.5
Coleoptera larvae[£]	0.7 ± 0.4	3.5 ± 1.7	0.3 ± 0.1	5.4 ± 4.1
Cicadellidae	25.8 ± 8.9b	58.5 ± 15.2a	69.6 ± 27.3	39.6 ± 14.1
Aphididae	4.2 ± 0.9a	0.8 ± 0.3b	1.4 ± 0.4	2.4 ± 1.0

Other Hemiptera[€]	3.3 ± 3.1	1.7 ± 0.6	6.5 ± 2.0	13.7 ± 6.0
Thripidae	0.1 ± 0.1	0.0 ± 0.0	0.2 ± 0.1b	6.6 ± 3.9a
Diptera	47.4 ± 11.0b	210.6 ± 58.9a	40 ± 13.5b	141.6 ± 27.4a
Acrididae	0.3 ± 0.1	0.3 ± 0.2	0.1 ± 0.1	0.1 ± 0.1
Gryllidae	0.7 ± 0.3	0.9 ± 0.4	1.2 ± 0.4	1.5 ± 0.5
Gryllotalpidae	-	-	0.2 ± 0.1	0.0 ± 0.0
Lepidoptera[¥]	0.7 ± 0.2	2.0 ± 0.6	2.2 ± 0.7	3.1 ± 1.3
Lepidoptera larvae	0.5 ± 0.3b	8.6 ± 3.1a	4.6 ± 3.5	8 ± 4.5
Acari	69.5 ± 33.3	21.7 ± 9.3	63.6 ± 31.2b	92.3 ± 20.6a
Collembola	6105.2 ± 4858.9	6142.5 ± 2263.2	5075.4 ± 3661.5	1792.8 ± 701.7
Psocoptera	0.7 ± 0.3	0.2 ± 0.2	0.1 ± 0.1b	4.2 ± 2.5a
Myriapoda	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1

Within a year, arthropod taxa means followed by same letters among turfgrass cover treatments within rows are not significantly different (Tukey – Kramer test, α = 0.05); Where no letters are provided for taxa, no significant difference among treatments at α = 0.05; [α]0%, 50%, and 100% turfgrass cover in sod field site was observed; [β]Represents the two sampling months when combined 14 d samples were collected from sod farms during each sampling month. Combined 14 d samples at a week interval were collected in June/July and August 2021 and July and September 2022; [‡]Scoliidae, Pompilidae, Mutilidae, Halictidae, Apidae and other unidentified nonparasitic hymenopterans were combined; [γ]Nitidulidae, Ptiliidae, Tenebrionidae, Mordellidae and all other unidentified beetles were combined; [£]All unidentified beetle larvae . [€]Ryparochromidae, Coreidae, Cydnidae, Delphacidae and all other unidentified hemipterans (adults and nymphs) were combined; [¥]All adult lepidopterans were combined; and [†]No statistical analysis was done.

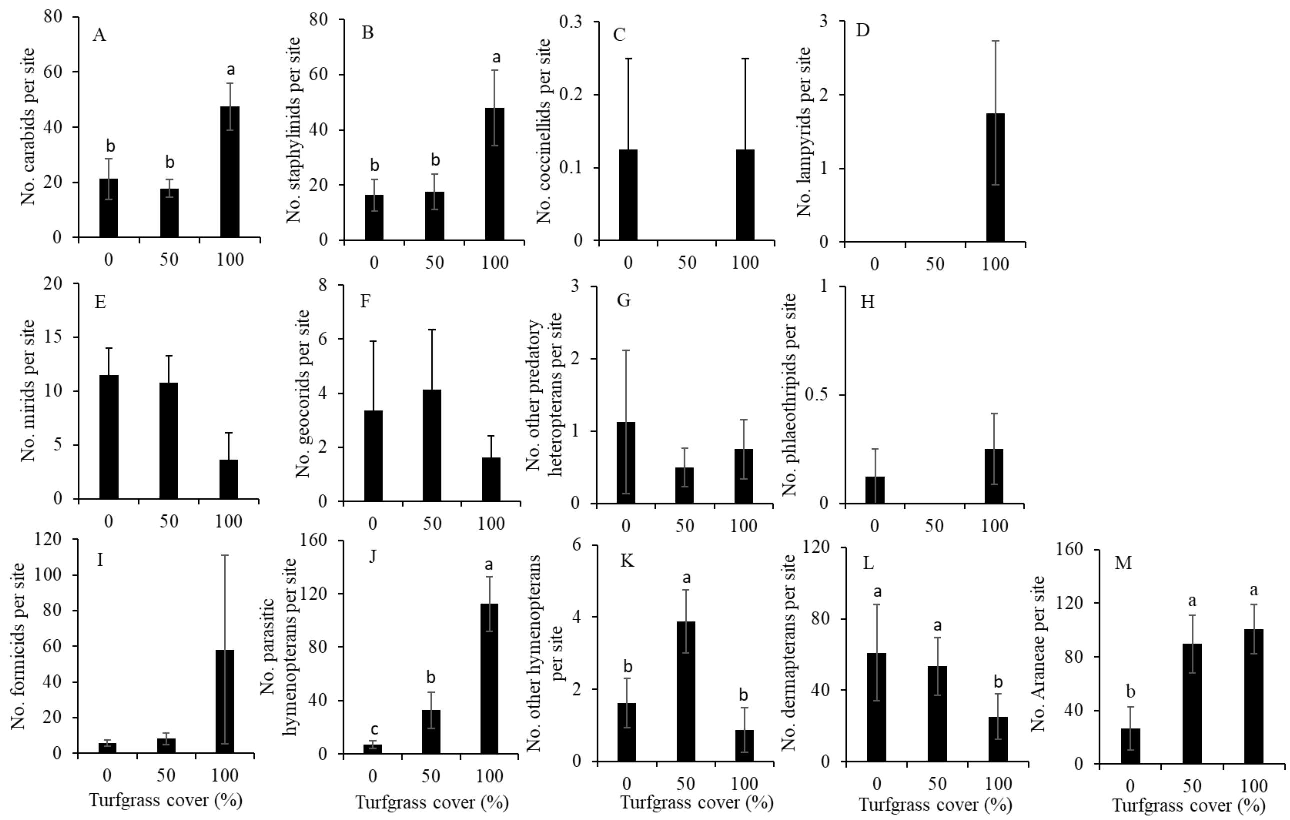

Fig. 2.1. Mean (± SE) numbers of (A) carabids, (B) staphylinids, (C) coccinellids, (D) lampyrids, (E), mirids, (F) geocorids, (G) other predatory heteropterans, (H) phlaeothripids, (I) formicids, (J) parasitic hymenopterans, (K) other hymenopterans, (L) dermapterans, and (M) Araneae collected in pitfall traps deployed on three percentage turfgrass cover in sod farms in 2021.

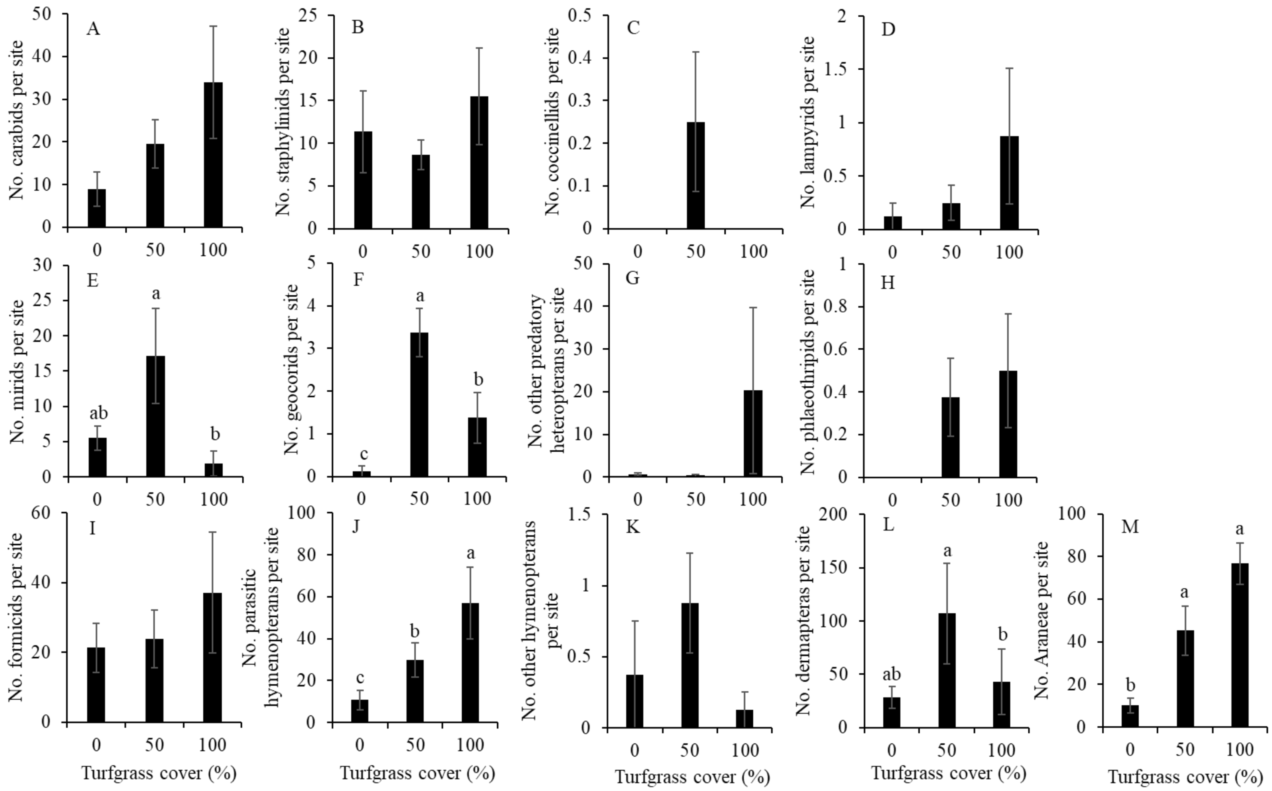

Fig. 2.2. Mean (± SE) numbers of (A) carabids, (B) staphylinids, (C) coccinellids, (D) lampyrids, (E) mirids, (F) geocorids, (G) other predatory heteropterans, (H) phlaeothripids, (I) formicids, (J) parasitic hymenopterans, (K) other hymenopterans, (L) dermapterans, and (M) Araneae collected in pitfall traps deployed on three turfgrass cover treatments in sod farms in 2022.

