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Areawide management of fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae), using selected cover crop plants

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Abstract

Background: Fall armyworm, *Spodoptera frugiperda* (J. E. Smith) is a migratory moth that annually migrates northward each spring from sites in southern Florida and southern Texas. This caterpillar pest feeds on and damages row, turf and vegetable crops in the eastern and central U.S. Before migrating in spring, it feeds on cover crops in central and eastern Florida and expands its populations. Our objective was to use multi-year studies to compare fall armyworm populations that develop in cover crop plants.

Methods: A series of field experiments and a laboratory feeding study were conducted to compare infestation and feeding of fall armyworm on different cover crop plants. Field experiments had plots planted with corn (*Zea mays* L.), sorghum-sudangrass [*Sorghum bicolor* (L.) Moench], a standard cover crop in Florida, and two alternative cover crops, sunn hemp (*Crotalaria juncea* L.) and cowpea [*Vigna unguiculata* (L.) Walpers spp. *unguiculata*]. Another trial compared populations in sorghum-sudangrass and in mixtures of sorghum-sudangrass with buckwheat (*Fagopyrum esculentum* Moench) or pearl millet (*Cenchrus americanus* (L.) Morrone). Fall armyworm larvae were fed and allowed to develop on different sunn hemp germplasm in a laboratory trial.

Results: Field populations of fall armyworm were highest on corn, followed by sorghum-sudangrass. Sunn hemp and cowpea had larval populations 70–96% less than on sorghum-sudangrass, suggesting replacement of this cover crop with either plant species might help reduce areawide populations of resident or migratory fall armyworm. Larvae collected from cover crop plots had parasitism levels that averaged 30%, with *Chelonus insularis* (Hymenoptera: Braconidae) emerging as the most commonly-collected species. Larval feeding on different sunn hemp germplasm lines resulted in no difference in weight gain.

Conclusions: Replacing sorghum-sudangrass with sunn hemp varieties or germplasm should be acceptable as a replacement cover crop for areawide management of fall armyworm.

Keywords: Sunn hemp, *Crotalaria*, Cowpeas, *Vigna*, Noctuidae

Introduction

Fall armyworm, *Spodoptera frugiperda* (J. E. Smith), is a native caterpillar pest of row, turf, and crops in the eastern and central U.S. (Braman et al. 2000; Luttrell and Mink 1999; Nuessly et al. 2007; Souza et al. 2013). This noctuid is a neotropical insect that annually migrates northward each spring from sites in southern

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Florida (Pair et al. 1986; Westbrook and Sparks 1986) and southern Texas (Pair et al. 1991; Raulston et al. 1986). Migratory haplotypes separating fall armyworm populations from Florida and Texas have been discovered, and intensive sampling of moths using sex pheromone-baited traps has provided a framework to describe migratory patterns (Nagoshi et al. 2012, 2014, 2015). Model simulations have been developed to help in the prediction of inter-annual variability of fall armyworm patterns including those in response to climate change and adoption of transgenic crop cultivars (Westbrook et al. 2016; Westbrook et al. 2019). Within the last 5 years, this species has invaded Africa (Goergen et al. 2016), India (Sharanabasappa et al. 2018), southeastern Asia (Li et al. 2019), and most recently Australia (FAO 2020).

Growers in Florida plant over 88,000 ha of vegetables, including over 15,000 ha of fresh market sweet corn in southern Florida counties (USDA/NASS 2017). The crop season occurs from October to May of the following year in the southern counties (Ozores-Hampton et al. 2017) and although fall armyworm is considered a serious pest in some crops, it is effectively controlled in commercial fields using insecticides (Nuessly and Webb 2017). Fall armyworm populations from overwintering areas in southern Florida move into secondary source areas located in northern Florida by April and May (Pair and Westbrook 1995). In these areas of Florida, over 10,000 ha of vegetable crops, primarily potatoes (*Solanum tuberosum* L.) and cabbage (*Brassica oleracea* L. var. *capitata*) are grown during January to May (Elwakil and Mossler 2016; USDA/NASS 2017). Although fall armyworm is not a pest in these crops, resident and migratory populations are present in most vegetable production areas in the state.

