Agricultural and Forest Entomology

Agricultural and Forest Entomology (2017), **19**, 332–340 DOI: 10.1111/afe.12213

Evaluating potential trap crops for managing leaffooted (Hemiptera: Coreidae) and phytophagous stink bug (Hemiptera: Pentatomidae) species in peaches

Clement Akotsen-Mensah*†[1], Rammohan R. Balusu*[1], Joseph Anikwe*‡ and Henry Y. Fadamiro*

Department of Entomology and Plant Pathology, Auburn University, 301 Funchess Hall, Auburn, AL 38649, U.S.A., †Department of Entomology, Rutgers University Agricultural Research and Extension Center, 121 Northville Road, Bridgeton, NJ 08302, U.S.A. and ‡Department of Zoology, University of Lagos, Akoka, Lagos 01-234, Nigeria

Abstract

1 The leaffooted bug (*Leptoglossus spp.*) and phytophagous stink bug species (*Euschistus* spp., *Nezara viridula*, *Chinavia hilare*) are the major hemipteran pests of fruit, vegetable, and grain crops in Alabama and other parts of the southeastern U.S.A.

2 The present study evaluated six winter host crops (hairy vetch, oats, rye, triticale, wheat and winter peas) and six summer host crops (buckwheat, brown top millet, grain sorghum, southern pea, pearl millet and sunflower) as potential trap crops for leaffooted and stink bugs in peaches from 2011 to 2013 in Alabama.

3 Experimental plots were arranged around a mature peach orchard in a randomized complete block design, and insect densities, as well as host plant phenology, were recorded at weekly intervals from March to May and July to August each year.

4 Wheat and oats attracted a significantly higher number of target insects than any other treatments evaluated in the winter trials. Sunflower, pearl millet and sorghum recorded a significantly higher number of insects than any other host crops evaluated in the summer. When the insects sampled were totalled across the season, leaffooted bugs (*Leptoglossus phyllopus*) dominated the pest complex (>70%), followed by brown stink bugs (mainly *Euchistus servus* Dallas). Target insects colonized the hosts mainly during the reproductive phase (including flowering and seed development) until plant senescence.

5 The results obtained in the present study suggests that a combination of wheat and oats may be used to detect the early presence of leaffooted and stink bugs in the spring, whereas sunflower, pearl millet and sorghum could be utilized during summer to detect and attract colonizing populations away from peach orchards.

Keywords Coreidae, peaches, Pentatomidae, pest management, plant phenology, trap crops.

Introduction

Peach (*Prunus persica* L.) is a key fruit crop in the U.S.A., with an estimated total annual production of 838 000 tons valued at $629.1 million (NASS, 2015). Peach production is a major industry in Alabama, with an annual production of approximately 12 000 tons of fruit mainly meant for the fresh market (Fadamiro *et al.*, 2009).

Similar to most fruit crops, peach production in Alabama and other parts of the southeastern U.S.A. is plagued with many insect pests. The most common ones recorded in recent times are the leaffooted bug *Leptoglossus phyllopus* (L.) (Coreidae) and endemic phytophagous stink bugs (Pentatomidae), primarily *Euschistus servus* (Say), *Euschistus tristigmus* (Say), *Chinavia hilare* (Say) and *Nezara viridula* (L.) (Majumdar, 2010). The potential economic impact of these insects is high because they also cause extensive damage to other major crops, including Satsuma citrus, apples, corn, peppers, nectarines, tomatoes and soybeans (Allen, 1969; Todd, 1989; Buntin & Greene, 2004; Xiao & Fadamiro, 2010; Smaniotto & Panizzi, 2015). Both adults and nymphs can cause serious damage by direct feeding on harvestable produce (McPherson & McPherson, 2000). Apart from the direct damage, leaffooted and stink bugs are also

Correspondence: Rammohan R. Balusu. Tel.: +1 334 844 1457; fax: +1 334 844 5005; e-mail: balusrr@auburn.edu

[1]These authors contributed equally to this work.

capable of transmitting plant diseases caused by *Nematospora coryli* Peglion, *Aureobasidium pullulans*, *Aspergillus niger* van Tieghem and other *Aspergillus* spp. (Mitchell, 2004; Medrano *et al.*, 2009). The injury left behind at the feeding site can also facilitate secondary infections by other plant pathogens (Mitchell, 2004).