CHAPTER 3

EFFECTS OF INSECTICIDES ON ABUNDANCE OF BENEFICIAL ARTHROPODS IN TURFGRASS

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Abstract Turfgrass provides habitat to various arthropods, including beneficial arthropods, herbivores, and detritivores. Chemical control is an important tactic used to manage major pests in turfgrass. However, the nontarget effects of insecticide are poorly understood, especially with newer insecticides available to turfgrass managers. Therefore, the objective of this study was to determine the effects of commonly used insecticides on beneficial arthropods in turfgrass. In 2022, two trials were conducted on the bermudagrass lawn. The treatments were bifenthrin, chlorantraniliprole, tetraniliprole, imidacloprid, acephate + imidacloprid, novaluron and methoxyfenozide, which were sprayed on bermudagrass (*Cynodon* spp.). Arthropods were sampled using the pitfall traps. Imidacloprid, acephate + imidacloprid and bifenthrin immediately affected the abundance of certain beneficial arthropods, such as mirids, geocorids and parasitic hymenopterans than on certain other beneficial arthropods, such as carabids, formicids and Araneae. Methoxyfenozide, novaluron, tetraniliprole and chlorantraniliprole were less disruptive to beneficial arthropods, such as carabids, staphylinids, mirids, geocorids, formicids, parasitic hymenopterans and spiders. This information will be utilized before selecting insecticides for pest management as part of integrated pest management in turfgrass.

Key words bermudagrass, pesticide, pitfall traps, predator, parasitoids

Turfgrass is a vital linkage connecting and integrating many ecosystems in urban and suburban landscapes. Besides turfgrass's critical role in the well-being of humans by serving our psychological and recreational needs, such as beautifying surroundings, arenas for recreational sports and communal meeting places, it also provides valuable indirect benefits, such as preventing soil erosion, reducing surface temperatures, helping visibility on roadsides, and reducing dust, glare and noises (Beard 1972, Duble 2001). Because of these benefits, turfgrass is the single largest irrigated crop and occupies 1.9% of the total land surface of the continental USA (Milesi et al. 2005). It is an integral component of the landscape in the southern USA, as it is planted and maintained in public, commercial and residential lawns, golf courses and athletic fields. As a major industry in Georgia, USA, turfgrass contributed $7.8 billion USD to the state's economy and provided 87,000 employment (Kane and Wolfe 2012). It is produced and sold from 10,337 ha in Georgia and the production was valued at $126.4 million USD in 2021 (GFGV 2022).

Turfgrass hosts a diverse group of arthropods, such as predators, parasitoids, pollinators, herbivores, and detritivores (Potter and Braman 1991, Braman et al. 2002, 2003, Joseph and Braman 2009, 2011, 2012, Del Toro and Ribbons 2020, Joseph et al. 2020, Singh and Joseph 2022) by providing essential food and refugia. These arthropod communities serve as a foundation for a resilient and self-regulating ecological unit in the landscape. However, as a monoculture, the equilibrium of the turfgrass ecosystem can be threatened by very high densities of herbivore species causing aesthetic and/or economic damage. Many arthropod pests have been reported from turfgrass, such as hunting billbug, *Sphenophorus venatus vestitus* Chittenden (Coleoptera: Curculionidae) (Gireesh and Joseph 2020), fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) (Sparks 1979, Potter and Braman 1991) and Japanese beetle, *Popillia japonica* Newman (Coleoptera: Scarabaeidae) (Potter and Braman 1991). Based on a recent survey, the sod farm producers and golf course superintendents indicated that armyworms, whitegrubs, *Phylophaga* spp. (Coleoptera: Scarabaeidae) and mole crickets (Orthoptera: Gryllotalpidae) are serious problems in turfgrass (Gireesh and Joseph 2022). Population increase of pestiferous arthropods could be delayed if low or residual populations of beneficial arthropods, such as predators and parasitoids, are prevalent in turfgrass, which rapidly respond and suppress the increasing densities of pestiferous arthropods. Many beneficial arthropods, such as anthocorids, Araneae, formicids, geocorids, mirids, lasiochilids, staphylinids and reduviids were collected from the residential lawns and sod farms (Joseph and Braman 2009, Bixby-Brosi et al. 2012, Singh and Joseph 2022). These beneficial arthropods were effective in reducing the pestiferous arthropods. For example, generalist predators, such as *Amara impuncticollis* (Say) (Coleoptera: Carabidae) and *Philonthus* spp. (Coleoptera: Staphylinidae) consume all instars of black cutworm, *Agrotis ipsilon* (Hufnagel) (Lepidoptera: Noctuidae) on golf course putting greens and fairways (Frank and Shrewsbury 2004). Similarly, many nontarget arthropods served as alternative prey resources for generalist predators and were important in attracting and maintaining predator communities (Frank and Shrewsbury 2004). Thus, healthy arthropod communities in turfgrass support arthropods at the third tropic level.

Chemical control is an important management tactic used in turfgrass systems (Gireesh and Joseph 2022) and is a practical method to prevent serious damage from pests (Potter and Braman 1991). On golf courses, insecticides are preventatively applied for pest management (Potter 1986, 1994, Potter and Braman 1991). Although chemical control tactics target a specific arthropod pest, they could indirectly affect the arthropod community. Because arthropods have diverse habitats, behavior and biology, certain nontargets may be exposed and affected more than others. Similarly, insecticide properties also vary by modes of action (IRAC 2023), modes of exposure, such as contact or systemic, and longevity of insecticide residues in the environment, such as shorter or longer residual activity (Nauen and Bretschneider 2002). For example, an organophosphate, chlorpyrifos reduced predatory activity of ants and spiders on sod webworm, *Crambus* spp. and *Pediasia* spp. (Lepidoptera: Pyralidae) eggs in Kentucky bluegrass (*Poa pratensis* L.) for at least 3 weeks post-application (Cockfield and Potter 1984). Another organophosphate, isopfenphos affected populations of nonoribatid mites, diplopods, collembolans, diplurans and staphylinids for > 40 weeks post-application (Vavrek and Niemczyk 1990). Application of organophosphates, isofenphos and diazinon reduced ant population, *Solenopsis molesta* (Say) (Hymenoptera: Formicidae) and their predation on whitegrubs of southern masked chafer, *Cyclocephala lurida* Bland (Coleoptera: Scarabaeide) (Zenger 1997). Thus, it is critical to determine the effects of commonly used insecticides on arthropods present in turfgrass. Moreover, new insecticides with diverse chemical properties have been available to managers and producers in turfgrass and their nontarget effects were not completely understood. Thus, the objective of this study was to determine the effects of commonly used older class (organophosphate and pyrethroids) and newer class (diamides, neonicotinoids and insect growth regulators) of insecticides to nontargets in turfgrass. The results will help to justify the predictive insecticidal exposure on nontargets in turfgrass (Stark et al. 1995).

Materials and Methods

Study site. In 2022, experiments were conducted on turfgrass research field at the University of Georgia, Griffin Campus, GA. The experiment was first conducted during June-July (trial 1) on 'Tifway' bermudagrass (*Cynodon* spp.) and then repeated (trial 2) during September-October on 'TifTuf' bermudagrass. The experimental site of trial 1 was surrounded by open field, whereas on one side of site was a glass greenhouse for trial 2. The plots were mowed at 5 cm height before the application of treatments for both experiments. Except another mowing after 18 d of the application of treatments, no other management practices were administered on the experimental sites throughout the sampling period. The sites used for trials 1 and 2 were irrigated daily with 3.8 cm of water once in every 48 h before the experiment began. The site used for trial 1 was fertilized once with 24-0-11 (N-P-K) fertilizer (Lesco Professional Turf Fertilizer, Siteone Landscape Supply LLC, GA, USA) at 197.9 kg per ha 13 d before start of the experiment. The site used for trial 2 was not fertilized. About 1% of experimental area was infested with weeds, such as white clover (*Trifolum repens* L.), henbit (*Lamium amplexicaule* L.), poana (*Poa annua* L.) and kyllinga (*Kyllinga brevifolia* Rottb.). Herbicides, such as monosodium acid methanearsonate (47.6% a.i.) (MSMA 6 Plus, Drexel Chemical Company, Memphis, TN, USA) at 3.3 L per ha and a combination product with dimethylamine salt of (+)-(R)-2-(2 methyl-4-cholorophenoxy) propionic acid (17.37% a.i.), 2,4-dicholorophenoxyacetic acid (18.74%) and dicamba (3,6-dichloro-o-anisic acid) (3.85% a.i.) at 0.012 L per L water (Trimec Southern, PBI/Gordon Corporation, KS, USA) were applied on the experimental sites as a routine application once a year. No fungicides or insecticides were applied prior to start of the experiments. Once the insecticide treatments were applied on the experimental plots, no regular management practices were carried out for the duration of the study.

Insecticides. Commonly used insecticides in turfgrass pest management were selected in the current study (UGA Extension 2022). The details on the class, the active ingredient, trade name, dose, mode of action, Insecticide Resistance Action Committee (IRAC) group and manufacturer are listed in Table 1. The insecticides were prepared at a water volume of 841.2 L per ha and applied on the plots using a sprayer. The sprayer was fabricated from a snapper mower

(Diversified Fabricators Inc., Griffin, GA, USA). The boom width and clearance height of the sprayer were 3 m and 0.8 m above the ground, respectively. Four flat spray nozzles (8004VS TEEJET, Teejet Technologies, Glendale Heights, IL, USA) at 0.5 m nozzle spacing were attached to the boom. The sprayer applied insecticide at 80˚ at 137.895 kPa. The treatments were applied only once at the beginning of the experiment. No adjuvant or surfactant was added to the insecticide solutions.