Many vegetable growers plant cover crops either before or after their main crop is harvested, including grass, cereal, temperate and tropical legumes, and brassica plant species (Newman et al. 2014; Snapp et al. 2005). Improving soil conditions (Cherr et al. 2006, 2007; Wang et al. 2005), suppressing weed populations (Adler and Chase 2007; Cho et al. 2015; Collins et al. 2008; Morris et al. 2015; Mosjidis and Wehtje 2011), and reducing plant parasitic nematode densities (Bhan et al. 2010; Braz et al. 2016; Crow et al. 2001; Gallaher and McSorley 1993) are some of the benefits growers realize by planting cover crops. Many Florida growers plant cover crops such as corn (*Zea mays* L.) for livestock forage or sorghum-sudangrass [*Sorghum bicolor* (L.) Moench] to increase soil organic matter. Sorghum-sudangrass is a warm-season annual grass hybrid that is used as a green manure cover crop following harvest of winter vegetables (Newman et al. 2014; Vendramini et al. 2015).

However, cover crop plants can also influence the size of pest insect populations. For example, *Spodoptera litura* (F.) develops well on certain plants such as sesbania (*Sesbania roxburghii* Merr.), rapeseed (*Brassica campestris* L. variety *chinensis*) and sunn hemp (*Crotalaria juncea* L.) and can develop large populations that then infest surrounding vegetable and row crops (Tuan et al. 2014). On the other hand, 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 (Meagher et al. 2004; Pair and Westbrook 1995). For areawide management of this pest, planting of alternate cover crops may reduce migrating populations.

Studies by Meagher et al. (2004) showed that sunn hemp and cowpea [*Vigna unguiculata* (L.) Walpers spp. *unguiculata*] have potential to reduce areawide populations of fall armyworm. Sunn hemp is a warm-season legume that is used in alternation with vegetable crops (Mansoor et al. 1997; Wang et al. 2015). 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; Hödtke et al. 2016). Our first objective in these experiments was to compare population densities of fall armyworm in field plots composed of corn, sorghum-sudangrass, sunn hemp, or cowpea. The earlier field studies were in northern Florida in an area where fall armyworm doesn't overwinter (Meagher et al. 2004). We wanted to use multi-year studies to compare cover crops in a location with overwintering populations (southern Florida), where overwintering populations may be present in some years (central Florida), and where fall armyworm populations are clearly migratory (northwest Florida). Since we expected sunn hemp to effectively reduce fall armyworm survival, our second objective was to compare larval feeding on different sunn hemp germplasm lines (Morris and Antonious 2013; Wang et al. 2006) in laboratory bioassays to determine the variability of larval weight gain and mortality.

Materials and methods

Cover crop plants

Cover crops were planted at three different locations in different years to compare fall armyworm numbers among the plant types. Treatments were located at the University of Florida Institute of Food and Agricultural Sciences (UF/IFAS) Everglades Research and Education Center, Belle Glade, Florida in 2011, the UF/IFAS North Florida Research and Education Center, Quincy, Florida in 2011 and 2012, and at the UF/IFAS Plant Science Research and Education Unit, Citra, Florida in 2012 and 2013 (Table 1). The experimental design at all

Table 1 Location, county, coordinates, year(s) of study, plot size, and cover crop plants used for the field experiments, 2011–2013

Location	County; Coordinates	Year(s)	Plot Size	Covers (seeding rate)
Belle Glade	Palm Beach N 26.657, W – 80.63	2011	12 rows × 30.5 m	SSG (4 seeds), SH (7), CP (7), fallow (unmanaged)
Citra	Marion N 29.41, W – 82.173	2012	8 rows × 15.24 m	corn (6), SSG (6), SH (3), CP (4)
		2013	12 rows × 15.24 m	corn (3), SSG (9), SH (12), 50:50 mix of SSG and SH (12)
		2018	6 rows × 15.24 m	SSG (0.68 kg), SSG (0.34 kg) + SH (0.34 kg), SSG (0.34 kg) + buckwheat (0.91 kg), SSG (0.34 kg) + millet (0.23 kg)
Quincy	Gadsden N 30.546, W – 84.599	2011	8 rows × 30.5 m	SSG (4), SH (7), cowpea (7), fallow (unmanaged)
		2012	10 rows × 15.24 m	corn (1.25), SSG (4), SH (6), CP (6)

All seed rates are number of seeds in 30.5 cm. In 2018, seeding rate is weight of seed per plot. CP: cowpea, SSG: sorghum-sudangrass, SH: sunn hemp

locations was a randomized complete block with 4 cover crop treatments, 4 blocks (replications), and plots were planted on 91.4 cm row centers. All plots were treated by pre-plant herbicides at locally recommend rates; after planting no pesticides were applied. Plots at Citra were irrigated with overhead irrigation throughout the season. Sunn hemp seed was an unknown germplasm (variety not stated) from South Africa (purchased from Petcher Seeds, Fruitdale, Alabama, USA), and was mixed with a cowpea-type *Rhizobium* inoculum before planting. Sorghum-sudangrass seed was Forage First Sudax SX-17 Sorghum x Sudangrass hybrid (Forage First, LaCrosse, Wisconsin, USA; now sold by Forage Genetics International, Nampa, Idaho, USA). Cowpea seed was ‘Iron & Clay’ and was purchased through local distributors and was mixed with a cowpea-type *Rhizobium* inoculum, also purchased at a local distributor, before planting.

