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Comparison of carabid densities in different cover crop species in north Florida

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Abstract

Many ground beetle species (Coleoptera: Carabidae) prey on noctuid larvae and pupae. Therefore, agricultural practices that maintain or even enhance carabid populations have the potential to reduce noctuid pest populations through predation. One such pest is the fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), a migratory pest of row, turf, and vegetable crops. Before migrating in spring from southern Florida and southern Texas, it feeds and develops on cover crops such as field corn and sorghum-sudangrass and expands its populations. Here we sampled the species and density of carabid populations that were active in cover crops with differing capacity to support fall armyworm development. Three cover crop species, sorghum-sudangrass, cowpea, and sunn hemp, were previously studied for their effects on fall armyworm populations, with sunn hemp showing high incompatibility with fall armyworm development. The cover crops were grown in 3 locations in north and north-central Florida and pitfall traps were used to compare numbers of carabid beetles caught in different cover crop treatments. Almost 2,000 predatory and omnivorous carabid beetles were collected. Three species in particular, *Calosoma sayi* Dejean, *Tetracha carolina* (L.), and *Cicindela punctulata* Olivier, are known predators of *S. frugiperda* in the laboratory and may aid in the reduction of populations in the field. There were no differences in beetle numbers among cover crop plants. In another trial, more beetles were collected in plots of a popular sunn hemp cultivar developed in the southeastern U.S., 'AU Golden', than in plots of another germplasm line, Tillage Sunn™. Further research should determine if the predatory species found in this study prey on *S. frugiperda* in the field and if this added mortality helps reduce crop damage.

Key Words: fall armyworm; ground beetles; sunn hemp; *Calosoma*; *Tetracha*; *Cicindela*; *Selenophorus*

Resumen

Muchas de las especies de escarabajos terrestres (Coleoptera: Carabidae) se alimentan de larvas y pupas de noctuidos. Por lo tanto, las prácticas agrícolas que mantienen o incluso mejoran las poblaciones de carábidos tienen el potencial de reducir las poblaciones de plagas noctuidas a través de la depredación. Una de esas plagas es el gusano cogollero, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), una plaga migratoria de cultivos en hileras, césped y hortalizas. Antes de migrar en primavera desde el sur de la Florida y el sur de Texas, se alimenta y se desarrolla con cultivos de cobertura como maíz y sorgo-pasto sudán con los cuales expande sus poblaciones. Aquí tomamos muestras de las especies y la densidad de las poblaciones de carábidos que estaban activos en cultivos de cobertura con diferentes capacidades para apoyar el desarrollo del gusano cogollero. Tres especies de cultivos de cobertura, sorgo-pasto sudán, caupí y cáñamo sunn, se estudiaron previamente por sus efectos sobre las poblaciones de gusano cogollero, y el cáñamo sunn mostró una alta incompatibilidad con el desarrollo del gusano cogollero. Se cultivaron los cultivos de cobertura en tres lugares del norte y centro-norte de la Florida y se utilizaron trampas de caída para comparar el número de escarabajos carábidos capturados en diferentes tratamientos de cultivos de cobertura. Se recolectaron casi 2.000 escarabajos carábidos depredadores y omnívoros. Tres especies en particular, *Calosoma sayi* Dejean, *Tetracha carolina* (L.) y *Cicindela punctulata* Olivier, son depredadores conocidos de *S. frugiperda* en el laboratorio y pueden ayudar a reducir las poblaciones en el campo. No hubo diferencias en el número de escarabajos entre las plantas de cultivos de cobertura. En otro ensayo, se recolectaron más escarabajos en parcelas del popular cultivar de cáñamo sunn desarrollado en el sureste de EE. UU., 'AU Golden', que en las parcelas de otra línea de germoplasma, Tillage Sunn™. Investigaciones adicionales deberían determinar si las especies depredadoras encontradas en este estudio se alimentan de *S. frugiperda* en el campo y si esta mortalidad adicional ayuda a reducir el daño a los cultivos.

Palabras Clave: gusano cogollero; escarabajos terrestres; cáñamo sunn; *Calosoma*; *Tetracha*; *Cicindela*; *Selenophorus*

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The fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), is a migratory neotropical noctuid pest of row, turf, and vegetable crops around the world. Originally this species only infested crops in the Western Hemisphere (Luginbill 1928; Andrews 1980; Montezano et al. 2018), but in recent years it has been documented in India (Sharanabasappa et al. 2018), southeast Asia (Dao et al. 2020), China (Jing et al. 2019), Korea (Lee et al. 2020), Australia (Cook et al. 2021) and in most sub-Saharan countries in Africa (Goergen et al. 2016; Tindo et al. 2017; Tambo et al. 2020). In North America, fall armyworm has continuous generations (overwintering) in southern Florida and southern Texas, before adults disperse north in the spring and summer months (Nagoshi et al. 2012; Westbrook et al. 2019). Fall armyworm populations from these areas in southern Florida move into secondary source areas (stepping-stone nurseries) located in northern Florida by Apr and May (Pair & Westbrook 1995), which are planted with vegetable crops in late winter and early spring (Elwakil & Mossler 2019; Zotarelli et al. 2021). These migrating moths oviposit, and larvae develop on vegetables and cover crops that are grown after the cash crops. Migrating populations then move from northern Florida to corn plantings further north to eventually infest crops as far north as southern Canada (Sparks 1979).

Many vegetable growers in Florida plant cover crops either before or after their main crop is harvested. These plants include grass, cereal, temperate and tropical legumes, and *Brassica* species (Snapp et al. 2005), which are used to improve soil conditions (Cherr et al. 2007), suppress weed populations (Adler & Chase 2007), and reduce plant parasitic nematode densities (Braz et al. 2016). Corn (*Zea mays* L.) and sorghum-sudangrass (*Sorghum bicolor* [L.] Moench × *S. bicolor* var. *sudanense* [Piper] Stapf.) (SSG) (both Poaceae) are 2 commonly planted grass species that are used for livestock forage and to increase soil organic matter (Wallau et al. 2022). Sorghum-sudangrass is a warm-season annual grass hybrid that is used as a green manure cover crop following harvest of winter vegetables (Vendramini et al. 2019).

However, cover crop plants can also influence the density of pest insect populations. For example, *Spodoptera litura* (Fabricius) develops well on certain plants such as sesbania (*Sesbania roxburghii* Merr.; Fabaceae) and rapeseed (*Brassicae campestris* L. variety *chinensis*; Brassicaceae) and can develop large populations that then infest surrounding vegetable and row crops (Tuan et al. 2014). Fall armyworm develops well on certain grass cover crops such as corn and sorghum-sudangrass, thereby increasing their populations to either infest adjoining crops or migrate northward (Pair & Westbrook 1995; Meagher et al. 2004, 2022).