Experiment design and sampling. The treatments were seven insecticides: bifenthrin, chlorantraniliprole, tetraniliprole, imidacloprid, acephate + imidacloprid, novaluron and methoxyfenozide (Table 3.1) plus water as control. These treatments were arranged in a randomized complete block design (RCBD) with four replications. The treatments were blocked from the edge of the field in the south to the center in the north of the open field. The size of the experimental plot was 12.2 m × 6.1 m and 9.1 m × 6.1 m in trials 1 and 2, respectively. As described in the previous section, the insecticide treatments were applied on the plots using a modified sprayer. The effect of insecticide treatments was evaluated using a pitfall trap. A pitfall trap was placed in the center of each plot to sample arthropods. The pitfall trap was prepared using a 473 mL solo plastic cup (Pro-Kal™ Polypropylene Clear Deli Containers: Fabri-Kal Corp, Kalamazoo, MI, USA) of dimensions 11.6 × 8.9 × 7.6 cm (top diameter × base diameter × height). The cups were deployed on the ground by digging holes using a 11.4 cm diameter cup-cutter used on the golf course putting greens. The solo cups were filled with 60 mL of ethylene glycol (NAPA Green Antifreeze and Coolant: Old World Industries, LLC, Northbrook, IL, USA) to preserve the trapped arthropods. The pitfall traps were covered by disposable plastic plates, supported by metal wires, which created shade over the trap. The pitfall trap was deployed on 0, 3, 13, 21 and 28 d post-application. The traps were serviced after 3 d of each deployment. The arthropods captured in pitfall traps were emptied into plastic bags and transported to the entomology laboratory. For trial 1, pitfall traps were deployed on 16, 19 and 29 June, 7 and 14 July 2022 and samples were collected on 19 and 22 June, 2, 10 and 17 July. For trial 2, pitfall traps were deployed on 15, 18 and 28 September, 6 and 13 October and samples were collected on 18 and 21 September, 1, 9 and 16 October 2022. The samples were temporarily stored at -18 °C for a week. The samples were later cleaned to remove unwanted debris, such as leaves or other fallen objects and stored in ~10 mL 70% ethanol in 20 mL plastic cups (PP, SARSTEDT AG & KG, Numbrecht, Germany).

The samples were identified to Class, Order, Family or genus using stereo microscope at 10× magnification (Nikon SMZ745T, Nikon Corporation, Tokyo, Japan). The dichotomous keys by Johnson and Triplehorn (2004) and identification guides by Evans (2014) were referenced for identification. Except parasitic wasps, earwigs and spiders, all the predatory arthropods captured at high densities were identified to families. The parasitic wasps were grouped as "parasitic hymenopterans". The members of Nabidae and Reduviidae captured were in low numbers and were combined under "other predatory Heteroptera". Arthropods that were collected in low densities, challenging to identify and no reports on beneficial activity were placed in other categories of specific taxa.

Statistical analyses. The arthropods collected from treatments at various sample collection dates were analyzed using Statistical Analysis Software (SAS Institute 2016). To determine the effects of insecticide, sample collection dates and their interactions on beneficial, herbivore and detritivore arthropods, the data were subjected to two-way analysis of variance (ANOVA) using PROC GLIMMIX procedure in SAS after log-transformation (ln[x+2]). The procedure used a generalized linear mixed model with Gaussian distribution. The estimation technique used was restricted maximum likelihood. The default options were selected due to the nature of data and degree of convergence. The data were first checked for normality of residuals using the PROC UNIVARIATE procedure in SAS through the Kolmogorov-Smirnov test ($P > 0.05$) before further analyses. The insecticide and the sample collection days were considered as fixed effects and the replications were random effects. The means and standard errors of the arthropods by insecticide and sample collection date treatments were calculated using the PROC MEANS procedure in SAS and the differences between means were calculated using Tukey-Kramer test ($P < 0.05$).

Further, those arthropod taxa that showed significant interactions between insecticide treatment and sample collection date were subjected to one-way ANOVA using PROC GLM procedure in SAS after log transformation (ln[x+2]). The means and standard errors were calculated by insecticide and sample collection date using the PROC MEANS procedure in SAS. The means were separated using Tukey's HSD test ($P < 0.05$). Statistical analyses were not performed for those taxa captured at very low densities.

Results

Overall, 9,728 and 3,542 beneficial arthropods were captured in pitfall traps in trials 1 and 2. The beneficial arthropods collected in high densities were carabids, staphylinids, mirids, geocorids, formicids, parasitic hymenopterans and spiders. In addition, low densities of lampyrids, reduviids, nabids, earwigs and phaleothripids were sampled. Apart from beneficial arthropods, many herbivore and detritivore arthropods were sampled.

Effects of insecticide

Beneficial arthropods. In trial 1, the numbers of staphylinids and mirids were significantly lower for the imidacloprid and acephate + imidacloprid treatments than for the water treatment

(Tables 3.2 and 3.4). The numbers of parasitic wasps were significantly lower for the acephate + imidacloprid treatment than for the water treatment (Tables 3.2 and 3.4). A significantly lower numbers of formicids was observed in the bifenthrin treatment than in the water treatment (Tables 3.2 and 3.4). However, the numbers of Araneae were significantly lower in the bifenthrin and acephate + imidacloprid treatments than in the water treatment (Tables 3.2 and 3.4). In trial 2, significantly lower numbers of Araneae were observed in the bifenthrin treatment than in the water treatment (Tables 3.2 and 3.4). Although the numbers of carabids, staphylinids and parasitic hymenopterans were significantly different for the insecticide treatments (Table 3.2), their numbers were not significantly different from the water treatment (Table 3.4). The numbers of mirids, geocorids and formicids were not significantly affected by the insecticide treatments (Table 3.2).

Herbivores and detritivores. In trial 1, the numbers of other coleopterans and collembolans were significantly lower for the imidacloprid and acephate + imidacloprid treatments than for the water treatment (Tables 3.3 and 3.5). Significantly lower densities of other hemipterans and thripids were collected for the imidacloprid, acephate + imidacloprid and novaluron treatments than for the water treatment (Tables 3.3 and 3.5). The numbers of elaterids were significantly lower in chlorantraniliprole and acephate + imidacloprid treatments than for the water treatment. All the insecticide treatments except methoxyfenozide treatment significantly reduced the densities of chrysomelids than in the water treatment. The numbers of Acari were significantly lower for the bifenthrin treatment than for the water treatment. The densities of taxa, such as anthicids, cicadellids, cydnids, dipterans and gryllotalpids were significantly different among insecticide treatments but were not significantly different from the water treatment (Table 3.3). The numbers of taxa, such as curculionids, scarabaeids and aphidids were not significantly different among insecticide treatments (Table 3.3). In trial 2, the numbers of collembolans were significantly lower for the imidacloprid and acephate + imidacloprid treatments than for the water treatment (Tables 3.3 and 3.5). Although the densities of elaterids, anthicids, aphidids, cydnids, other hemipterans, dipterans and Acari were significantly different among insecticide treatments, they were not significantly different from the water treatment (Tables 3.3 and 3.5). The densities of taxa, such as curculionids, scarabaeids, other coleopterans, cicadellids and thripids, were not significantly different among insecticide treatments (Table 3.3).

Effects of sample collection date

Beneficial arthropods. For those taxa where the interactions between insecticide treatment and sample collection date were not significantly different, the effects of sample collected dates are presented for all insecticides combined (Table 3.2). In trial 1, the numbers of carabids were significantly lower for the 6, 16 and 24 d post-application treatments than for the 3 d post-application treatment (Tables 3.2 and 3.6). The densities of mirids were significantly lower for the 3, 24 and 31 d post-application treatments than for the 16 d post-application treatment. Significantly lower densities of geocorids were observed 3 and 6 d post-application treatments than for the 16 and 31 d post-application treatments. The numbers of parasitic hymenopterans were significantly lower for the 3, 6 and 24 d post-application treatments than for the 16 and 31 d post-application treatments. The numbers of Araneae were significantly lower in 24 d post-application treatments than for the 16 and 31 d post-application treatments. There were no significant differences among sample collection dates for staphylinids and formicids (Table 3.2). In trial 2, the numbers of staphylinids were significantly lower for the 6, 16 and 24 d post-application treatments than for the 3 d post-application treatment (Tables 3.2 and 3.6). The densities of mirids were significantly lower 16 and 24 d post-application treatments than for the

31 d post-application treatments. The densities of formicids were significantly less abundant for the 16 and 24 d post-application treatments than for the 3, 6 and 31 d post-application treatments. The numbers of parasitic hymenopterans and Araneae were significantly lower for the 16, 24 and 31 d post-application treatments than for the 3 d post-application treatments (Tables 3.2 and 3.6). There were no significant differences among sample collection dates for carabids and geocorids (Table 3.2).

Herbivores and detritivores. In trial 1, the numbers of curculionids were significantly lower for up to 16 d post-application treatments than for the 31 d post-application treatment (Tables 3.3 and 3.7). The numbers of scarabaeids were significantly greater for the 3 and 16 d post-application treatments than for the 6, 24 and 31 d post-application treatments. The numbers of aphidids were significantly lower on the 24 d post-application treatment than on others treatments. The counts of cydnidis were significantly lower for up to 16 d post-application treatments than for 24 d post-application treatment (Tables 3.3 and 3.7). The numbers of anthicid were significantly lower for up to the 24 d post-application treatments than for the 31 d post-application treatment. The chrysomelids were significantly greater in numbers at the 16 d post-application treatment than at the 31 d post-application treatment. The numbers of other coleopterans were significantly lower for the 3, 6 and 24 d post-application treatments than for the 31 d post-application treatments (Tables 3.3 and 3.7). The counts of elaterids, cicadellids and collembolans were significantly lower for the 3 and 6 d post-application treatments than for the 16 d post-application treatment and thereafter, their densities were significantly lower for the 24 or 31 d or both post-application treatments (Tables 3.3 and 3.7). The counts of gryllotalpids were significantly greater for the 3 d post-application treatments and henceforth their numbers remained low for up to 31 d post-application treatment. Significantly lower densities of Acari were observed for up to 24 d post-application treatments than for the 31 d post-application treatment. However, the numbers of other hemipterans and thripids were significantly greater for the 3, 6 and 16 d post-application treatments than for the 24 and 31 d post-application treatments. There were no significant differences among sample collection dates for dipterans (Table 3.3). In trial 2, the numbers of curculionids were significantly greater for the 3 d post-application treatment than for the remaining post-application treatments (Tables 3.3 and 3.7). The densities of scarabaeids were significantly greater for the 6 d post-application treatment than for the remaining post-application treatments. The densities of anthicids were significantly more abundant for the 3 d post-application treatment than for the 16 and 24 d post-application treatments. Significantly lower densities of dipterans were observed for the 3, 24 and 31 d post-application treatments than for the 6 and 16 d post-application treatments. The numbers of dipterans were significantly lower for the 3, 24 and 31 d post-application treatments than for the 6 and 16 d post-application treatments (Tables 3.3 and 3.7). The densities of collembolans and Acari were significantly lower for the 16 and 24 d post-application treatments than for the 3, 6 and 31 d post-application treatments (Tables 3.3 and 3.7).

Interaction effects between insecticide and sample collection date

***Beneficial arthropods*.** Except for densities of mirids in trial 1, no interaction effect between the insecticide treatments and sample collection dates on beneficial taxa was observed in both trials (Table 3.2). For the 3 d post-application treatment, the densities of mirids were significantly lower for the bifenthrin, imidacloprid and acephate + imidacloprid treatments than for the remaining treatments, including water treatment (Table 3.2; Fig. 1A). For the 6, 16, 24 and 31 d post-application treatments, the numbers of mirids were not significantly different among insecticide treatments.