Peach, a high value crop mainly produced for the fresh market, has zero tolerance for insect damage. As a result, growers typically rely on multiple calendar applications of conventional pesticides to produce unblemished fruits (Akotsen-Mensah *et al.*, 2011). Extensive use of insecticides has resulted in many drawbacks, including pest resistance, food toxicity and environmental pollution (Kanga *et al.*, 1999; Atanassov *et al.*, 2003; Grutzmacher *et al.*, 2004). In addition, many of the broad spectrum insecticides (i.e. organophosphates, carbamates, pyrethroids and neonicotinoids) used against other key insect pests in peaches, which also provide some protection against leaffooted and phytophagous stink bugs, are being lost through governmental regulations (FQPA, 1996). Many plant bugs, including leaffooted and stink bugs, which were previously minor pests, are assuming key pest status in peaches as a result of the loss of some of these effective but broad-spectrum insecticides, including parathion-methyl (PennCap-M®, United Phosphorus, Inc., King of Prussia, Pennsylvania) and azinphos-methyl (Guthion®, Makhteshim-Agan of North America, Inc., Raleigh, North Carolina). Therefore, alternative management tactics are needed to avoid a situation where the loss of these insecticides may force growers to choose between compliance or business survival. Furthermore, the difficulty in scouting for leaffooted and stink bugs in orchards is another key challenge growers are facing. Currently, the use of sweep nets is a recommended tool for monitoring these pests in vegetable and field crops. However, this is impractical in tree fruit orchards. Reliable pest monitoring techniques is critical for precise timing of insecticide application for effective management and the elimination of calendar-based, preventive insecticide sprays.

Studies have shown that trap cropping strategy potentially offers a sound alternative pest management tool against stink bugs in a wide range of crops, including fruit, vegetable and row crop production (McPherson & Newsom, 1984; Todd & Schumann, 1988; Tillman, 2006; Swezey *et al.*, 2007; Mizell *et al.*, 2008; Soergel *et al.*, 2015; Nielsen *et al.*, 2016). Trap cropping is a strategy in which highly attractive host plants are planted to attract, intercept, retain and/or reduce targeted insect pests to reduce damage to the main crop (Hokkanen, 1991; Shelton & Badenes-Perez, 2006). Although leaffooted and stink bugs are polyphagous insects, they show preference for certain host plants as a food source or oviposition site, and exhibit strong 'edge effect' behavior by colonizing field margins first before moving into the centre of the field (Blaauw *et al.*, 2016). This movement pattern can therefore be exploited to develop a trap cropping system for management of these insect pests (Mizell *et al.*, 2008). For example, early-maturing soybeans and cowpeas were used as trap crops to protect soybean main crop from *N. viridula* damage (Todd & Schumann, 1988). Researchers in New Zealand were also able to reduce stink bug damage on sweet corn by using black mustard [*Sinapis alba* (L.)] as a trap crop (Rae *et al.*, 2002). Recently, Soergel *et al.* (2015) found sunflower as a potential trap crop for brown marmorated stink bug *Halyomorpha halys* (Stål) in pepper fields. It was reported that *H. halys* populations were much higher in the sunflower trap crop compared with pepper as main crop. However, no difference in fruit damage in peppers was reported.