For areawide management of fall armyworm, planting of alternate cover crops may reduce migrating populations. A study by Meagher et al. (2004) showed that sunn hemp (*Crotalaria juncea* L.) and cowpea (*Vigna unguiculata* [L.] Walpers subsp. *unguiculata*) (both Fabaceae) have the potential to reduce areawide populations of fall armyworm. Sunn hemp is a warm-season legume that is used in alternation with vegetable crops (Mansoer et al. 1997). The first sunn hemp cultivar commercialized in the U.S. was the Hawaiian cultivar 'Tropic Sun' (Rotar & Joy 1983), but other varieties or germplasm lines from Africa and Asia also are used as cover crops in the U.S. (Cho et al. 2016). Cowpea is a warm-season annual legume that alone or mixed with sorghum-sudangrass can be used as a cover crop or intercrop with vegetables (Cho et al. 2012; Harrison et al. 2014). More comprehensive studies after Meagher et al. (2004) showed sunn hemp and cowpea had fall armyworm populations 70–96% less than sorghum-sudangrass (Meagher et al. 2022), concluding that substituting sorghum-sudangrass with these plants could be preferable as a replacement cover crops for areawide management of fall armyworm.

Cover crops can contribute an ecological service by producing flowers that provide resources for pollinators and insect food for predators and parasitoids (Campbell et al. 2016). Many natural enemy species attack *S. frugiperda*, including parasitoids, pathogens, and predators (Nagoshi & Meagher 2022), and the agricultural habitat is an important factor in conserving the numbers of natural enemies present (Landis et al. 2000). Working with a new domestic sunn hemp cultivar, research showed that substantial flowering and seed production in the summer was possible at the latitude of north-central Florida (Meagher et al. 2017). These may sustain populations of beneficial insects including epigeal predators. In the present study, our main objective was to compare carabid populations in plots grown with different cover crop species and to identify predator and omnivore species active in north and north-central Florida agroecosystems. Our subobjectives were to calculate diversity indices of carabid populations in these cover crop plots and to determine if carabid density is affected by sunn hemp genotype and planting season (spring vs. summer).

Materials and Methods

STUDY SITES 2011–2013

Cover crops were planted at the University of Florida (UF) North Florida Research and Education Center, Quincy, Florida in 2011 and 2012 (Gadsden county; 30.5460000 °N, 84.5990000 °W), and at the UF/IFAS (Institute of Food and Agricultural Sciences) Plant Science Research and Education Unit, Citra, Florida in 2012 and 2013 (Marion county; 29.4100000 °N, 82.1730000 °W). These plots were the same ones used for the fall armyworm infestation trials (Meagher et al. 2022). Briefly, the experimental design at both locations was a randomized complete block with 4 cover crop treatments, 4 blocks, and 6–12 row plots that were 15.24–30.50 m long and were planted on 91.4 cm row centers. All plots were treated by pre-plant herbicides at locally recommended application rates; after planting no pesticides were applied. Plots at Quincy were planted 7 Jul 2011 (cowpeas, fallow, sunn hemp, and sorghum-sudangrass) and 12 Jun 2012 (corn, cowpeas, sunn hemp, and sorghum-sudangrass) and were naturally irrigated. The fallow plots at Quincy in 2011 were tilled and left undisturbed so that weed growth could progress through the season. Plots at Citra were planted on 3 Jul 2012 (corn, cowpeas, sunn hemp, and sorghum-sudangrass) and 11 Jun 2013 (corn, sunn hemp, sorghum-sudangrass, and a 50:50 mix of sunn hemp and sorghum-sudangrass) and had overhead irrigation throughout the season. Sunn hemp seed used in 2011–2013 was an unknown germplasm line (variety not stated) from South Africa (purchased from Petcher Seeds, Fruitdale, Alabama, U.S.A.), and was mixed with a cowpea-type *Rhizobium* inoculum before planting. Sorghum-sudangrass seed was Forage First Sudax SX-17 Sorghum × Sudangrass hybrid (Forage First, LaCrosse, Wisconsin, U.S.A.; now sold by Forage Genetics International, Nampa, Idaho, U.S.A.). Cowpea seed was of the 'Iron & Clay' variety and was purchased through local distributors and was mixed with a cowpea-type *Rhizobium* inoculum, also purchased at a local distributor, before planting.

STUDY SITE 2016

In 2016, 2 lines of sunn hemp were planted on 2 different dates. The first planting date was 11 Mar, followed by another planting on 27 Jul. 'AU Golden' (purchased Apr 2015 from Petcher Seeds, Fruitdale, Alabama, U.S.A.) and Tillage Sunn™ (purchased Mar 2014 from Hancock Seed Co., Dade City, Florida, U.S.A.), were planted at the United States Department of Agriculture, Agricultural Research Services (USDA-ARS) Tallahassee laboratory in Leon county, Florida (30.4750000 °N, 84.1700000 °W). Each treatment had 4 replicates (planting date × sunn hemp line) for a total of 16 plots. Each plot was 7.6 m per side, with a 2.1 m buffer between plots. The experimental field was prepared with a field cultivator and a pre-emergent herbicide, pendimethalin (Prowl®, BASF, Florham Park, New Jersey, U.S.A.), was applied at 2.24 kg/ha with a backpack sprayer on 7 Mar 2016. Mechanical weed control and hand weeding were used in the plots post-emergence. Sunn hemp seeds were broadcast at 13.45 kg/ha, raked in, and irrigated with tripod stand sprinklers until germination. The plots were ratooned (cut back and allowed to regrow) once on 15 Jun to promote re-flowering.

SAMPLING

Each pitfall trap was constructed by placing a red plastic cup (532.3 mL, Solo Cup Co., Lake Forest, Illinois, U.S.A.) in the ground to hold soil in place and placing another red plastic cup inside containing approximately 150 mL of either a detergent solution (mixture of a couple drops of liquid dish washing detergent [Dawn, Procter and Gamble, Cincinnati, Ohio, U.S.A.] in 3.8 L water), or diluted propylene glycol, which trapped and preserved crawling insects. Traps were covered by a roof (23 × 28 cm) made from wire and the top half of a Pherocon® insect monitoring trap (Trécé Inc., Adair, Oklahoma, U.S.A.). Captured insects were removed and preserved in 70% ethyl alcohol until they were pinned for identification.