Herbivores and detritivores. In trial 1, for the bifenthrin, chlorantraniliprole, tetraniliprole, novaluron and water treatments, the sample collection date treatments were not significantly different for the densities of cydnids, whereas for imidacloprid, acephate + imidacloprid and methoxyfenozide treatments, the densities of cydnids were significantly lower for 3 and 6 d than for the 16, 24 and 31 d post-application treatments (Table 3.3; Fig. 3.1B). The numbers of other hemipterans were not significantly different for the bifenthrin, imidacloprid, acephate + imidacloprid and novaluron treatments among post-application treatments, whereas for the chlorantraniliprole and tetraniliprole, the densities were significantly greater for the 3 and 6 d post-application treatments than for the 24 and 31 d post-application treatments (Table 3, Fig. 3.1C). The numbers of thripids collected were significantly lower with the bifenthrin treatment at the 3 and 6 d post-application treatments compared to at the 16 d -application treatment, whereas their densities were significantly lower with the chlorantraniliprole treatment at the 6, 16 and 24 d post-application treatments compared to at the 3 and 31 d post-application treatments (Table 3.3, Fig. 3.1D). The densities of collembolans were significantly lower at the 3 and 6 d post-application treatments than at the 16 and 24 post-application treatments for the bifenthrin treatment, whereas their densities were low but not significantly different regardless of sample collection date treatments for the acephate + imidacloprid treatment (Table 3.3, Fig. 3.1E). In trial 2, the numbers of collembolans were significantly lower for the acephate + imidacloprid treatment than for the water treatment at the 3 and 31 d post-application treatment (Table 3.4, Fig. 3.1F). This effect was not observed with other insecticide treatments.

Discussion

We sought to understand the shorter and longer-term nontarget effects of commonly used insecticides in turfgrass on beneficial arthropods, herbivores, and detritivores. Results show that imidacloprid, acephate + imidacloprid and bifenthrin affected the abundance of beneficial arthropods soon after application for a shorter term for certain arthropods than some other beneficial arthropods, where the impact was slow acting. Previously, imidacloprid was reported as very toxic to larvae of *Hippodomia convergens* Guérin-Méneville (Coleoptera: Coccinellidae) when directly exposed, causing 100% mortality (Santos et al. 2017). The soil core extraction samples from turfgrass showed that imidacloprid could affect the densities of hemipterans, thysanopterans, coleopterans and collembolans (Peck 2009). When adult ground beetles, *Harpalus pennsylvanicus* DeGeer (Coleoptera: Carabidae), were exposed to imidacloprid by topical and dietary routes, the movement of beetles was impaired (Kunkel et al. 2001). In contrast, imidacloprid induced limited effects on the hunting behavior of tiger beetle, *Megacephala carolina carolina* L. (Coleoptera: Carabidae) larvae (Joseph 2023). Besides formicids and spiders, low numbers of most beneficial insects were observed from imidacloprid + acephate treated plots than other insecticides in the current study. Previous studies reported that organophosphates were highly toxic to natural enemies (Bacci et al. 2009, Cordeiro et al. 2010, Fernandes et al. 2016). The higher toxicity of organophosphates, including acephate, might be connected to their physical properties, such as low water solubility (0.91 g per L at 25 °C) and high molecular weight (183.16 g per mole) (Berg et al. 2003) resulting in higher affinity to waxy compounds on insect cuticle than other insecticides with high water solubility and low molecular weight (Fraenkel and Rudall 1940, Vincent and Wegst 2004). Bifenthrin is highly toxic and can induce negative effects to many natural enemies (Cordeiro et al. 2010, Rodrigues et al. 2013, Fernandes et al. 2016, Joseph 2023), although the negative effects of bifenthrin were relatively lower than imidacloprid or acephate + imidacloprid in the current study. A previous study showed that the hunting behavior of larvae and adults *M. carolina carolina* L. (Coleoptera:

Carabidae) was altered in bifenthrin-treated areas (Joseph 2023). In the current study, lower densities of formicids and spiders were observed on bifenthrin-treated plots than on nontreated plots. The bifenthrin acts on the peripheral nervous system of arthropods (Christensen et al. 2009, Rinkevich et al. 2013, Fernandes et al. 2016). This property could have repelled ants and spiders away from treated plots leading to their low captures in the traps in the current study. This suggests that the effects of bifenthrin, imidacloprid and acephate + imidacloprid should be further characterized to understand specific lethal or sublethal effects on specific beneficial arthropod groups.

In the current study, chlorantraniliprole, tetraniliprole, methoxyfenozide, and novaluron induced minimal negative effects on beneficial arthropods. Greater densities of carabids, staphylinids, mirids, geocorids, formicids, parasitic hymenopterans and spiders were recovered from anthranilic diamides, chlorantraniliprole and tetraniliprole treated plots than from the nontreated plots. The survival of turfgrass predators, *H. pennsylvanicus,* and turfgrass parasitoids, *Tiphia vernalis* Rohwer (Hymenoptera: Tiphiidae) and *Copidosoma bakeri* Howard (Hymenoptera: Encyrtidae), was less affected by chlorantraniliprole in laboratory studies (Larson et al. 2014). Similarly, chlorantraniliprole-treated plots had a low impact on pitfall trap captures of predatory groups, such as formicids, staphylinids, carabids, lycosids and linyphiidids in the golf course (Larson et al. 2012). In soybean, chlorantraniliprole had a greater impact on lepidopterans than on other predatory groups, such as anthocorids, spiders and geocorids (Whalen et al. 2016). Similarly, chlorantraniliprole was less sensitive to parasitoid wasps, *Aphidius rhopalosiphi* (DeStephani-Perez) (Hymenoptera: Aphidiinae), *Aphelinus mali* Haldeman (Hymenoptera: Eulophidae), *Dolichogenidea tasmanica* Cameron (Hymenoptera:

Braconidae), *Diadegma semiclausum* Hellen (Hymenoptera: Ichneumonidae) and several *Trichogramma* spp. (Hymenoptera: Trichogrammatidae) in a laboratory (Brugger et al. 2010). In laboratory bioassays, when chlorantraniliprole was applied as topical, residual and oral routes, it was toxic to natural enemies, such as *Chrysoperla carnea* (Stephens) (Neuroptera: Chrysopidae) (Amarasekare et al. 2016). Chlorantraniliprole and tetraniliprole are diamides and act on the ryanodine receptor (RyR) of arthropods, specifically lepidopteran pests (Cordova et al. 2006, Lahm et al. 2007, Dupont 2008, Teixeira and Andaloro 2013, Kadala et al. 2020). Additionally, it is possible that the habit and hunting behavior of beneficial arthropods also contribute to low exposure to these insecticides. Thus, more research is needed to determine the mechanisms of diamide exposure on nontargets considering their habit, movement and hunting behavior in turfgrass.

Insect growth regulators, methoxyfenozide and novaluron, had minimal impact on densities of staphylinids, mirids, geocorids and parasitic hymenopterans in the current study. This result is consistent with previous studies where novaluron had minimal negative effects on many nontargets (Cutler and Scott-Dupree 2007, Roubos et al. 2014) particularly, *Deraeocoris brevis* (Uhler) (Hemiptera: Miridae) (Kim et al. 2006), *Orius laevigatus* Fieber (Hemiptera: Anthocoridae), *Amblyseius swiirskii* (Athias-Henriot) (Acari: Phytoseiidae) (Colomer et al. 2011), *Aphidius colemani* Viereck (Hymenoptera: Braconidae) (Stara et al. 2011), larvae of *Hyposoter didymator* Thunberg (Hymenoptera: Ichneumonidae) (Schneider et al. 2004) and *Trichogramma* nr. *Brassicae* (Hymenoptera: Trichogrammatidae) (Hewa-Kapuge et al. 2003). Carlson et al. (2001) reported methoxyfenozide was safe for nontarget invertebrates and highly toxic to caterpillar pests. Methoxyfenozide acts on the molting process and are very specific to lepidopterans by inducing premature molting resulting in larval mortality (Nauen and Bretschneider 2002). However, novaluron can be toxic to beneficial arthropods (Cutler and Scott-Dupree 2007), such as *Chrysoperla carnea* (Stephens) (Neuroptera: Chrysopidae) as shown in a laboratory study (Amarasekare et al. 2016). Novaluron is benzoylphenyl urea which acts on chitin synthesis, very specific on lepidopterans and coleopteran pests (Cutler and Scott-Dupree 2007). Thus, methoxyfenozide and novaluron are promising insecticides for lepidopteran pests, such as *S. frugiperda* in turfgrass, with limited effects on nontargets.

The effects of insecticides were immediate on some arthropods, such as mirids, geocorids and parasitic hymenopterans at exposure. In contrast, insecticide effects were delayed for others, such as carabids and staphylinids, where their captures decreased after a week's delay. These variations in insecticide effects on beneficial arthropods could be related to many reasons. Firstly, active ingredients may not be stable, and they degenerate into moderate to low toxic derivatives at various rates in field conditions, which could decrease the dose and affect the toxicity of the active ingredients (Byerlee et al. 2009, Eijaza et al. 2015, Fernandes et al. 2016). Additionally, temperature and light can play a major role in the degradation of active ingredients, affecting the sensitivity of various arthropods (DeLorenzo et al. 2006, Sharma et al. 2014, Li et al. 2020). Similarly biotic factors, such as the activity of microorganisms, can affect the insecticide dose over time (Zuo et al. 2015). Because the degradation of insecticides is very common in the field than in laboratory conditions (Byerlee et al. 2009), the effective doses and residual activity should be determined after field studies. Secondly, the mode of action of the active ingredient can influence the toxicity and exposure to arthropods (Sparks and Nauen 2015). For example, the modes of action of organophosphates and pyrethroids on insects were acetylcholinesterase inhibitors and voltage-gated sodium channel, respectively (Nauen and Bretschneider 2002). Neonicotinoids, such as imidacloprid, affects the nicotinic acetylcholine receptor in the central nervous system of insect (Nauen and Bretschneider 2002, Tomizawa and Casida 2005). The pests, such as hemipterans, some coleopterans, dipterans and lepidopterans, are exposed to the lethal dose of imidacloprid via ingestion and contact (Elbert et al. 1998, Nauen and Bretschneider 2002). When compared to organophosphates and pyrethroids, neonicotinoids are effective at low doses as systemic and has extended residual activity (Tomizawa and Casida 2003), especially effective on piercing and sucking insects (Simon-Delso et al. 2015). Thus, the chemical properties of active ingredients may have contributed to low captures of certain arthropods on imidacloprid treated plots in the current study.