Although several studies have investigated the effectiveness of trap crops as pest management tools in annual cropping systems, little is known about the use of this strategy in perennial crops where pest management is more complicated by carry-over of insects from one season to the next (Prokopy, 1994; Aluja *et al.*, 1997). Moreover, because of the tendency of stink bugs to prefer taller host plant species, the trap crops identified for leaffooted and stink bugs in annual crops may not be effective (in terms of attraction and competitiveness of trap crop versus the cash crop) in perennial cropping systems (Potting *et al.*, 2005, Mizell *et al.*, 2008). Because many factors influence the effectiveness and feasibility of using an attractive host plant as a trap crop, it is important to evaluate and develop a customized functional trap cropping system for leaffooted and stink bugs in peaches. Although the work by Mizell *et al.* (2008) reported that trap crop is a promising tactic for the management of hemipteran pests, no study has been conducted in a perennial orchard system aiming to determine the importance of trap cropping as a management tool for these bugs. Thus, as a first step in achieving the goal of managing leaffooted and stink bugs using trap crops in peach orchards, we evaluated various host plants as winter and summer trap crops with the aim of identifying a single species or combination of species that will be effective in attracting early immigration of overwintering and late season populations. Accordingly, we hope to gain knowledge on the host preference of leaffooted and stink bugs under perennial orchard conditions, and ultimately apply this information for the development of trap cropping strategy to manage these pests in peaches.

Materials and methods

Field trials were conducted from October to April, and May to September during 2011 and 2012, but only from October to April during 2013 at the Auburn University's E. V. Smith Research Center, Tallassee, Alabama, U.S.A. Treatments for evaluation consisted of host plants that grow through winter season but flower or mature in early spring (hereinafter referred to as 'winter trap crops'), and host plants that grow in spring/summer season (hereinafter referred to as 'summer trap crops'). Six host plants were selected for evaluation as winter trap crops: oats (*Avena sativa* L., variety 'Horizon'), hairy vetch (*Vicia villosa* Roth, variety 'Hairy'), rye (*Secale cereal* L., variety 'Wrens Abruzzi'), triticale (*Triticale hexaploid* Lart, variety 'Monark'), wheat (*Triticum aestivum* L., variety Pioneer 26r12) and winter peas (*Pisum sativum* L., variety 'Whistler'). Six host plants were also selected for evaluation as summer trap crops: brown top millet (*Brachiaria ramose L.*, variety 'Florida brown'), buckwheat (*Fagopyrum sagittatum* Gilib, variety 'Mancan'), grain sorghum (*Sorghum bicolor* L., variety 'Dekalb 54-00'), pearl millet (*Pennisetum glaucum* L., variety 'Tifleaf III'), southern pea (*Vigna unguiculata* L.) and sunflower (*Helianthus annuus* L., variety 'Peredovik'). These host plants were selected based on their ability to attract leaffooted bugs, stink bugs and other plant bug species (McPherson, 1982; Mizell *et al.*, 2008)

Table 1 Planting dates and end of the trial for each season

Season	Year	Sowing of seed	End of trial
Winter	2010/2011	15 October 2010	26 April 2011
	2011/2012	20 October 2011	10 May 2012
	2012/2013	27 October 2012	15 May 2013
Summer	2012	18 May 2012	15 September 2012
	2013	27 May 2013	5 August 2013

and in correspondence to appropriate phenological stages at the time that the insects are ready to colonize peaches. Buckwheat was included because, in addition to attracting the stink bugs, it can also attract natural enemies (Platt, 1997; Ruberson, 2011). Table 1 indicates the periods when both the winter and summer host plants were sown. The treatment plots were established around the four borders (perimeter) of a 5-year-old, mature peach orchard variety 'Flameprince' covering approximately 0.7 ha (2.0 acres) (Fig. 1). Seeds were purchased from Kelly Ag of Hartford, LLC (Hartford, Alabama) and Adams-Briscoe Seed Company (Jackson, Georgia). In winter and summer 2011, seeds were sown directly in the experimental plots measuring 10 × 6 m (length × width) with a spacing of approximately 1.5 m between plots and approximately 10 m away from the border rows of the peach orchard. However, for the trials conducted in 2012 and 2013, the plot size was increased to 15 × 12 m (length × width) and only crops that did well in the 2011 trials were evaluated further (i.e. fewer treatments in 2012 and 2013). For example, out of the six total test plants, only the three most promising plants (oats, rye, and wheat) were identified as potential trap crops in the winter 2011 trial; therefore, only these three crops were evaluated further in 2012 and 2013. These host plants were selected based on various factors, including attractiveness, ease of agronomic management, deer resistance and the potential to provide some economic value to growers. For example, winter pea attracted insects, although the plants were voraciously consumed by deer, which reduced plant stands even though those that survived performed well in some cases. Similarly, three summer host plants (sunflower, pearl millet and sorghum) were selected as potential trap crops in summer 2011 for further evaluation. Plots with unmanaged weeds (unplanted) were used as a control. Seed rate used for each host plant was increased approximately by 2–5% than those recommended for commercial production of each crop which served as an insurance against poor germination. During winter 2011, all the host plants were established well except and the few triticale plants established in the plots were sampled.