Pitfall traps were placed in the middle of each cover crop plot (16 per site) at Quincy and Citra in 2011–2013 to monitor ground beetle populations. In 2011 at Quincy, traps were set 30 Aug and checked 7 and 28 Sep. In 2012 at Quincy, traps were set 12 Jul and checked 16, 20, and 27 Jul, 2, 10, and 16 Aug. In 2012 at Citra, traps were set 3 Aug and checked 9, 17, 24, and 30 Aug, 11 and 20 Sep. In 2013 at Citra, traps were set 9 Jul and checked 16 and 23 Jul, 16 Aug, and 20 Sep. The Citra and Quincy sites had missing data due to heavy local rainfall during thunderstorms during the season or tropical activity (Tropical Storm Debby in Jun 2011). Thus, traps were active for 29 d at Quincy in 2011, 34 d at Quincy in 2012, 48 d at Citra in 2012, and 73 d at Citra in 2013.

In Tallahassee in 2016, 8 of the 24 plots were randomly selected and pitfall traps were set in 2 locations per plot. One trap was placed approximately 30 cm into the sunn hemp plot and another trap was placed approximately 2 m into the plot. In addition to these traps, 5 pitfall traps were randomly placed between the sunn hemp plots in open areas without a plant canopy, to serve as controls. All pitfall traps were set for 48 hrs approximately every 2 wks from 13 Jun until 18 Nov 2016. The Tallahassee site had missing data due to heavy local thunderstorms during the season or tropical activity (Tropical Storm Colin in Jun, Hurricane Hermine in Aug, and Tropical Storm Julia in Sep). Thus, total captures represent 2 d of activity for 7 wks of the first planting and 3 wks of the second planting.

Beetles were identified using several resources (Bell 1960; Downie & Arnett Jr. 1996; Ciegler 2000; Ball & Bousquet 2001; Choate 2003; Bousquet 2010; 2012; Pearson et al. 2015). Voucher specimens are kept at USDA-ARS CMAVE (Center for Medical, Agricultural and Veterinary Entomology) in Gainesville, Florida.

STATISTICAL ANALYSIS

Diversity indices incorporate species richness and species evenness into a single value, however, it is often difficult to interpret the meaning of the single statistic (Ludwig & Reynolds 1988). Hill (1973) developed several diversity numbers, organized by Ludwig & Reynolds (1988). They are,

$$N0 = S,$$

where S = the number of species present in the sample and is considered species richness. The second number is:

$$N1 = e^{H'},$$

where $e^{H'}$ is the exponent of Shannon's index (H'), which measures the average degree of uncertainly in predicting to what species an individual chosen at random from a collection of species and individuals will belong (Ludwig & Reynolds 1988). Shannon's index is:

$$H' = -(\sum p_i \ln p_i),$$

where p_i = proportional abundance of the i^{th} species (Shannon & Weaver 1949). The final number is:

$$N2 = 1 / D,$$

where $D = \sum p_i^2$ and is known as Simpson's diversity index (or λ) (Simpson 1949), which measures the probability that 2 individuals drawn at random from a population belong to the same species (Ludwig & Reynolds 1988). Therefore, N0 = the number of species, N1 = the number of abundant species in the sample, and N2 = the number of very abundant species in the sample (Ludwig & Reynolds 1988). These indices were calculated across sampling dates (sampling dates were combined) for each replication and compared across cover crop treatments for Quincy in 2011 and Quincy in 2012. They were not calculated for Citra in 2012 or Citra in 2013 as too few carabids were captured. The indices also were calculated for the Tallahassee 2016 results across the Mar and Jul plantings by comparing species numbers across sampling dates in 'AU Golden' vs. Tillage Sunn™ plots and the 2 sampling positions.

The evenness index was calculated using the modified Hill's ratio (Hill 1973) as:

$$E = (1 / D)-1 / e^{H'}-1.$$

With this modification, E approaches zero as a single species becomes more and more dominant (Alatalo 1981), and is relatively unaffected by species richness (Ludwig & Reynolds 1988).

All statistical comparisons were conducted using SAS (SAS Institute 2016). Data were first analyzed using Box-Cox (PROC TRANSREG) and PROC UNIVARIATE to find the optimal normalizing transformation (Osborne 2010). As many numbers were zero, 0.1 was added before transformation. The number of carabid beetles were compared across cover crop treatments using PROC GLIMMIX, and the LSMEANS statement with an adjusted Tukey test used to separate variable means. Both sampling date and block were listed as random variables. For the Tallahassee 2016 data, cultivar, and sampling position, plus the cultivar × position interaction, were compared for each planting date. Sampling date and block were listed as random variables. Diversity indices also were compared across treatments using PROC GLIMMIX and the LSMEANS (adjusted Tukey) test.

Results

SPECIES ABUNDANCE

Sixteen species from 4 subfamilies and 6 tribes were identified from Quincy, Citra, and Tallahassee (Table 1). The most common species found at Quincy and Tallahassee was *Tetracha carolina* (L.), a large tiger beetle. Fair numbers of *Selenophorus palliatus* (F.), *Calosoma sayi* Dejean, and *Cicindela punctulata* Olivier also were found in these locations. Only 5 beetles were found at Citra 2013, 1 *S. palliatus* and 4 unidentified individuals of multiple species (not possible to identify to species due to damage).

QUINCY AND CITRA

The plots in Quincy and Citra were designed to compare movement of carabid populations within and between different cover crop species. At Quincy in 2011 there was a difference in number of carabids found among

Table 1. Number and relative abundance (percent of total) of carabids found in Quincy in 2011 and 2012, Citra in 2012, and Tallahassee in 2016, Florida.

Subfamily	Tribe	Species and Functional Group	Quincy 2011	Quincy 2012	Citra 2012	Tallahassee 2016
Carabinae	Carabini	*Calosoma sayi* Dejean[C]	33 (24.1)	0	2 (12.5)	12 (1.4)
Cicindelinae	Megacephalini	*Tetracha carolina* (L.)[C]	47 (34.3)	724 (72.6)	0	331 (39.2)
		T. virginica (L.)[C]	0	3 (0.3)	0	20 (2.4)
	Cicindelini	*Cicindela* (*Cicindelidia*) *punctulata* Olivier[C]	12 (8.8)	87 (8.7)	0	42 (5.0)
Scaritinae	Pasimachini	*Pasimachus subsulcatus* Say[C]	0	1 (0.1)	1 (6.25)	0
		P. sublaevis (Palisot de Beauvois)[C]	0	0	0	13 (1.5)
Harpalinae	Chlaeniini	*Chlaenius tomentosus* (Say)[C]	1 (0.7)	1 (0.1)	0	1 (0.1)
		C. erythropus Germar[U]	0	1 (0.1)	0	0
		C. laticollis Say[U]	0	3 (0.3)	0	0
	Harpalini	*Amblygnathus iripennis* (Say)[U]	0	0	0	2 (0.2)
		Anisodactylus merula (Germar)[O]	9 (6.6)	6 (0.6)	2 (12.5)	46 (5.4)
		Harpalus pensylvanicus (DeGeer)[O]	16 (11.7)	1 (0.1)	1 (6.25)	59 (7.0)
		H. gravis LeConte[O?]	1 (0.7)	1 (0.1)	1 (6.25)	57 (6.7)
		Harpalus sp.	1 (0.7)	0	0	0
		Selenophorus palliatus (F.)[O]	8 (5.8)	156 (15.6)	9 (56.25)	260 (30.8)
	Lebiini	*Calleida decora* (F.)[C]	0	0	0	2 (0.2)
		Unidentified	9 (6.6)	13 (1.3)	0	0
Total Number			137	997	16	845
Number of species			9	12	6	12