Among the herbivore and detritivores, imidacloprid and acephate + imidacloprid severely impacted collembolans, elaterids, and other coleopterans, other hemipterans and thripids. Turfgrass habitat is considered one of the quick systems to recover beneficial arthropod densities to satisfactory levels after insecticide exposure (Arnold and Potter 1987, Terry et al. 1993). However, continuous dependence on insecticides for pest control can be detrimental to the health of nontarget arthropod communities (Peck 2009). Reduction in nontarget arthropod communities in turfgrass can disrupt various ecological processes, such as nutrient recycling, litter decomposition, pollination and biological control of pests (Potter 1993, Kunkel et al. 2001, Zenger and Gibb 2001, Rogers and Potter 2003, Larson et al. 2012). For example, low densities of collembolans might lead to low densities of beneficial arthropods, such as carabids and staphylinids, which are alternate nutrient resource for them (Bohac 1999, Kielty et al. 1999). Similarly, collembolans play significant role in decomposition of organic matter and help in nutrient recycling in turfgrass (Rusek 1998, Peck 2009). Thus, as part of IPM program, it is important to consider the health of arthropod communities besides conserving predatory arthropods.

Many studies reported an abundance of parasitic wasps and predators besides other arthropods from turfgrass system (Braman and Pendley 1993, Reng-Moss et al. 1998, Braman et al. 2002, Joseph and Braman 2011, Joseph et al. 2020, Singh and Joseph 2022). The current and previous studies indicate that turfgrass is rich in arthropod biodiversity. This biodiversity can help achieve natural pest control in the turfgrass system, similar to various agricultural systems (Losey and Vaughan 2006, Janssen et al. 2007, Gurr et al. 2016). The current study shows that bifenthrin, imidacloprid, and acephate + imidacloprid were more toxic in beneficial arthropods than chlorantraniliprole, tetraniliprole, novaluron and methoxyfenozide. More studies will help researchers to understand the lethal and sublethal effects of specific insecticides and exposure routes on specific beneficial arthropods in turfgrass systems. The current study provides a foundation so that insecticide or beneficial arthropod-mediated effects can be further studied. The current study shows that insecticides, such as chlorantraniliprole, tetraniliprole, novaluron and methoxyfenozide should be used for the target pests, if possible, as they are likely to have minimum impact on nontargets. Although this study showed which insecticides and when they impacted the densities of beneficial arthropods in turfgrass, it is still unclear how the predation and parasitization from these beneficial arthropods are affected when mediated by these insecticides in turfgrass. Thus, more studies are warranted to determine the effects of these insecticides on predation and parasitization in turfgrass.

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Table 3.1. Details of insecticides applied on bermudagrass in trials 1 and 2.

Class/subclass	Brand name	a.i. (%)	IRAC[b] Group	Rate[a] (L per ha)	Manufacturer	Targeted pest
Pyrethroid	Talstar One™	Bifenthrin (7.9%)	3A	1.6	FMC Corporation, Philadelphia PA	Billbug adult
Diamide	Acelepryn®	Chlorantraniliprole (18.4%)	28	1.5	Syngenta Crop Protection, Greensboro, NC	Billbug
Diamide	Tetrino™	Tetraniliprole (4.07%)	28	2.3	Bayer R&D Services, LLC, Chesterfield, MO	Billbug
Neonicotinoid	Merit® 2F	Imidacloprid (21.4%)	4A	2.0	Bayer CropScience, Durham, NC	Billbug larva
Organophosphate + neonicotinoid	Avatar® PLX	Acephate (50%) + imidacloprid (5%)	1B + 4A	8.8*	Aquatrols Cor. of America, Paulsboro, NJ	Mole cricket
IGR†	Suprado	Novaluron (10%)	15	9.9	Control Solutions Inc., Pasadena, TX	Billbug larva
IGR	Intrepid 2F®	Methoxyfenozide (22.6%)	18	1.2	Corteva Agriscience LLC, Indianapolis, IN	Fall armyworm

[a] Rate calculated for the product; [b]Insecticide Resistance Action Committee; †Insect growth regulator; and *kg per ha. Insecticide solution was prepared in 841.2 L per ha of water.

Table 3.2. The effects of insecticide treatment, sample collection date and their interactions on predatory arthropods in pitfall traps.

Taxa	Insecticide			Sample collection date*			Insecticide × sample collection date		
	F	df	*P*	*F*	df	*P*	*F*	df	*P*
Trial 1[a]									
Carabidae	4.4	7,117	<0.001	7.5	4,117	<0.001	0.7	28,117	0.902
Staphylinidae	6.2	7,117	<0.001	2.2	4,117	0.077	0.7	28,117	0.838
Miridae	6.9	7,117	<0.001	43.7	4,117	<0.001	2.6	28,117	<0.001
Geocoridae	4.1	7,117	0.001	6.3	4,117	<0.001	0.8	28,117	0.788
Formicidae	6.1	7,117	<0.001	0.9	4,117	0.449	0.9	28,117	0.677
Parasitic Hymenoptera	9.2	7,117	<0.001	11.5	4,117	<0.001	0.8	28,117	0.725
Araneae†	11.1	7,117	<0.001	5.9	4,117	<0.001	1.3	28,117	0.149
Trial 2[b]									
Carabidae	3.5	7,117	0.002	2.0	4,117	0.105	0.8	28,117	0.786
Staphylinidae	4.1	7,117	0.001	10.6	4,117	<0.001	0.8	28,117	0.707
Miridae	0.5	7,117	0.861	3.5	4,117	0.010	0.7	28,117	0.896
Geocoridae	1.1	7,117	0.365	1.0	4,117	0.400	0.7	28,117	0.863
Formicidae	3.0	7,117	0.007	17.8	4,117	<0.001	0.8	28,117	0.760
Parasitic Hymenoptera	2.5	7,117	0.021	9.8	4,117	<0.001	1.0	28,117	0.511
Araneae†	11.3	7,117	<0.001	13.6	4,117	<0.001	1.2	28,117	0.260

*Five sample collection dates: 3, 6, 16, 24 and 31 d post-first application of insecticide treatment. The pitfall traps were exposed for 3 d before collection. [a]June-July 2022; [b]September-October 2022; and †All spiders, irrespective of families, combined. Plot sizes for trials 1 and 2 were 12.2 m × 6.1 m and 9.1 m × 6.1 m, respectively. Bermudagrass cultivars used in trials 1 and 2 were 'Tifway' and 'TifTuf'.

Table 3.3. The effects of insecticide treatment, sample collection date and their interactions on herbivorous and detritivorous arthropods in pitfall traps.

Taxa	Insecticide			Sample collection date*			Insecticide × sampling date		
	F	df	*P*	*F*	df	*P*	*F*	df	*P*
Trial 1[a]									
Curculionidae	1.3	7,117	0.240	11.6	4,117	<0.001	0.7	28,117	0.851
Scarabaeidae	1.7	7,117	0.113	8.1	4,117	<0.001	1.1	28,117	0.386
Elateridae	3.5	7,117	0.002	7.0	4,117	<0.001	1.5	28,117	0.067
Anthicidae	8.6	7,117	<0.001	33.6	4,117	<0.001	1.3	28,117	0.143
Chrysomelidae	7.6	7,117	<0.001	2.8	4,117	0.028	1.2	28,117	0.253
Other Coleoptera[β]	6.6	7,117	<0.001	9.8	4,117	<0.001	0.9	28,117	0.656
Cicadellidae	3.8	7,117	<0.001	9.6	4,117	<0.001	0.7	28,117	0.865
Aphididae	1.4	7,117	0.215	2.7	4,117	0.035	1.5	28,117	0.072
Cydnidae	4.2	7,117	<0.001	11.6	4,117	<0.001	2.8	28,117	<0.001
Other Hemiptera[γ]	28.7	7,117	<0.001	8.4	4,117	<0.001	2.1	28,117	0.004
Diptera[δ]	3.8	7,117	<0.001	0.9	4,117	0.471	0.7	28,117	0.892
Gryllotalpidae	2.5	7,117	0.020	48.2	4,117	<0.001	1.6	28,117	0.050
Thripidae	5.4	7,117	<0.001	8.0	4,117	<0.001	1.8	28,117	0.013
Collembola[δ]	18.7	7,117	<0.001	17.9	4,117	<0.001	1.7	28,117	0.032
Acari[δ]	8.1	7,117	<0.001	25.1	4,117	<0.001	1.2	28,117	0.240
Trial 2[b]									
Curculionidae	1.4	7,117	0.194	9.6	4,117	<0.001	0.8	28,117	0.698
Scarabaeidae	1.0	7,117	0.408	7.5	4,117	<0.001	0.7	28,117	0.820
Elateridae	2.5	7,117	0.020	1.6	4,117	0.184	1.0	28,117	0.423
Anticidae	3.8	7,117	0.001	6.9	4,117	<0.001	0.6	28,117	0.941
Chrysomelidae	-[†]	-	-	-	-	-	-	-	-
Other Coleoptera[β]	1.0	7,117	0.467	1.8	4,117	0.138	0.7	28,117	0.881
Cicadellidae	1.5	7,117	0.179	0.9	4,117	0.450	0.9	28,117	0.564
Aphididae	2.7	7,117	0.013	0.2	4,117	0.925	0.5	28,117	0.968
Cydnidae	3.6	7,117	0.002	1.7	4,117	0.162	0.9	28,117	0.665
Other Hemiptera[γ]	3.3	7,117	0.003	0.7	4,117	0.600	0.3	28,117	1.000
Diptera[δ]	4.8	7,117	<0.001	11.7	4,117	<0.001	1.0	28,117	0.419
Gryllotalpidae	-[†]	-	-	-	-	-	-	-	-
Thripidae	0.6	7,117	0.786	1.0	4,117	0.418	1.1	28,117	0.359
Collembola[δ]	14.6	7,117	<0.001	37.5	4,117	<0.001	2.0	28,117	0.006
Acari[δ]	3.5	7,117	0.002	22.4	4,117	<0.001	1.3	28,117	0.165

[*]Five sample collection dates: 3, 6, 16, 24 and 31 d post-first application of insecticide treatment; [a]June-July 2022; [b]September-October 2022; [β]Consists of unidentified adults; [γ]Consists of unidentified adults and nymphs; [δ]All families combined; and [†]None captured. Plot sizes for trials 1 and 2 were 12.2 m × 6.1 m and 9.1 m × 6.1 m, respectively. Bermudagrass cultivars used in trials 1 and 2 were 'Tifway' and 'TifTuf'.