The Belle Glade plots were planted 5 July 2011 and treatments consisted of sorghum-sudangrass, sunn hemp, cowpea, and a fallow treatment (prepared but nothing planted and left unmanaged). The Quincy 2011 trial, planted 7 July, contained the same four treatments. The Quincy 2012 trial, planted 12 June, contained plots of corn (DKC 66-94 RR2, DeKalb Genetics Corp., DeKalb, Illinois, USA), sorghum-sudangrass, sunn hemp, and cowpea. The Citra 2012 trial, planted 3 July, contained corn (‘Trucker’s Favorite’, purchased through a local distributor), sorghum-sudangrass, sunn hemp, and cowpea. Corn replaced fallow treatments because discussions with local growers indicated that it was used commonly as a cover crop to produce forage. The Citra 2013 trial, planted 11 June, contained corn (‘Trucker’s Favorite’), sorghum-sudangrass, sunn hemp, and a mix of sorghum-sudangrass and sunn hemp at a 50:50 by volume. Further discussions with growers indicated that the price of sunn hemp was a consideration in cover crop choice, therefore mixing with sorghum-sudangrass would reduce the price. More specific information about the locations and plots are in Table 1.

Fall armyworm larvae were counted in each plot by randomly selecting 3 sites per plot (row number by number of paces). Instead of using a long tape measure, the number of paces along the plot row was calculated. For example, if the plot row was 70 paces long, a random number from 1 to 69 was chosen along with the randomly selected row. Plants were thoroughly searched for the presence of naturally-occurring larvae along one-meter row at each site. When larvae were discovered, they were placed in diet cups with plant material and transported back to the laboratory for parasitoid emergence following the methods of Meagher et al. (2016). Larval fate included finishing development and becoming a moth (live), dying due to unclassified circumstances such as disease or handling (dead), or being parasitized and producing an adult parasitoid.

The Belle Glade 2011 trial was only sampled 2 and 24 August due to the presence of earwig predators and the lack of a fall armyworm population in the plots (see Results). The Quincy 2011 trial was sampled 16 August, 6 and 27 September. The Quincy 2012 trial was sampled 12, 20, and 27 July and 2 August. The Citra 2012 trial was sampled 3, 9, 17, 24, and 31 August, and 11 and 21 September. The Citra 2013 trial was sampled 30 July, and 6, 15, and 23 August; only 2 sites per plot were selected in this trial.

Additional cover crop plants were used in the Citra 2018 trial because there was local acceptance for using buckwheat (*Fagopyrum esculentum* Moench) and pearl millet [*Cenchrus americanus* (L.) Morrone]. A randomized complete block design of 4 treatments and 4 blocks compared fall armyworm populations in plots with sorghum-sudangrass alone, sorghum-sudangrass + sunn hemp, sorghum-sudangrass + buckwheat, and sorghum-sudangrass + pearl millet. All seed was purchased from Petcher Seeds in June (Fruitdale, Alabama, USA) and planted 25 June. In each plot, a 1-m row was randomly selected (row number, number of paces) and all plants in that row were removed. The number of

fall armyworm-injured sorghum-sudangrass plants were divided by the total number of sorghum-sudangrass plants to calculate the percent sorghum-sudangrass plants infested. Sunn hemp and buckwheat plants were not infested, and no larvae were recovered. Young millet plants were difficult to separate from young sorghum-sudangrass plants, therefore the percent infested calculation for that treatment is based on all plants in the row. Plots were sampled 26 July, 6 August, and 14 August 2018.