Functional group based on predominant diet as carnivorous (C), omnivorous (O), or unknown (U). L. = Linnaeus, F. = Fabricius. Reference sources are located in the discussion.

cover crops (Table 2). Traps set in the fallow and cowpea plots caught more carabids (62.1% and 25.8% of all beetles collected, respectively) than those in sunn hemp (6.5%) or sorghum-sudangrass (5.5%) plots. *Cicindela punctulata* and *S. palliatus* were only found in fallow plots; more *C. sayi* were found in cowpea and fallow plots than sunn hemp or sorghum-sudangrass plots ($P = 0.0031$). High numbers of carabids were found at Quincy in 2012

Table 2. Number (mean ± SE) of carabid beetles found per day in cover crop plots in Quincy, Floida 2011 and 2012, and in sunn hemp plots in Tallahassee, Florida 2016.

Site	Treatment	Total	Predators[a]	Omnivores[b]
Quincy 2011	cowpea	0.468 ± 0.140 a	0.366 ± 0.123 a	0.055 ± 0.036 b
	fallow	1.126 ± 0.389 a	0.700 ± 0.248 a	0.333 ± 0.125 a
	sunn hemp	0.118 ± 0.041 b	0.100 ± 0.044 b	0.018 ± 0.013 b
	SSG[c]	0.100 ± 0.050 b	0.094 ± 0.051 b	0.006 ± 0.006 b
		$F_{3, 24} = 11.44$, $P < 0.0001$	$F_{3, 24} = 8.62$, $P = 0.0005$	$F_{3, 24} = 7.56$, $P = 0.0010$
Quincy 2012	corn	2.070 ± 0.387 a	1.643 ± 0.373 a	0.362 ± 0.127 a
	cowpea	1.993 ± 0.364 a	1.536 ± 0.320 a	0.450 ± 0.177 a
	sunn hemp	2.044 ± 0.354 a	1.492 ± 0.300 a	0.531 ± 0.223 a
	SSG	1.958 ± 0.478 a	1.735 ± 0.493 a	0.222 ± 0.088 a
		$F_{3, 83} = 0.80$, $P = 0.4991$	$F_{3, 83} = 0.10$, $P = 0.9587$	$F_{3, 83} = 0.46$, $P = 0.7104$
Tallahassee 2016				
Planting date 11 Mar	'AU Golden'	3.40 ± 0.453 a	1.545 ± 0.366 a	1.836 ± 0.267 a
	Tillage Sunn™	1.628 ± 0.341 b	1.181 ± 0.254 a	0.447 ± 0.140 b
		$\|t_{89}\| = 5.01$, $P < 0.0001$	$\|t_{89}\| = 0.99$, $P = 0.3253$	$\|t_{89}\| = 6.37$, $P < 0.0001$
	trap 2 m	2.157 ± 0.328 b	1.147 ± 0.193 a	1.010 ± 0.215 a
	trap 30 cm	3.010 ± 0.505 a	1.608 ± 0.416 a	1.382 ± 0.266 a
		$\|t_{89}\| = 2.03$, $P = 0.0454$	$\|t_{89}\| = 0.79$, $P = 0.4312$	$\|t_{89}\| = 1.08$, $P = 0.2841$
Planting date 27 Jul	'AU Golden'	0.708 ± 0.202 a	0.0 ± 0.0 a	0.708 ± 0.202 b
	Tillage Sunn™	1.021 ± 0.191 a	0.021 ± 0.021 a	1.00 ± 0.183 a
		$\|t_{39}\| = 1.99$, $P = 0.0541$	$\|t_{39}\| = 1.0$, $P = 0.3235$	$\|t_{39}\| = 2.17$, $P = 0.0359$
	trap 2 m	1.0 ± 0.02 a	0.021 ± 0.021 a	0.979 ± 0.191 a
	trap 30 cm	0.729 ± 0.195 a	0.0 ± 0.0 a	0.729 ± 0.195 a
		$\|t_{39}\| = 1.15$, $P = 0.2579$	$\|t_{39}\| = 1.0$, $P = 0.3235$	$\|t_{39}\| = 1.07$, $P = 0.2902$

[a]Predators include the following species: *Calosoma sayi*, *Tetracha carolina*, *T. virginica*, *Cicindela punctulata*, *Pasimachus sublaevis*, *P. subsulcatus*, *Chlaenius tomentosus*, *C. erythropus*, *C. laticollis*, and *Calleida decora.*

[b]Omnivores include the following species: *Anisodactylus merula*, *Harpalus pensylvanicus*, *Harpalus gravis*, *Harpalus* sp., and *Selenophorus palliatus*.

[c]Sorghum-sudangrass

Means followed by the same letter in each site/year are not significantly different, $P > 0.05$.

(n = 997). Beetles were evenly distributed among cover crops, with a mean of 2 carabids per day per cover crop. Over 700 *T. carolina* and over 150 *S. palliatus* were found during the season, with higher numbers of *T. carolina* found in Aug and higher numbers of *S. palliatus* found in Jul (Fig. 1). At Citra in 2012, low numbers of carabids were collected (n = 16), with 7 found in the cowpea plots, 6 in the corn plots, and 3 in the sunn hemp plots. No carabids were collected in the sorghum-sudangrass plots. At Citra in 2013, even lower numbers of carabids were collected (n = 5), with 2 each in the corn and mixed plots and 1 found in the sunn hemp plots. No further statistical analysis was completed with the results from Citra in 2013.