Table 3.4. Mean (± SE) numbers of beneficial arthropods collected in pitfall traps from plots treated with various treatments on bermudagrass in trials 1 and 2.

Taxa	Bifenthrin	Chlorantraniliprole	Tetraniliprole	Imidacloprid	Acephate + imidacloprid	Novaluron	Methoxyfenozide	Water
Trial 1[a]								
Carabidae	5.4 ± 1a	3.8 ± 0.6ab	5.2 ± 1.4ab	2.1 ± 0.5b	1.8 ± 0.3b	2.7 ± 0.6ab	5.4 ± 0.8a	3.7 ± 0.6ab
Staphylinidae	0.9 ± 0.3bc	1.1 ± 0.2bc	1.7 ± 0.3abc	0.6 ± 0.2c	0.6 ± 0.2c	2.4 ± 0.7abc	4.2 ± 0.9a	2.2 ± 0.4ab
Lampyridae[c]	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1
Miridae	2.7 ± 0.8bcd	4.6 ± 1.0ab	4.5 ± 1.1abc	1.8 ± 0.6d	1.9 ± 0.8cd	2.3 ± 0.6bcd	5.6 ± 1.2a	4.9 ± 0.9ab
Geocoridae	0.8 ± 0.2ab	1.1 ± 0.2a	0.6 ± 0.2ab	0.2 ± 0.1b	0.3 ± 0.1b	0.5 ± 0.2ab	1.3 ± 0.3a	0.9 ± 0.2ab
Other predatory Heteroptera[cd]	0.0 ± 0.0	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1
Formicidae	8.5 ± 1.6b	18.5 ± 3.8a	20.9 ± 3.5a	25.6 ± 4.2a	16.1 ± 2.6ab	27.8 ± 6.4a	34.2 ± 4.3a	20.9 ± 3.3a
Parasitic Hymenoptera	17.6 ± 5.5cd	32.3 ± 5.3ab	24.7 ± 6abc	15.3 ± 3.2bcd	9.6 ± 2.4d	18.6 ± 3bcd	49 ± 8.1a	21.5 ± 3.3abc
Dermaptera[e]	0.5 ± 0.2	0.3 ± 0.2	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.2	0.1 ± 0.1	0.4 ± 0.2
Phlaeothripidae[c]	0.0 ± 0.0	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.4 ± 0.2	0.2 ± 0.1	0.2 ± 0.1
Araneae[†]	2.3 ± 0.6c	5.4 ± 0.7ab	6.1 ± 0.6ab	4.7 ± 0.5ab	3.6 ± 0.5bc	6.5 ± 0.7ab	8.6 ± 1.2a	7.8 ± 0.8a
Trial 2[b]								
Carabidae	1.2 ± 0.3a	0.5 ± 0.2ab	1 ± 0.4ab	0.2 ± 0.1b	0.3 ± 0.1b	0.5 ± 0.2ab	0.5 ± 0.2ab	0.7 ± 0.2ab
Staphylinidae	0.7 ± 0.2b	0.7 ± 0.2b	1.4 ± 0.4ab	0.4 ± 0.2b	0.8 ± 0.4b	1.1 ± 0.3ab	3.1 ± 0.8a	1.5 ± 0.7ab
Lampyridae[c]	-[f]	-	-	-	-	-	-	-
Miridae	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.2	0.0 ± 0.0
Geocoridae	0.0 ± 0.0	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Other predatory Heteroptera[cd]	0.1 ± 0.1	0.4 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.5 ± 0.2	0.2 ± 0.1	0.2 ± 0.1
Formicidae	8.4 ± 1.9	11.6 ± 1.7	13.9 ± 2.2	22.5 ± 6.3	12.2 ± 2.3	12.8 ± 2.9	8.3 ± 1.7	10.3 ± 3.2
Parasitic Hymenoptera	2.8 ± 0.5b	5.3 ± 1.3ab	7.0 ± 1.1a	4.3 ± 0.8ab	3.7 ± 0.7ab	4.6 ± 0.6ab	5.5 ± 1.0ab	5.7 ± 1.1ab
Dermaptera[c]	0.2 ± 0.1	0.1 ± 0.0	0.4 ± 0.2	0.1 ± 0.1	0.1 ± 0	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Phlaeothripidae[c]	0.1 ± 0.0	0.2 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.1 ± 0.1	0.3 ± 0.2
Araneae[†]	0.3 ± 0.1c	2.9 ± 0.7b	5.5 ± 1.0a	2.4 ± 0.4b	1.8 ± 0.4b	2.3 ± 0.4b	2.9 ± 0.6b	2.0 ± 0.4b

[a]June-July 2022; [b]September-October 2022; [c]No statistical analysis was performed because of density captures; [d]Adults and nymphs of reduviids and nabids were combined; [e]Adults and immatures of dermapterans were combined. [f]No captures reported; and [†]All spiders, irrespective of families, combined. Arthropod taxa means followed by the same letters for the insecticide treatments within rows are not significantly different (Tukey-Kramer test, *P* = 0.05). When not significantly different among treatments (*P* = 0.05), no letters are given.

Table 3.5. Mean (± SE) numbers of herbivore and detritivore arthropods collected in pitfall traps from plots treated with various treatments on bermudagrass in trials 1 and 2.

Taxa	Bifenthrin	Chlorantraniliprole	Tetraniliprole	Imidacloprid	Acephate + imidacloprid	Novaluron	Methoxyfenozide	Water
Trial 1[a]								
Curculionidae	1.4 ± 0.4	1.6 ± 0.4	2.3 ± 0.6	1.1 ± 0.3	1.0 ± 0.4	1.1 ± 0.3	1.7 ± 0.6	1.6 ± 0.3
Scarabaeidae	0.4 ± 0.1	0.8 ± 0.3	0.9 ± 0.2	0.5 ± 0.2	0.5 ± 0.2	1.2 ± 0.3	1.1 ± 0.4	1.1 ± 0.3
Elateridae	0.9 ± 0.3ab	0.2 ± 0.1b	0.5 ± 0.2ab	0.3 ± 0.2ab	0.1 ± 0.1b	0.8 ± 0.4ab	1.0 ± 0.3ab	1.1 ± 0.3a
Silvanidae[c]	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.2 ± 0.2	0.1 ± 0.1	0.7 ± 0.4	0.2 ± 0.2	0.5 ± 0.4
Anthicidae	1.7 ± 0.6b	1.9 ± 0.6b	1.0 ± 0.4b	1.2 ± 0.4b	2.2 ± 0.6b	2.7 ± 0.9b	8.1 ± 2.2a	3.5 ± 1.2b
Chrysomelidae	0.5 ± 0.4bc	0.1 ± 0.1c	0.1 ± 0.1c	0.1 ± 0.1c	0.1 ± 0.1c	0.6 ± 0.2bc	1.3 ± 0.4ab	2.7 ± 1.0a
Other Coleoptera[d]	0.9 ± 0.3bdc	2.2 ± 0.6abc	1.7 ± 0.6bdc	0.3 ± 0.1d	0.5 ± 0.1dc	3.1 ± 1.0abc	4.5 ± 1.1a	3.3 ±1.1ab
Coleoptera larvae	0.0 ± 0.0	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.3 ± 0.1	0.4 ± 0.1
Cicadellidae	1.2 ± 0.4bc	2.0 ± 0.4abc	4.7 ± 1.4a	0.7 ± 0.2c	1.0 ± 0.3bc	1.9 ± 0.5abc	2.9 ± 0.6ab	1.9 ± 0.5abc
Aphididae	0.2 ± 0.1	0.3 ± 0.2	0.1 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.3 ± 0.2	0.5 ± 0.2	0.3 ± 0.1
Cydnidae	0.6 ± 0.4c	1.5 ± 0.3abc	0.5 ± 0.2bc	2.2 ± 0.6ab	3.1 ± 0.8a	1.2 ± 0.5abc	1.5 ± 0.4abc	1.3 ± 0.4abc
Other Hemiptera[e]	1.9 ± 0.6b	9.8 ± 1.5a	10.2 ± 2.1a	0.8 ± 0.2b	0.6 ± 0.2b	2.1 ± 0.8b	10.2 ± 2.3a	7.4 ± 1.5a
Diptera[f]	5.2 ± 0.9ab	7.7 ± 1.5a	7.5 ± 1.0a	3.9 ± 0.7ab	9.8 ± 3.8a	2.6 ± 0.6b	9.2 ± 2.1a	4.9 ± 0.5ab
Lepidoptera[c]	0.0 ± 0.0	0.3 ± 0.2	0.1 ± 0.1	0.5 ± 0.3	0.0 ± 0.0	0.2 ± 0.1	0.3 ± 0.1	0.2 ± 0.1
Lepidoptera larvae[c]	0.0 ± 0.0	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.1	0.0 ± 0.0
Gryllidae[c]	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Gryllotalpidae	2.9 ± 1.1a	2.7 ± 0.9ab	1.4 ± 0.4ab	0.8 ± 0.4b	2.6 ± 1.0ab	1.7 ± 0.5ab	2.9 ± 1.0a	1.7 ± 0.5ab
Thripidae	1.0 ± 0.4ab	0.9 ± 0.2ab	0.7 ± 0.3ab	0.2 ± 0.1b	0.2 ± 0.1b	0.3 ± 0.2b	1.4 ± 0.4a	1.5 ± 0.3a
Psocoptera[c]	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Collembola	673.6 ± 173.4a	330.7 ± 56.2a	584.5 ± 171.8a	69.8 ± 12.4b	67.8 ± 23.5b	347.1 ± 56a	576 ± 96.9a	504.9 ± 107.1a
Acari	52.2 ± 17.9b	158.7 ± 26a	134.1 ± 29.6a	134.8 ± 32.2a	130.1 ± 33.1a	144.7 ± 35.4a	102.3 ± 18.1a	131.9 ± 24.5a
Myriapoda[c]	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Trial 2[b]								
Curculionidae	1.8 ± 0.3	2.2 ± 0.6	1.8 ± 0.3	1.5 ± 0.3	1.0 ± 0.2	1.1 ± 0.3	2.0 ± 0.4	1.7 ± 0.5
Scarabaeidae	0.2 ± 0.1	0.4 ± 0.2	0.5 ± 0.2	0.3 ± 0.1	0.2 ± 0.1	0.6 ± 0.2	0.7 ± 0.4	0.1 ± 0.1
Elateridae	0.3 ± 0.1a	0.2 ± 0.1ab	0.0 ± 0.0b	0.0 ± 0.0b	0.1 ± 0.0ab	0.0 ± 0.0b	0.2 ± 0.1ab	0.0 ± 0.0b
Silvanidae[c]	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.0
Anthicidae	0.6 ± 0.2b	2.1 ± 0.6ab	1.1 ± 0.2ab	0.4 ± 0.2b	0.6 ± 0.3b	1.0 ± 0.3ab	2.6 ± 0.6a	1.5 ± 0.4ab
Chrysomelidae	-[g]	-	-	-	-	-	-	-
Other Coleoptera[d]	0.0 ± 0.0	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.4 ± 0.3	0.1 ± 0.1	0.3 ± 0.2	0.1 ± 0.1