Border row plants

The experiment in 2017 in Citra was designed to test the hypothesis that corn could be protected from fall armyworm injury by planting border rows of either sorghum-sudangrass or sunn hemp next to the corn. A randomized complete block design of 4 treatments and 4 blocks compared fall armyworm populations in 2 rows of corn ('Trucker's Favorite', purchased through a local distributor; planted 18 July) that had two rows of either sunn hemp alone or a mixture with sorghum-sudangrass (25, 50, or 75% of the mixture) planted on 5 July on both sides. The 6-row \times 15.24 m plots had either sunn hemp (0.68 kg), sunn hemp (0.17 kg) + sorghum-sudangrass (0.51 kg), sunn hemp (0.34 kg) + sorghum-sudangrass (0.34 kg), or sunn hemp (0.51 kg) + sorghum-sudangrass (0.17 kg) planted. In each plot, a 1-m row was randomly selected (row number, number of paces) and all corn plants in that row were removed. The number of fall armyworm-injured plants were divided by the total number of plants to calculate the percent corn plants infested. The four border rows were sampled in the same way, randomizing row number plus number of paces. Percent infested plants (sunn hemp or sorghum-sudangrass) and number of larvae collected were documented. Samples were taken 3 August, 14 August, and 28 August 2017.

Feeding study

Seventeen lines of sunn hemp germplasm seeds were obtained from the USDA-ARS Plant Genetic Resources Conservation Unit, Griffin, Georgia, and were grown in 3.8-L pots in a greenhouse at ambient temperature. Plants were fertilized weekly with Miracle-Gro® 15-30-15 plant food (Marysville, Ohio, USA). No pesticides were applied to the plants. Leaves from plants aged ca. 6 wk. old were placed in rearing tray cells (BIO-RT-32 cell, Frontier, Newark, Delaware, USA) on top of Whatman No. 1 filter paper that was cut to fit and moistened with 0.3 mL deionized water. A corn strain fall armyworm colony (<1 year old) collected from sweet corn in southern Florida (Hendry Co.) was used in the feeding study. Culture procedures followed Meagher et al. (2011). Neonates were individually added to the cells using a camel hair's

brush. Cells were covered with gas permeable adhesive tabs (BIO-CV-4, Frontier, Newark, Delaware, USA), and each of the 3 replications contained 16 cells (16 neonates) per sunn hemp line. Trays were kept in an environmental chamber set at 24.8 °C, 70% RH, and 13 h/11 h light/dark photoperiod. After 5 d, moisture and plant material were checked and replaced as needed, respectively. Larval mortality (defined as not moving after touching with a camel hair's brush) was calculated for each rep by the formula: (number of dead larvae/16) \times 100. Larval weights (Sartorius Model Precision Balance BP221S, Göttingen, Germany) were recorded after 9 days.

Statistics

All analyses were conducted using SAS (SAS 9.4, SAS Institute 2012). All data were first analyzed using Box-Cox (PROC TRANSREG) and PROC UNIVARIATE to find the optimal normalizing transformation (Osborne 2010). Since many numbers were zero, 0.1 was added before transformation. Fall armyworm numbers in the field studies were analyzed using PROC GLIMMIX, with cover crop treatment as the fixed variable and date and block as the random variables. In all analyses LSMEANS with an adjusted Tukey test was used to separate variable means. Each location and year were analyzed separately.

Since relatively low numbers of fall armyworm were collected and returned to the laboratory for parasitoid emergence, cover crop treatment differences were compared using a randomized complete block design in PROC GLIMMIX, with treatment as the fixed variable and location as the random variable.

The feeding study was analyzed using a nested design (16 larvae per replication) in PROC GLIMMIX, with germplasm line as the fixed variable and replication within germplasm line as the random variable. Mortality was analyzed as a randomized complete block in PROC GLIMMIX with germplasm line as the fixed variable and replication as the random variable.

Results

Cover crop plots

No fall armyworm larvae were found at the Belle Glade 2011 trial, likely due to the presence of *Doru taeniatum* (Dohrn) (Dermaptera: Forficulidae). Samples taken 24 August showed that sorghum-sudangrass contained more earwigs than sunn hemp or cowpea plants (16.5 ± 2.1 , 2.25 ± 0.75 , 0.75 ± 0.48 , respectively; $F_{2,6} = 52.1$, $p = 0.0002$). Other insects and weeds were found in the plots. The sunn hemp plots by September attracted large numbers of the green June beetle, *Cotinus nitida* (L.) (Coleoptera: Scarabaeidae). The cowpea plots contained noticeable populations of Hawaiian beet webworm, *Spoladea recurvalis* (F.) (Lepidoptera: Crambidae)

Table 2 Number of fall armyworm larvae per meter row in different cover crop plots, 2011, 2012, 2013, and 2018, Quincy and Citra, Florida