As interest in this research was the availability of predators against fall armyworm, species found at Quincy and Citra were categorized into 2 functional groups. Predatory carabid species include *C. sayi*, *T. carolina*, *T. virginica* (L.), *C. punctulata*, *P. subsulcatus* Say (*P. sublaevis* (Palisot de Beauvois) in the Tallahassee trials)*, C. tomentosus* (Say), *C. erythropus* Germar, and *C. laticollis* Say. Some species are listed as both predators and seed feeders, so they were considered omnivorous for the analysis (*A. merula* (Germar), *H. pensylvanicus* (DeGeer), *H. gravis* LeConte, and *S. palliatus*). Although the diet of *H. gravis* is unknown, it is most likely phytophagous or omnivorous, so it was considered omnivorous for the analysis. More predators were found in the fallow and cowpea plots and fewer in the sunn hemp and sorghum-sudangrass plots in Quincy in 2011 (Table 2). Omnivorous species were found in higher numbers in the fallow plots compared with the other cover crops. Predatory and omnivorous species were evenly distributed among cover crops in Quincy in 2012.

TALLAHASSEE

These experiments were designed to compare carabid populations moving within plots of 2 different sunn hemp germplasm lines that were planted at 2 different times of the season. Mar-planted plots had over 6 times more carabids collected than Jul-planted plots (n = 527 vs. n = 83, respectively). Therefore, comparisons between sunn hemp germplasm and trap position were analyzed separately for the 2 planting dates. For the Mar-planted plots, higher numbers of carabids per day were found in plots of 'AU Golden' than Tillage Sunn™ (Table 2). This result is mostly because of the collection of a higher number of *S. palliatus*: 'AU Golden' 1.273 ± 0.202 vs. Tillage Sunn™ 0.394 ± 0.136, t_{89} = 4.54; $P < 0.001$). However, similar numbers of the predatory species *T. carolina* were found in the 2 sunn hemp lines ('AU Golden' 1.109 ± 0.266 vs. Tillage Sunn™ 1.0 ± 0.202 carabids per day, t_{89} = 0.12; P = 0.9054). Traps placed further inside the plots (2.0 m) collected slightly fewer carabids per day than those just inside the plots (30 cm).

Grouping species as either predators or omnivores provided differences between germplasm lines. In the Mar-planted plots, there was no difference in numbers of predatory species collected in the 2 germplasm lines (Table 2; Fig. 2). However, the 'AU Golden' plots had more omnivores than the Tillage Sunn™ plots due to the collection of high numbers of *S. palliatus* (Table 2; Fig. 3). Differences between the inside and outside sampling positions were not found with predators or omnivores.

In the Jul-planted plots, there was a trend for more carabids found in the Tillage Sunn™ plots than in the 'AU Golden' plots. This result was the consequence of the collection of large numbers of *A. merula* (n = 14), *H. gravis* (n = 48), and *H. pensylvanicus* (n = 15) in plots planted later in the season. Only 1 predator was collected in the Jul plots (*C. punctulata* in a Tillage Sunn™ plot). For omnivores, more carabids were found in the Tillage Sunn™ plots than in the 'AU Golden' plots. There were no differences in collection of carabids in traps placed 2 m or 30 cm within the plots.

Traps placed outside of the sunn hemp plots in the border rows (controls) caught high numbers of carabids (n = 235), with *T. carolina*

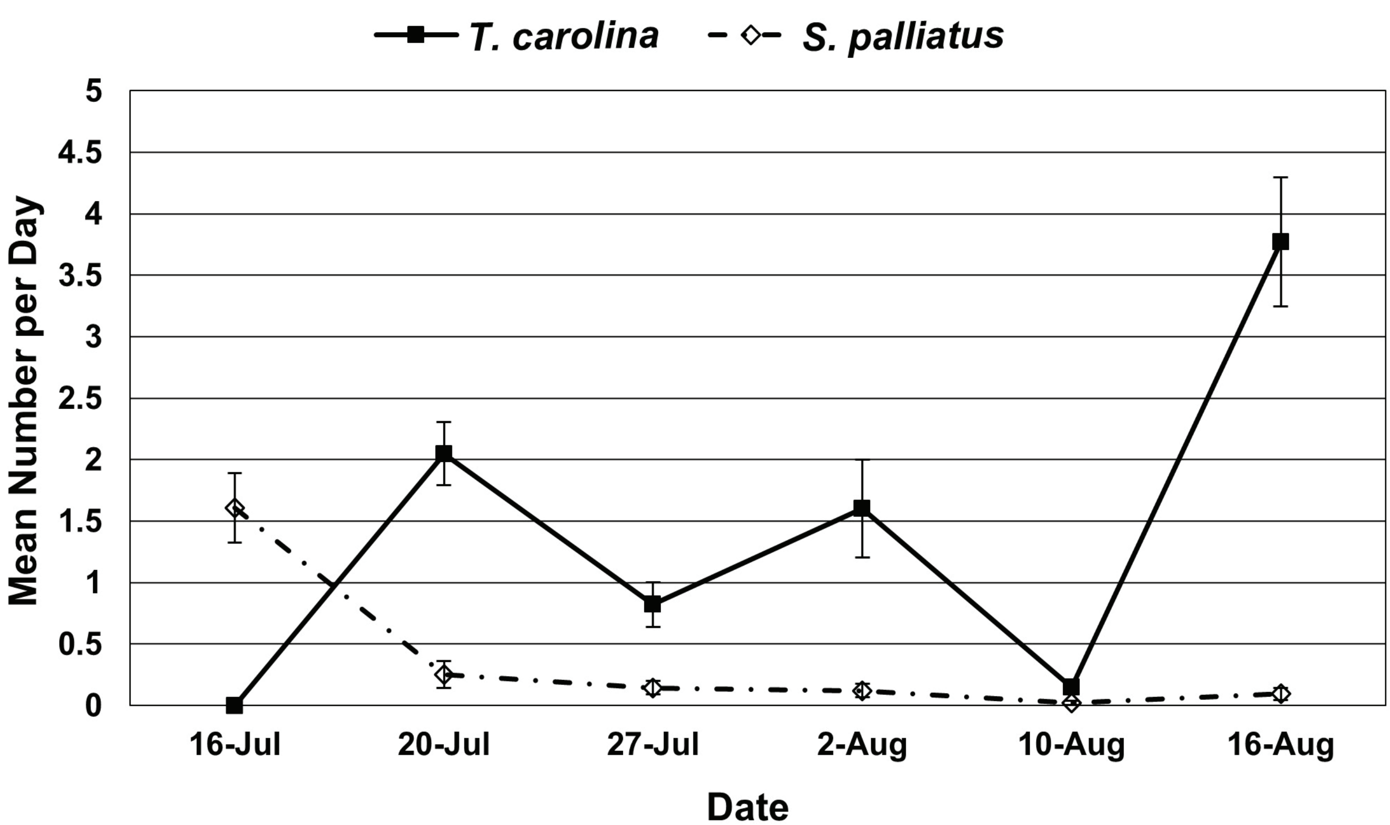

Fig. 1 Number of *Tetracha carolina* and *Selenophorus palliatus* per day found in cover crops in Quincy, Florida in 2012 (mean ± SE; n = 8).