Coleoptera larvae	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.2	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Cicadellidae	0.2 ± 0.1	0.3 ± 0.1	0.8 ± 0.3	0.1 ± 0.1	0.3 ± 0.2	0.5 ± 0.2	0.5 ± 0.2	0.5 ± 0.2
Aphididae	0.2 ± 0.1ab	0.3 ± 0.2ab	0.1 ± 0.0b	1.7 ± 0.8a	0.1 ± 0.0b	0.5 ± 0.2ab	0.0 ± 0.0b	0.3 ± 0.2ab
Cydnidae	0.0 ± 0.0b	0.1 ± 0.1ab	0.0 ± 0.0b	0.2 ± 0.1ab	0.5 ± 0.2a	0.0 ± 0.0b	0.0 ± 0.0b	0.1 ± 0.0b
Other Hemiptera[e]	0.2 ± 0.2b	11.3 ± 6.7ab	4.2 ± 3.2ab	92.7 ± 52.3a	3.5 ± 1.6ab	3.6 ± 2.3ab	0.8 ± 0.2b	0.9 ± 0.3b
Diptera[f]	3.1 ± 0.5b	4.6 ± 0.7ab	5.6 ± 0.9ab	5.6 ± 0.9ab	7.6 ± 1.4a	4.3 ± 0.6ab	3.4 ± 0.6b	3.4 ± 0.8b
Lepidoptera[c]	0.0 ± 0.0	0.2 ± 0.1	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.2 ± 0.1
Lepidoptera larvae[c]	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Gryllidae[c]	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1
Gryllotalpidae	-[g]	-	-	-	-	-	-	-
Thripidae	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.0	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0
Psocoptera[c]	0.0 ± 0.0	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.4 ± 0.3	0.2 ± 0.1	0.0 ± 0.0
Collembola	11.4 ± 3.7a	3.7 ± 1.1b	19.8 ± 5.9a	3.5 ± 0.8b	1.9 ± 0.6b	18.3 ± 6.1a	13.8 ± 4.2a	11.1 ± 3.4a
Acari	4.6 ± 1.4b	6.6 ± 1.9ab	8.8 ± 2.8ab	3.2 ± 1.1b	5.0 ± 2.8b	16.5 ± 4.8a	6.9 ± 2.4ab	5.7 ± 1.7ab
Myriapoda[c]	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

[a]June-July 2022; [b]September-October 2022; [c]No statistical analysis was performed for these taxa due to low captures; [d]Unidentified adult coleopteran beetles; [e]Unidentified hemipteran adults and nymphs; [f]All adults; and [g]No captures reported. Arthropod taxa means followed by the same letters for the insecticide treatments within rows are not significantly different (Tukey-Kramer test, P = 0.05). When not significantly different among treatments (P = 0.05), no letters are given.

Table 3.6. Mean (± SE) numbers of beneficial arthropods collected in pitfall traps post-application of insecticide treatments on bermudagrass in trials 1 and 2.

Taxa	Sample collection date				
	3	6	16	24	31
Trial 1[a]					
Carabidae	6.5 ± 0.9a	2.8 ± 0.5b	3 ± 0.4b	2.7 ± 0.5b	3.7 ± 0.6b
Staphylinidae	2.0 ± 0.5	1.3 ± 0.3	1.2 ± 0.3	1.5 ± 0.4	2.4 ± 0.5
Lampyridae[c]	0.0 ± 0.0	0.1 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Miridae	4.2 ± 0.7b	5.2 ± 0.9ab	6.5 ± 0.7a	1.5 ± 0.3c	0.2 ± 0.1d
Geocoridae	0.2 ± 0.1b	0.4 ± 0.1b	1.1 ± 0.2a	0.6 ± 0.1ab	1.1 ± 0.2a
Other predatory Heteroptera[cd]	0.0 ± 0.0	0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.0 ± 0.0
Formicidae	26.0 ± 3.5	16.8 ± 2.1	21.9 ± 3.4	19.5 ± 3.4	23.5 ± 3.6
Parasitic Hymenoptera	13.5 ± 2.3b	16.7 ± 2.7b	40.8 ± 6.3a	16.3 ± 2.6b	30.5 ± 4.3a
Dermaptera[ce]	0.2 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	0.3 ± 0.1	0.1 ± 0.1
Phlaeothripidae[c]	0.3 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
Araneae[†]	5.7 ± 0.7ab	5.8 ± 0.8ab	6.0 ± 0.7a	3.8 ± 0.5b	6.8 ± 0.5a
Trial 2[b]					
Carabidae	0.7 ± 0.2	0.8 ± 0.2	0.5 ± 0.2	0.3 ± 0.1	0.6 ± 0.2
Staphylinidae	2.6 ± 0.5a	1.3 ± 0.5b	0.8 ± 0.3bc	0.1 ± 0.1c	1.2 ± 0.3ab
Lampyridae[c]	-[f]	-	-	-	-
Miridae	0.0 ± 0.0ab	0.0 ± 0.0ab	0.0 ± 0.0b	0.0 ± 0.0b	0.3 ± 0.1a
Geocoridae	0.1 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0
Other predatory Heteroptera[cd]	0.3 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.3 ± 0.1
Formicidae	23.5 ± 4.1a	14.1 ± 2.1a	6.8 ± 1.1b	5.5 ± 0.9b	12.5 ± 1.6a
Parasitic Hymenoptera	7.7 ± 1.0a	6.0 ± 0.7ab	4.1 ± 0.7bc	2.3 ± 0.4c	4.1 ± 0.5bc
Dermaptera[ce]	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1
Phlaeothripidae[c]	0.1 ± 0.0	0.3 ± 0.2	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Araneae[†]	4.3 ± 0.7a	3.2 ± 0.5ab	1.8 ± 0.3bc	0.9 ± 0.2c	2.3 ± 0.3b

[a]June-July 2022; [b]September-October 2022; [c]No statistical analysis was performed because of density captures; [d]Adults and nymphs of reduviids and nabids were combined; [e]Adults and immatures of dermapterans were combined; [f]No captures reported; and [†]All spiders, irrespective of families, combined. Arthropod taxa means followed by the same letters for the sample collection dates within

rows are not significantly different (Tukey-Kramer test, $P = 0.05$). When not significantly different among treatments ($P = 0.05$), no letters are given.

Table 3.7. Mean (± SE) numbers of herbivore and detritivore arthropods collected in pitfall traps post-application of insecticide treatments on bermudagrass in trials 1 and 2.

Taxa	Sample collection date				
	3	6	16	24	31
Trial 1[a]					
Curculionidae	0.5 ± 0.1c	0.6 ± 0.1c	1.3 ± 0.2bc	2.3 ± 0.4ab	2.6 ± 0.4a
Scarabaeidae	1.3 ± 0.3a	0.3 ± 0.1b	1.3 ± 0.2a	0.5 ± 0.2b	0.4 ± 0.1b
Elateridae	0.6 ± 0.2b	0.1 ± 0.1b	1.3 ± 0.3a	0.4 ± 0.2b	0.4 ± 0.1b
Silvanidae[c]	0.2 ± 0.2	0.0 ± 0.0	0.1 ± 0.1	0.2 ± 0.1	0.6 ± 0.3
Anthicidae	0.7 ± 0.3c	0.3 ± 0.1c	2.1 ± 0.5b	3.7 ± 0.7b	7.1 ± 1.5a
Chrysomelidae	0.6 ± 0.3ab	0.7 ± 0.4ab	1.3 ± 0.5a	0.6 ± 0.2ab	0.1 ± 0.1b
Other Coleoptera[d]	0.7 ± 0.2c	0.8 ± 0.2bc	2.6 ± 0.6ab	2.1 ± 0.6bc	4.2 ± 0.9a
Coleoptera larvae	0.1 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1
Cicadellidae	1.2 ± 0.3bc	1.4 ± 0.5bc	4.0 ± 0.8a	0.8 ± 0.2c	2.6 ± 0.5ab
Aphididae	0.3 ± 0.1ab	0.3 ± 0.1ab	0.4 ± 0.1a	0.1 ± 0.0b	0.1 ± 0.1ab
Cydnidae	1.1 ± 0.2bc	0.3 ± 0.1c	0.9 ± 0.2c	2.7 ± 0.5a	2.4 ± 0.5ab
Other Hemiptera[e]	7.7 ± 1.4a	7.7 ± 1.9a	6.7 ± 1.4a	2.2 ± 0.3b	2.6 ± 0.5b
Diptera[f]	5.0 ± 0.9	6.6 ± 0.9	7.4 ± 1.3	5.9 ± 1.0	6.7 ± 2.4
Lepidoptera[c]	0.3 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	0.2 ± 0.2	0.0 ± 0.0
Lepidoptera larvae[c]	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Gryllidae[c]	0.0 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1
Gryllotalpidae	7.0 ± 0.9a	1.1 ± 0.2b	1.1 ± 0.2b	0.7 ± 0.2b	0.5 ± 0.2b
Thripidae	1.0 ± 0.2a	1.3 ± 0.3a	1.0 ± 0.3a	0.3 ± 0.1b	0.2 ± 0.1b
Psocoptera[c]	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Collembola	326.1 ± 43.9bc	154.1 ± 25.5d	825.3 ± 140a	467.0 ± 90.7b	198.7 ± 36.0cd
Acari	129.3 ± 23.4b	44.9 ± 9.2c	66.9 ± 9b	125.2 ± 17.9b	251.6 ± 25.6a
Myriapoda[c]	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Trial 2[b]					
Curculionidae	2.8 ± 0.3a	1.6 ± 0.3b	1.7 ± 0.4b	1.0 ± 0.2b	0.9 ± 0.2b
Scarabaeidae	0.3 ± 0.1b	1.0 ± 0.3a	0.2 ± 0.1b	0.0 ± 0.0b	0.2 ± 0.1b
Elateridae	0.2 ± 0.1	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.0
Silvanidae[c]	0.1 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Anthicidae	2.0 ± 0.3a	1.3 ± 0.3ab	0.8 ± 0.2bc	0.3 ± 0.1c	1.8 ± 0.5ab
Chrysomelidae	-[g]	-	-	-	-
Other Coleoptera[d]	0.4 ± 0.2	0.2 ± 0.1	0.2 ± 0.1	0.0 ± 0.0	0.1 ± 0.0
Coleoptera larvae	0.2 ± 0.1	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Cicadellidae	0.2 ± 0.1	0.4 ± 0.1	0.4 ± 0.1	0.6 ± 0.2	0.4 ± 0.1