Location/year	Treatment	Fall armyworm per meter row ^a
Quincy 2011	Sorghum-sudangrass	1.0 ± 0.59 a
	Cowpeas	0.08 ± 0.08 a
	Sunn hemp	0 ± 0 b
	Fallow	0 ± 0 b
		$F_{3,9} = 4.73, P = 0.0302$
Quincy 2012	Corn	1.21 ± 0.36 a
	Sorghum-sudangrass	0.65 ± 0.13 a
	Sunn hemp	0.08 ± 0.06 b
	Cowpeas	0.02 ± 0.02 b
		$F_{3,54} = 17.31, P < 0.0001$
Citra 2012	Corn	1.71 ± 0.28 a
	Sorghum-sudangrass	0.73 ± 0.2 b
	Sunn hemp	0.05 ± 0.03 c
	Cowpeas	0.01 ± 0.01 c
		$F_{3,91} = 44.92, P < 0.0001$
Citra 2013	Corn	2.875 ± 1.02 a
	Sorghum-sudangrass	1.1875 ± 0.83 b
	Mix	0.375 ± 0.25 b
	Sunn hemp	0.125 ± 0.06 b
		$F_{3,54} = 7.46, P = 0.0003$
Citra 2018	Sorghum-sudangrass + millet	4.7 ± 2.4 a
	Sorghum-sudangrass + buckwheat	1.8 ± 0.08 a
	Sorghum-sudangrass + sunn hemp	1.7 ± 0.7 a
	Sorghum-sudangrass	1.5 ± 0.5 a
		$F_{3,38} = 0.51, P = 0.6755$

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

^a Data in all experiments except Citra 2018 were transformed using $Y^{-0.5}$. Data in Citra 2018 was transformed using $Y^{-0.25}$

and several mirid and pentatomid species (not identified) (data not shown). Finally, by September all plots contained spiny pigweed, *Amaranthus spinosus* L., especially the fallow plots.

For the other locations, relatively low numbers of fall armyworm larvae were found in all plots, with an average of 0.25, 0.50, 0.626, 1.14, and 2.38 larvae per meter row for Quincy 2011, 2012, Citra 2012, 2013, and 2018, respectively (Table 2). In the only trial where corn was not planted (Quincy 2011), sorghum-sudangrass had more larvae than the other three treatments. However, this was from only one sample date (16 August), as all other sampling found no larvae. In the other trials, corn plots contained relatively high numbers of larvae per meter row (Table 2). Sorghum-sudangrass contained as many larvae as corn in Quincy 2012, but fewer in Citra 2012 and 2013. This cover crop treatment generally had more larvae than both sunn hemp and cowpea plots, although statistically similar to both covers in Quincy 2011. Sorghum-sudangrass contained numerically but

not statistically higher numbers of larvae than the sunn hemp and sunn hemp + sorghum-sudangrass mixed plots in 2013.

The trial at Citra 2018 contained plots of sorghum-sudangrass alone, or intercropped with sunn hemp, buckwheat, or millet. A total of 112 larvae were collected from the 4 treatments across 3 dates, with more larvae found during the July sampling (82) than the 2 August samples (22 and 8). Numerically more larvae were found in sorghum-sudangrass + millet plots, but this difference was not significant (Table 2). Percent infested plants was above 70% and was similar across cover treatments (sorghum-sudangrass + millet, $89.5 \pm 3.7\%$, sorghum-sudangrass + buckwheat, $79.5 \pm 9.7\%$, sorghum-sudangrass + sunn hemp, $77.8 \pm 9.6\%$, and sorghum-sudangrass, $73.4 \pm 8.8\%$; $F_{3,38} = 0.51, p = 0.6755$).

Larval parasitism

Fall armyworm larvae from corn (284), sorghum-sudangrass (130) and sunn hemp plots (19) during Quincy 2011

Table 3 Number of fall armyworm larvae per meter row and percent infested plants for corn and cover plants in different mixtures (25, 50, or 75%) of border row plots, 2017, Citra, Florida