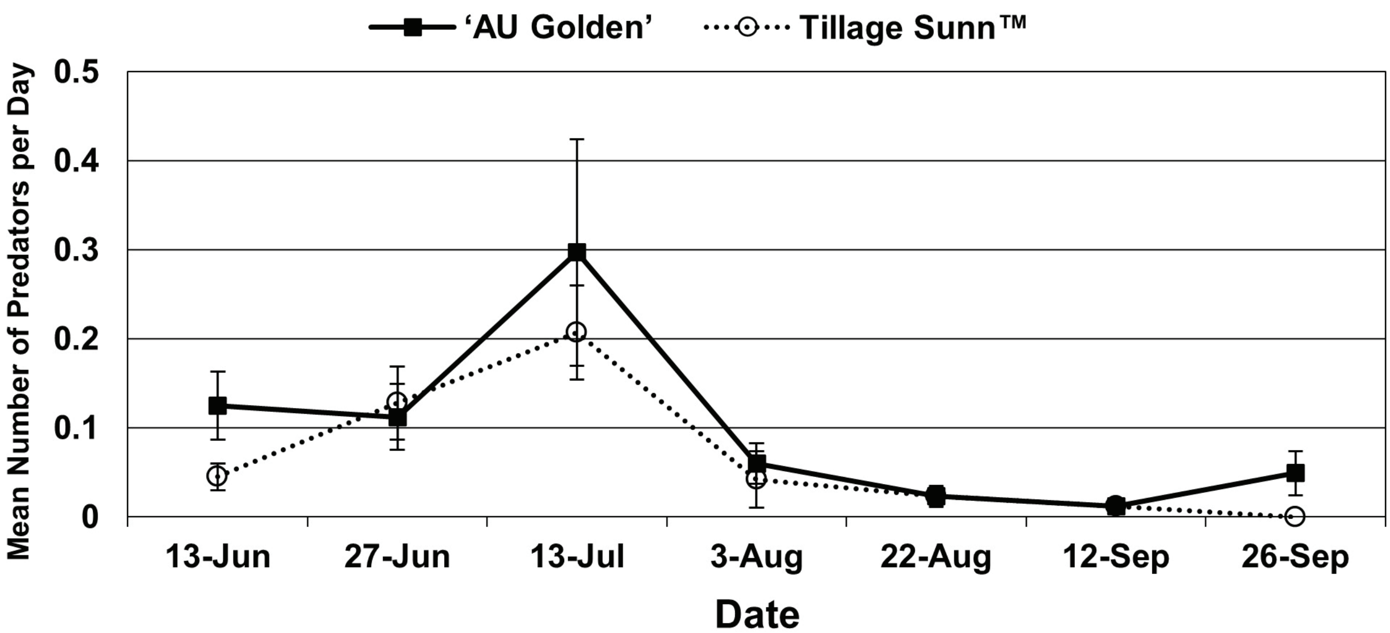

Fig. 2 Number of predator carabid species found in 2 sunn hemp germplasm lines in plots planted in Mar 2016 in Tallahassee, Florida (mean ± SE; *n* = 8).

(*n* = 115) and *S. palliatus* (*n* = 78) the most commonly found. This result suggests high mobility between areas with plant cover and bare ground.

SPECIES DIVERSITY INDICES

Species diversity, richness, and evenness values are shown in Table 3. For Quincy in 2011, the SSG plots did not contain enough carabids for the indices to be calculated. Species richness (S) and the 2 diversity indices (exponent of Shannon's index, $e^{H'}$ and inverse of Simpson's diversity index, 1/D) were higher in the fallow plots than in the cowpeas and sunn hemp plots. The evenness index was similar across cover plots. There were no differences in any of the indices among cover plots for the Quincy sampling in 2012. The results from Tallahassee in 2016 showed that species richness, $e^{H'}$, and 1/D were higher for samples taken from 'AU Golden' plots than in Tillage Sunn™ plots in the Mar plantings. Evenness was similar between sunn hemp lines. Species richness was higher in traps placed 30 cm into the plots compared with 2 m into the plots; all other comparisons did not produce a significant difference. Species richness was not different between 'AU Golden'