Aphididae	0.5 ± 0.4	0.3 ± 0.3	0.4 ± 0.2	0.4 ± 0.2	0.3 ± 0.1
Cydnidae	0.1 ± 0.0	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.3 ± 0.1
Other Hemiptera[e]	10.5 ± 8.8	8.1 ± 5.9	8.7 ± 7.4	6.7 ± 4.0	39.2 ± 31.7
Diptera[f]	3.7 ± 0.7b	5.9 ± 0.5a	7.0 ± 1.0a	4.0 ± 0.6b	2.8 ± 0.4b
Lepidoptera[c]	0.0 ± 0.0	0.1 ± 0.1	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Lepidoptera larvae[c]	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Gryllidae[c]	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.0	0.0 ± 0.0
Gryllotalpidae	-[g]	-	-	-	-
Thripidae	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Psocoptera[c]	0.2 ± 0.1	0.3 ± 0.2	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Collembola	8.4 ± 1.4b	11.4 ± 2.8b	3.1 ± 0.8c	1.9 ± 0.4c	27.3 ± 5.3a
Acari	9.6 ± 2.5b	8.0 ± 1.7b	1.6 ± 0.3c	1.3 ± 0.3c	15.2 ± 3.1a
Myriapoda[c]	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.0

[a]June-July 2022; [b]September-October 2022; [c]No statistical analysis was performed for these taxa due to low captures; [d]Unidentified adult coleopteran beetles; [e]Unidentified hemipteran adults and nymphs; [f]all adults; and [g]No captures reported. Arthropod taxa means followed by the same letters for the sample collection dates within rows are not significantly different (Tukey-Kramer test, P = 0.05). When not significantly different among treatments (P = 0.05), no letters are given.

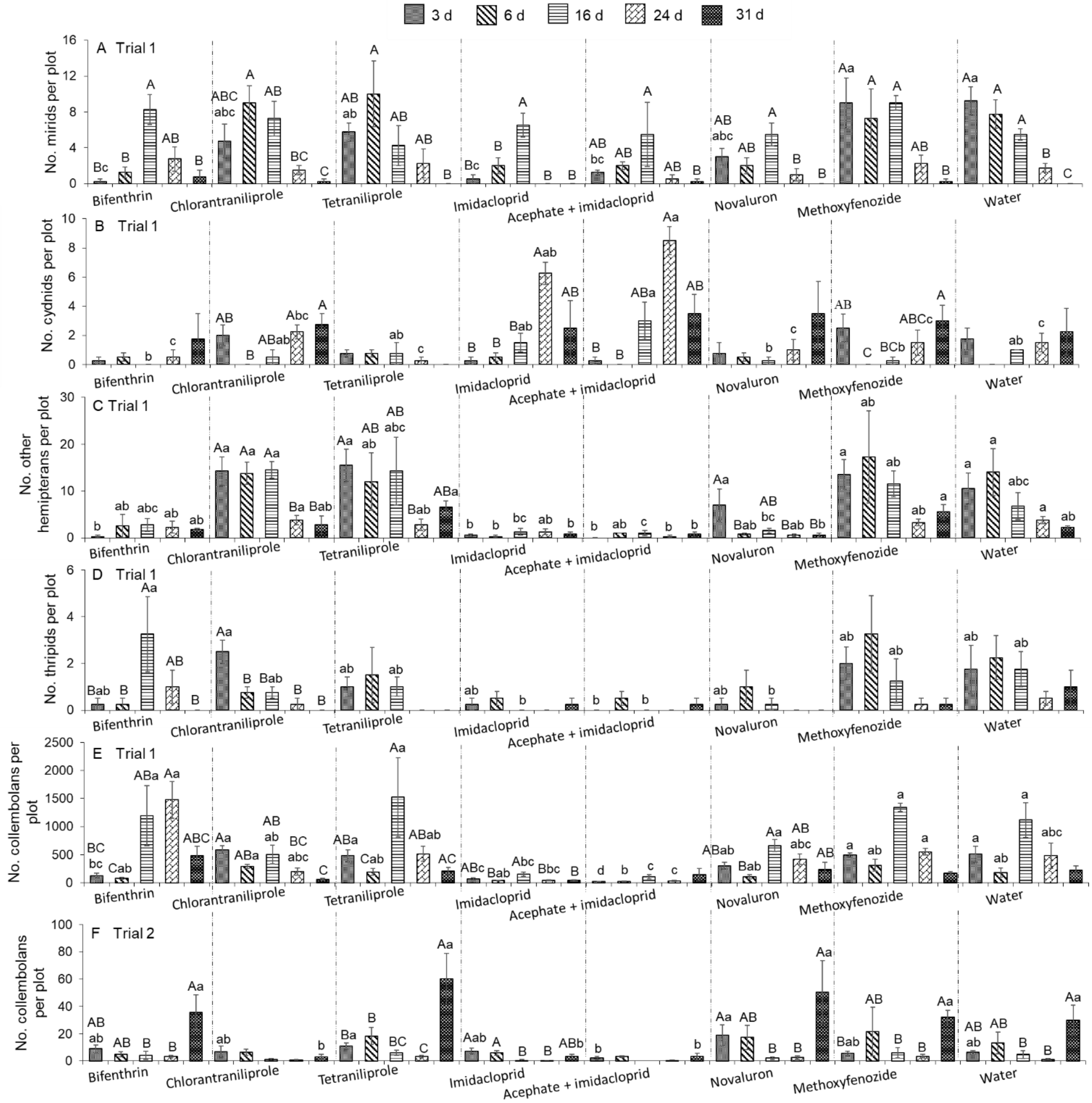

Fig. 3.1. Mean (±SE) numbers of (A) mirids, (B) cydnids, (C) other hemipterans, (D) thripids and (E) collembolans in trial 1, and (F) collembolans in trial 2 collected in pitfall traps deployed on different treatment plots on sampling days after application of insecticides. Bars with the same uppercase letters within the insecticide treatment are not significantly different at α = 0.05 (Tukey's HSD test), whereas the bars of the same filled pattern across the insecticide treatment with the same lowercase letters are not significantly different at α = 0.05 (Tukey's HSD test).

CHAPTER 4

SUMMARY

Two important studies were conducted as part of this thesis. These two studies established a foundation by documenting how the occurrence and abundance of beneficial arthropods are affected by turfgrass growth cover and commonly used insecticides. The information on the effects of turfgrass cover on beneficial arthropods will help to understand when to use the management tactics, such as insecticide spray so that the insecticide effects on the beneficial arthropods can be minimized. Ideally, insecticides are applied when beneficial arthropods are at low densities. This strategy would be less disruptive to the health and population dynamics of beneficial arthropods. Secondly, we sought to understand how commonly used insecticides affect beneficial arthropods to know what to expect when using various insecticides. Overall, the aim was to refine the integrated pest management strategies for many turfgrass pests with minimal disruption to beneficial arthropods.

Among turfgrass pests, hunting billbug, *Sphenophorus venatus vestitus* Chittenden (Coleoptera: Curculionidae) is a severe pest in sod farms. High densities of billbugs occur at various stages of turfgrass in sod farms. To develop an effective IPM strategy for *S. venatus vestitus*, it is critical to understand the relative abundance of beneficial arthropods at various stages of turfgrass growth in sod farms. It is especially important to determine when to use the insecticides with minimal disruption to beneficial arthropods. In 2021 and 2022, zoysiagrass (*Zoysia* spp.) sod fields with 0%, 50%, and 100% turfgrass cover were selected in sod farms, and arthropods abundance was documented using pitfall traps. The numbers of carabids, staphylinids, parasitic hymenopterans, and Araneae in 2021, and the parasitic hymenopterans, and Araneae in 2022 were significantly lower for the 0 and/or 50% turfgrass cover treatments than for the 100% turfgrass cover treatment. However, captures of dermapterans were significantly lower in the 100% than in the 0% and 50% turfgrass cover treatments in 2021, whereas in the 100% turfgrass cover treatment than in the 50% turfgrass cover treatment in 2022. The densities of other hymenopterans in 2021 and mirids in 2022 were less abundant in the 100% turfgrass cover treatment than in the 50% turfgrass cover treatment. Thus, beneficial arthropods were abundant at all stages of turfgrass cover but tended to be lower when turfgrass cover was < 100%.

Secondly, chemical control is an important tactic used to manage major pests in turfgrass. However, their nontarget effects are poorly understood, especially with newer insecticides available to turfgrass managers. Therefore, the objective of this study was to determine the effects of commonly used insecticides on beneficial arthropods in turfgrass. In 2022, two trials were conducted on the bermudagrass lawn. The treatments were bifenthrin, chlorantraniliprole, tetraniliprole, imidacloprid, acephate + imidacloprid, novaluron and methoxyfenozide were sprayed on bermudagrass (*Cynodon* spp.). Imidacloprid, acephate + imidacloprid and bifenthrin induced an immediate effect on the abundance of certain beneficial arthropods, such as mirids, geocorids and parasitic hymenopterans for a shorter term, than others, such as carabids, formicids and Araneae, which elicited a delay response. Methoxyfenozide, novaluron, tetraniliprole and chlorantraniliprole were less disruptive to beneficial arthropods, such as carabids, staphylinids, mirids, geocorids, formicids, parasitic hymenopterans and spiders.

Therefore, these studies showed that methoxyfenozide, novaluron, tetraniliprole and chlorantraniliprole have minimal effects on beneficial arthropods. The best window for applying insecticides for *S. venatus vestitus* management could be when turfgrass is at the early stages of growth and development. More research are still warranted to validate the effects of these insecticides when applied at various stages of turfgrass growth on *S. venatus vestitus* control. The new information learned through current studies will be utilized before selection and application of insecticide for integrated management of pest in turfgrass.