Treatment	Number of larvae in corn ^a	Percent infested corn plants ^b	Number of larvae in cover plants ^c	Percent infested cover plants ^d
SH	0.667 ± 0.284 a	61.3 ± 10.3 a	0.0 ± 0.0 b	11.9 ± 4.5 a
SH 25, SSG 75	0.92 ± 0.336 a	48.3 ± 11.1 a	0.5 ± 0.23 ab	30.9 ± 9.0 a
SH 50, SSG 50	0.667 ± 0.284 a	43.9 ± 9.0 a	0.75 ± 0.579 a	26.2 ± 5.0 a
SH 75, SSG 25	2.08 ± 1.07 a	55.7 ± 10.0 a	0.583 ± 0.193 a	27.9 ± 7.0 a
	$F_{3,39} = 0.31, p = 0.8214$	$F_{3,39} = 0.82, p = 0.4914$	$F_{3,39} = 3.02, p = 0.0410$	$F_{3,39} = 1.81, p = 0.1614$

SH = sunn hemp, SSG = sorghum-sudangrass

^a Data transformed using $Y^{0.25}$ ^b Data transformed using $Y^{0.75}$ ^c Data transformed using $Y^{1.25}$. Means followed by the same letter are not significantly different, $P > 0.05$ ^d Data transformed using $Y^{0.25}$

and 2012 and Citra 2012 and 2013 were brought back to the laboratory and held for parasitoid emergence. Only 8 larvae were recovered from the cowpea plots and that information was not included in the analysis. Larvae collected in Citra 2017 and 2018 were not returned to the

laboratory. Overall, 38% of the larvae completed development, with a higher percentage of those collected in the sorghum-sudangrass plots ($61.6 \pm 0.6\%$) than the sunn hemp plots ($15.0 \pm 7.6\%$), while the percentage from the corn plots was intermediate ($38.3 \pm 5.6\%$; $F_{2,4} = 18.0$,

Table 4 Larval weight and mortality of fall armyworm after 9 days feeding on leaves of different sunn hemp germplasm

PI No	Identifier ^a	Origin ^a	Larval wt. (mg) (9 d) ^b	Mortality (%) ^c
468956	'Tropic Sun'	USA	32.6 ± 3.16	0.0 ± 0.0 c
561720	IAC-1	Brazil	25.1 ± 3.66	8.4 ± 2.1 ab
314239	Col No 524	Former Soviet Union	24.1 ± 3.28	6.3 ± 3.6 ab
426626	Sanni K-98	Pakistan	22.8 ± 2.33	6.3 ± 3.6 ab
250487	K681	India	21.1 ± 2.43	6.3 ± 3.6 ab
346297	n.a	India	18.9 ± 1.76	0.0 ± 0.0 c
250485	K679	India	18.9 ± 3.17	10.4 ± 7.5 ab
391567	T'ai-yang-ma	South Africa	18.7 ± 1.56	12.5 ± 3.6 a
'AU Golden' ^d	n.a	USA	17.7 ± 1.49	0.0 ± 0.0 c
207657 ^e	n.a	Sri Lanka	16.8 ± 1.63	8.4 ± 2.1 ab
322377 ^f	IRI 2473	Brazil	16.6 ± 1.45	14.6 ± 4.2 a
'Tropic Sun' ^g	n.a	USA	16.3 ± 1.58	8.4 ± 5.5 ab
Tillage Sunn ^{TMh}	n.a	India	15.3 ± 1.54	4.2 ± 4.2 bc
South Africa ⁱ	n.a	South Africa	14.8 ± 1.58	12.5 ± 0 a
337080	n.a	Brazil	13.9 ± 1.81	8.4 ± 2.1 ab
219717	n.a	Myanmar	11.5 ± 1.01	8.4 ± 5.5 ab
250486	K680	India	11.4 ± 1.4	10.4 ± 7.5 ab

^a Wang et al. (2006); Morris and Antonious (2013)^b Data were transformed using $Y^{0.25}$. Means were not different among germplasm lines, $F = 0.56$; $df = 16, 34$; $P = 0.8899$ ^c Data were transformed using $Y^{0.25}$. Means followed by the same letter are not significantly different, $F = 2.7$; $df = 16, 32$; $P = 0.0083$ ^d Purchased from Petcher Seeds, Fruitdale, Alabama, USA^e Accession selected to create 'AU Durbin'^f Accession selected to create 'AU Golden'^g Purchased from Molokai Seed Co., Kaunakakai, Hawaii, USA^h Germplasm from Hancock Seed Co., Dade City, Florida, USAⁱ Unknown germplasm (VNK) purchased through Petcher Seeds, Fruitdale, Alabama