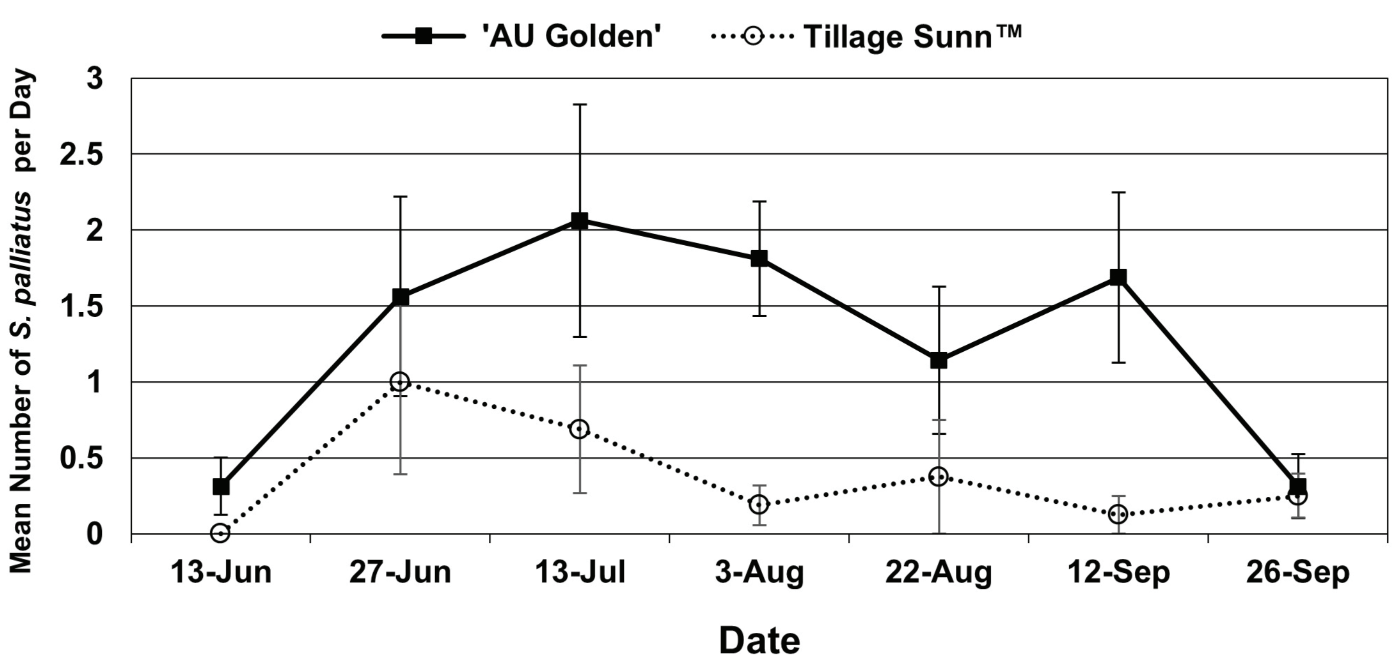

Fig. 3 Number of *Selenophorus palliatus* found in 2 sunn hemp germplasm lines in plots planted in Mar 2016 in Tallahassee, Florida (mean ± SE; *n* = 8).

Table 3. Species diversity indices of carabid beetles compared across different sites and cover crop treatments in Florida.

Site	Treatment	S	$e^{H'}$	1 / D	E
Quincy 2011	cowpea	2.25 ± 0.25 b	1.88 ± 0.119 b	1.73 ± 0.135 b	0.812 ± 0.086 a
	fallow	5.75 ± 1.03 a	4.67 ± 0.989 a	4.05 ± 0.892 a	0.786 ± 0.063 a
	sunn hemp	2.00 ± 0.0 b	1.92 ± 0.082 b	1.87 ± 0.133 ab	0.932 ± 0.068 a
		$F_{2,7}$ = 17.73, P = 0.0018	$F_{2,7}$ = 8.31, P = 0.0142	$F_{2,7}$ = 5.65, P = 0.0346	$F_{2,7}$ = 1.57, P = 0.2741
Quincy 2012	corn	4.75 ± 0.85 a	2.41 ± 0.388 a	1.90 ± 0.304 a	0.596 ± 0.081 a
	cowpea	3.75 ± 0.75 a	2.44 ± 0.289 a	2.08 ± 0.283 a	0.724 ± 0.081 a
	sunn hemp	3.75 ± 0.25 a	2.36 ± 0.363 a	1.96 ± 0.336 a	0.650 ± 0.072 a
	SSG[a]	3.50 ± 0.29 a	1.60 ± 0.129 a	1.31 ± 0.073 a	0.502 ± 0.023 a
		$F_{3,11}$ = 0.71, P = 0.5637	$F_{3,11}$ = 1.76, P = 0.2127	$F_{3,11}$ = 2.0, P = 0.1722	$F_{3,11}$ = 2.68, P = 0.0982
Tallahassee 2016					
planting date 11 Mar	'AU Golden'	6.50 ± 0.463 a	4.16 ± 0.292 a	3.63 ± 0.256 a	0.739 ± 0.023 a
	Tillage Sunn™	3.57 ± 0.369 b	2.60 ± 0.221 b	2.18 ± 0.183 b	0.743 ± 0.054 a
		$\|t_{10}\|$ = 5.64, P = 0.0002	$\|t_{10}\|$ = 4.25, P = 0.0017	$\|t_{10}\|$ = 3.87, P = 0.0031	$\|t_{10}\|$ = 0.96, P = 0.3417
	trap 2 m	4.57 ± 0.719 b	3.31 ± 0.432 a	2.79 ± 0.334 a	0.786 ± 0.045 a
	trap 30 cm	5.63 ± 0.653 a	3.54 ± 0.376 a	2.84 ± 0.316 a	0.702 ± 0.028 a
		$\|t_{10}\|$ = 2.35, P = 0.0407	$\|t_{10}\|$ = 0.95, P = 0.3642	$\|t_{10}\|$ = 0.44, P = 0.6677	$\|t_{10}\|$ = 1.81, P = 0.1004
planting date 27 Jul	'AU Golden'	2.83 ± 0.307 a	2.65 ± 0.275 a	2.50 ± 0.254 a	0.914 ± 0.022 a
	Tillage Sunn™	2.25 ± 0.164 a	1.88 ± 0.125 b	1.69 ± 0.111 b	0.768 ± 0.044 b
		$\|t_9\|$ = 1.9, P = 0.0895	$\|t_9\|$ = 3.11, P = 0.0125	$\|t_9\|$ = 3.49, P = 0.0069	$\|t_9\|$ = 2.75, P = 0.0226
	trap 2 m	2.57 ± 0.202 a	2.25 ± 0.185 a	2.06 ± 0.185 a	0.830 ± 0.042 a
	trap 30 cm	2.43 ± 0.297 a	2.16 ± 0.297 a	2.01 ± 0.287 a	0.831 ± 0.054 a
		$\|t_9\|$ = 0.27, P = 0.7929	$\|t_9\|$ = 0.71, P = 0.4938	$\|t_9\|$ = 0.42, P = 0.6841	$\|t_9\|$ = 0.41, P = 0.6933

[a]Sorghum-sudangrass
Means followed by the same letter in each site/year are not significantly different, $P > 0.05$.

and Tillage Sunn™ plots in the Jul plantings, however both diversity indices and evenness were higher in results from the 'AU Golden' plots. Finally, all species diversity indices were similar from samples taken in the 2 sampling positions in the Jul-planted plots.

Discussion

Many of the carabid species collected have been associated with preying on noctuid larvae in general, and *S. frugiperda* specifically. *Calosoma sayi* has been shown to be a predator of *S. frugiperda* larvae, prepupae, pupae, and adults in laboratory trials (Young 1985a; 2008), and as a possible vector of fall armyworm pathogens after feeding on infected larvae (Young & Hamm 1985). *Tetracha carolina* showed promise as a predator of *S. frugiperda* in laboratory trials and in turfgrass habitats (Nachappa et al. 2006; Young 2012), and *T. virginica* is most likely a similar type of predator (Pearson et al. 2015). *Cicindela punctulata* and *Chlaenius tomentosus* were both shown to feed and survive on fall armyworm larvae in laboratory trials (Young 2005). Using radioactive-labeled prey, *Calleida decora* (F.) was shown to feed on eggs and larvae of several noctuids in soybean fields (McCarty et al. 1980). This behavior was confirmed using *Anticarsia gemmatalis* (Hübner; Lepidoptera: Eribidae) as prey in laboratory and field cage tests (Fuller 1988). Two species of *Pasimachus* found in this study, *subsulcatus* and *sublaevis*, are both known to be predators (Purrington & Drake 2005). Several species collected are known as both predators and seed feeders. These include *A. merula* (Torres & Ruberson 2005; Shearin et al. 2007), *H. pensylvanicus* (Kirk 1973; Westerman et al. 2008; Youngerman et al. 2020), and *S. palliatus* (Torres & Ruberson 2005; Messer & Raber 2021). Although Torres & Ruberson (2005) noted that the feeding behavior of *H. gravis* was unknown, we placed this species in the omnivore group because of similarities with other member species.