$P=0.0100$). Alternatively, 31% of the collected larvae died due to disease or handling, with a higher percentage from the sunn hemp plots ($56.7 \pm 23.3\%$) than the corn ($19.4 \pm 3.8\%$) or sorghum-sudangrass plots ($17.2 \pm 2.2\%$). However, this difference among cover treatments was not significant ($F_{2,4}=2.9$, $P=0.1676$). Parasitism due to all species was not different among treatments and averaged 30%. The egg-larval species *Chelonus insularis* Cresson (Hymenoptera: Braconidae) emerged from larvae at an average of 15%, and was collected at a higher percentage from larvae collected in the corn plots ($32.5 \pm 8.5\%$) than those in the sunn hemp plots ($3.3 \pm 3.3\%$), while emergence from larvae in the sorghum-sudangrass plots was intermediate ($9.8 \pm 3.8\%$; $F_{2,4}=7.2$, $P=0.0470$). The larval endoparasitoid *Cotesia marginiventris* (Cresson) (Hymenoptera: Braconidae) averaged 10% parasitism, while other species such as *Aleiodes laphygmae* (Viereck) (Hymenoptera: Braconidae), *Meteorus* spp. (Hymenoptera: Braconidae), *Euplectrus platyhyphenae* Howard (Hymenoptera: Eulophidae) and unidentified species of Tachinidae made up the last 5% parasitism.

Border row plants

There was no difference in the number of larvae collected or percent corn plants infested, whether sunn hemp alone or a mixture of sunn hemp and sorghum-sudangrass was planted adjacent to the corn in the Citra 2017 trial (Table 3). More larvae (29) were collected in corn during the first sampling date (2 weeks after planting) than during the last sampling date (2). In the cover crop plants, fewer larvae were found in sunn hemp compared to mixtures with sorghum-sudangrass (Table 3). Between 40 and a little over 60% of corn plants were infested by fall armyworm, compared to less than 31% of the cover plants.

Feeding studies

Fall armyworm larvae were fed leaves from different sunn hemp germplasm for 9 days, with an overall weight of 18.7 ± 0.56 mg. The overall model was not significant ($F_{16,34}=0.56$; $P=0.8899$), although numerically larvae feeding on PI 468,956 (32.6 mg) were heavier than larvae feeding on PI 250,486 and PI 219,717 (Table 4). Larval mortality ranged from 0 to 14.6%, with 13/17 lines having similar percentages (Table 4).

Discussion

Sorghum-sudangrass is a common cover crop planted after spring vegetables in areas of Florida which contain overwintering populations of fall armyworm and in areas known as stepping-stone nurseries or secondary source sites (Pair and Westbrook 1995). These secondary source sites can produce large numbers of migratory moths that

continue northward in the spring and summer infesting much of the central and northeastern U.S. Our experiments were conducted in different locations and using different cover crop plants such as sunn hemp, cowpeas, corn, buckwheat, and pearl millet to determine appropriate replacements for sorghum-sudangrass.

Unfortunately, the trial at an overwintering site in Belle Glade produced no information for the use of cover crops in fall armyworm management, as no fall armyworm larvae were found in the treatment plants. The lack of larvae in the whorls was probably due to the earwig *D. taeniatum*, which was found in large numbers in sorghum-sudangrass plants because this predator hides in the whorls of grasses and females raise their young in these locations (Jones et al. 1988). This and related *Doru* spp. are well known predators of *S. frugiperda* in central and South America (Castillejos et al. 2001; Jones et al. 1988; Sueldo et al. 2010). Therefore, it isn't known if fall armyworm populations that survive in areas of continuous generations are affected by cover crop plants or how these particular cover crop plants develop under growing conditions in southern Florida.

The Quincy 2011 trial had only one date where fall armyworm larvae were collected. Heavy summer rains after the initial sample date may have contributed to severe reductions in populations, as dislodgment and drowning are important mortality factors for young larvae (Varella et al. 2015). As expected in the other trials, fewer fall armyworm larvae were found on sunn hemp and cowpea plants than on sorghum-sudangrass or corn. The fall armyworm population found on sunn hemp was 89, 94, and 90% smaller than that found on sorghum-sudangrass for the Quincy 2012, Citra 2012, and Citra 2013 locations, respectively. This percent reduction in population levels compares favorably to reductions of 83 and 95% in plots from an earlier study (Meagher et al. 2004). Those larvae found on sunn hemp were exposed to parasitism at the same level as larvae found on the other cover crop treatments. For cowpea, the difference in fall armyworm numbers compared with sorghum-sudangrass is even more dramatic, with plots in our study and that of Meagher et al. (2004) all showing reductions of over 96%. Cowpea is attractive to neonate *S. frugiperda* (Carroll et al. 2008), but growth is slow and there is high mortality after establishment (Meagher et al. 2004). However, several other insect pests (Miridae, Pentatomidae) were found in our trials, which possibly would negate its positive effects for fall armyworm areawide management. Addition of buckwheat and pearl millet to sorghum-sudangrass did not reduce fall armyworm infestation, and in fact over 2.5 times more larvae were found in the mixture with pearl millet than sorghum-sudangrass alone.