Maintaining carabid populations within crop fields can increase predation of prey on or under the soil surface (Young 1985a; Clark et al. 1994; Menalled et al. 1999), although few field studies have shown that carabids are directly responsible for significant pest mortality (Douglas et al. 2015; Cividanes 2021). Cover crop species can have a positive effect on the activity of ground beetle species, including both prey and seed predators (Westerman et al. 2008; Ward et al. 2011; Hakeem et al. 2021). However, there is no guarantee that carabid activity in cover crops or refuge/strip plots will lead to higher activity in neighboring crop fields (Carmona & Landis 1999). Disturbances within crop fields, such as tillage practices have mixed influence on carabid populations. Some studies in various field (Brust et al. 1985; Clark et al. 1997) and horticultural systems (Lewis et al. 2016) have shown that tillage practices negatively affect populations, however, several studies demonstrate that tillage has little to no influence in the activity of carabids (Belaoussoff et al. 2003; Pretorius et al. 2018; Jowett et al. 2021). Finally, to be a good predator of fall armyworm, activity on plants such as in plant whorls or along the stalks could be important. Several predatory species, such as *C. sayi*, *C. punctulata*, and *C. tomentosus* are known to be active flyers, as they are captured in light traps (Young 1985b, 2005). Few studies have documented arboreal activity on plants (Lövei & Szentkirály 1984; Young 2008).

In our study, species richness, the exponent of Shannon's index ($e^{H'}$) and the inverse of Simpson's diversity index (1/D) were higher in plots that were not planted with a cover crop. None of the indices were different among cover crops species in Quincy (2011 and 2012). When just sunn hemp was planted (Tallahassee in 2016), more carabids were found in Mar-planted plots than July-planted plots. Certainly, the seasonal biology of these insects is an important factor in collecting these species, as carabid species have been shown to exhibit distinct temporal niches (Leslie et al. 2009). For example, *T. carolina* was found from Jul through mid-Oct in a non-agricultural field site in Mississippi (Young 2011, 2015a), although larval activity can range from Sep to the following Jun (Young 2015b). The life cycle of *C. sayi* has been difficult to document, as both single and multiple generations per season have been proposed (Price & Shepard 1978; Young 2007). Young (2007) showed that adults produced in Jul to Aug overwinter, reproduce in spring, and die before winter, although one study suggested early-summer males only survive 115 d in the laboratory (Young 1985b). Species richness and the diversity indices were found to be higher in 'AU Golden' than in Tillage Sunn™ plots, a result of more species collected in traps under these plants. It is unknown why there was this difference, although past research has shown 'AU Golden' to be a much better flower producer during summer and early fall than Tillage Sunn™ (Meagher et al. 2017; Meagher et al. 2019). Perhaps flowering attracts more prey or provides added cover for these epigeal species. Other studies suggest the importance of plant type in the abundance of carabid species (Ward et al. 2011; Jowett et al. 2021).

The carabid species *C. sayi*, *T. carolina*, and *C. punctulata* are just one group of predators that have been shown to attack fall armyworm in field crops, pasture grasses, and turf grasses. Other groups, such as the earwigs *Doru taeniatum* (Dohrn) (Dermaptera: Forficulidae) and *Labidura riparia* (Pallas) (Dermaptera: Labiduridae) (Jones et al. 1988; Kharboutli & Mack 1993), the spiders *Cheiracanthium inclusum* (Hentz) (Araneae: Miturgidae) and *Hibana* spp. (Araneae: Anyphaenidae) (Pfannenstiel 2008; Gallagher et al. 2013), the predatory bugs *Geocoris* spp. (Hemiptera: Geocoridae) and *Orius insidiosus* (Hemiptera: Anthocoridae) (Isenhour et al. 1990; Joseph & Braman 2009), the coccinellid *Coleomegilla maculata* (DeGeer) (Coleoptera: Coccinellidae) (Gross et al. 1985), *Polistes* spp. wasps (Hymenoptera: Vespidae) (Held et al. 2008), and ants such as *Solenopsis invicta* Buren (Hymenoptera: Formicidae) (Hay-Roe et al. 2016) can influence predation in these habitats, sometimes with negative interactions (Tryon 1986). Unlike for parasitoid species, especially egg parasitoids, inoculative or inundative release of predators for control of noctuid pests is rare. The exception may be earwigs, where improvements to artificial diets for laboratory rearing (Pasini et al. 2007) and use of pollen and chemicals to attract and maintain populations in the crop field have potential to increase their importance (Naranjo-Guevara et al. 2017; Marucci et al. 2019). Further research with all these groups is needed to determine in-field mortality levels necessary to reduce fall armyworm populations.

In conclusion, almost 2,000 predatory and omnivorous carabid beetles were collected in traditional and alternative cover crops in north and north-central Florida. These alternative cover crops (cowpeas and sunn hemp) were grown to replace cover plants (sorghum-sudangrass and corn), which are known to increase field populations of *S. frugiperda*. Three carabid species in particular, *C. sayi*, *T. carolina*, and *C. punctulata*, readily feed on different stages of *S. frugiperda* in the laboratory (Young 1985a, 2005, 2008, 2012; Nachappa et al. 2006) and may aid in the reduction of *S. frugiperda* populations in the field. More carabid species, a higher number of abundant species, and a higher number of very abundant species were found in fallow plots in Quincy in the first year of the study. In Tallahassee, more species, higher numbers of abundant species, and higher numbers of very abundant species were found during the early planting date in 'AU Golden' plots vs. Tillage Sunn™ plots. Sunn hemp plots planted in the summer showed lower diversity indices overall compared with the spring-planted plots, but samples from 'AU Golden' plots still contained higher numbers of abundant species and higher numbers of very abundant species than Tillage Sunn™ plots. Generally, species evenness was similar across all cover crops. Further research should determine if the predatory species are feeding on *S. frugiperda* in the field and if they can help reduce crop damage.

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