Earlier studies by Pair and Westbrook (1995) and Meagher et al. (2004) suggested that sorghum-sudangrass cover crops could produce 320 million adults/ha if 50% of the larvae survived to adulthood. The amount of sorghum-sudangrass grown as a cover crop in the southern Florida sweet corn area isn't known, but over 15,000 ha of sweet corn were planted in 2015 (USDA/NASS 2017). If $\frac{1}{4}$ of the land is planted to a sorghum-sudangrass cover, then over 1.2 trillion adult moths are potentially produced (320 million adults per ha \times 3750 ha). These moths would be possible migrants in the spring or would be available for reinfestation of future crops; therefore, reductions of over 90% in areas grown to sunn hemp could reduce fall armyworm populations which would be helpful to areawide management.

New varieties of sunn hemp are now available to growers (Mosjidis 2014), therefore a comparison of fall armyworm feeding with the older varieties and potential breeding germplasm was needed. Larvae feeding on plants of PI 468956, the germplasm used to develop 'Tropic Sun' (Wang et al. 2006), were numerically the heaviest larvae and larval weight was similar to a previous study (Meagher et al. 2004). It's surprising that larvae feeding on plants produced from seed purchased as 'Tropic Sun' from Hawaii were half as small, although the difference was not significant. Larval weights from feeding on 'AU Golden' and on PI 322377, the germplasm line used to create this cultivar (Cho et al. 2016; Mosjidis 2014), were very similar to Tillage SunnTM, one of the other lines used in a Florida sunn hemp flowering study (Meagher et al. 2017). The line from South Africa that was used in the field trials in this study produced small larvae with relatively high levels of mortality, similar to work conducted in Brazil (Dias et al. 2016).

Diversifying corn agroecosystems with additional plant species has been a strategy to manage fall armyworm populations in subtropical and tropical areas of the Americas. Strategies either involve early planting of a specified cover crop species followed by no-till cultivation of the corn crop (Dias et al. 2016), no-till cultivation along with weedy plant seed mixtures or into already established natural weed associations (Altieri 1980; Altieri and Whitcomb 1980), or intercropping with other crop plants (Altieri 1980). These strategies generally achieve the goal of lower pest populations and higher natural enemy activity; however, they can be field-specific and have no areawide pest suppression benefit. Our attempt to protect a corn planting by border rows of sunn hemp plus mixes of sorghum-sudangrass in the Citra 2017 trial was unsuccessful. However, more research should be conducted using push-pull technology that repels fall armyworm from host plots while attracting them to border row plants (Midega et al. 2018).

Our strategy in temperate areas is to replace a conventionally-planted cover crop that is known to be a good host plant and instead plant one or more cover crop species, such as cowpeas and sunn hemp, that are not favorable hosts to fall armyworm. Sunn hemp has that potential as results from our study and others suggest it is a poor host for fall armyworm due to low weight gain, longer developmental times, and higher mortality than other cover crop species (Dias et al. 2016; Meagher et al. 2004). Sunn hemp also has additional benefits that will help it fit into the agricultural systems of the southeastern U.S. (Schomberg et al. 2007; Wang et al. 2008), including attracting a variety of Hymenopteran pollinators (Meagher et al. 2019, 2020). However, additional research is needed to determine the influence of cover crops on the population dynamics of fall armyworm and thereby the potential effect of changes in cover crop choice. In particular we need to determine the extent to which different cover crops serve as refuges for fall armyworm populations when cooler or warmer winters influence the size of the overwintering and secondary source areas (Garcia et al. 2017).

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Authors' contributions

The project was conceived by RLM, RNN, SJF, and JKW; data analyzed by RLM; manuscript written by RLM and RNN; DLW provided field plots at Quincy; JBM provided sunn hemp germplasm; JTB and AJR provided technical support; manuscript reviewed by all authors. All authors read and approved and the final manuscript.

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Availability of data and materials

The datasets during and/or analyzed during the current study available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

No ethics approval or consent is needed.

Competing interests

The authors declare that they have no competing interests.

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