In all seasons, experimental plots were laid out in a randomized complete block design replicated around four sections (east, west, south and north) of the orchard (Fig. 1). Host plants were maintained using standard agronomic practices, such as weeding, fertilizer application and irrigation, as necessary during each season. No disease management programme was applied to the host plants because of very little evidence of disease incidence, except the smut disease on oats. The peach orchard was managed using standard disease (fungicides) and weed management (herbicides) practices throughout the study period.

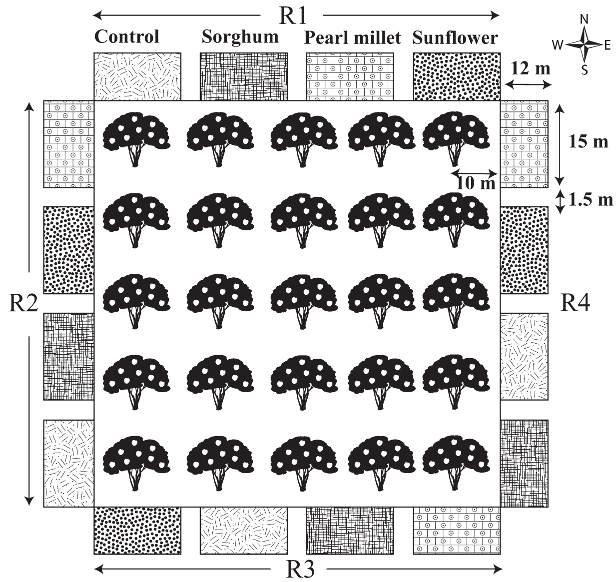

Figure 1 General sketch of the experimental area showing the distribution of treatments in a randomized complete block design with four replicates around the peach orchard.

Data collection

Three sampling methods were used in each plot to determine the abundance of leaffooted bugs (mainly *L. phyllopus* but also some *Leptoglossus zonatus* Dallas), brown stink bugs (*E. servus*) and green stink bugs (mainly *N. viridula* and *C. hilare*). The methods included unbaited yellow pyramid traps (Mizell & Tedders, 1995; Mizell *et al.*, 1997), visual observation and sweep netting. These three sampling methods were used because our preliminary results in 2010 showed that a single sampling method could not adequately sample all the species of leaffooted and stink bugs due to different architectures of the host plants. This was caried out for all seasons, except in summer 2012 and 2013, where unbaited yellow pyramid traps were excluded because the results from the previous season (2011) showed that the unbaited trap did not perform well with respect to capturing the target insects.

Insect sampling for the winter seasons was initiated when temperatures warmed up (~70 °F) in early spring (approximately mid-March) and continued until all the host plants had senesced (mid-May). Winter trap crops were then replaced with summer trap crops and sampled until the end of the peach harvest period (mid-August to September). Sampling was typically carried out in the morning, except on a few days where it was performed in the afternoon as a result of weather conditions that prevented sampling in the morning. During each sampling date, 10 plants were randomly selected per plot and a period of 1 min/plant was spent to visually inspect and record the presence of leaffooted bugs, and stink bugs. In addition, 10 sweeps were made in a zigzag pattern along the diagonal of the plot, and the number of adults and nymphs were also counted and recorded. The use of a sweep net was limited after some time because plants like rye, grain sorghum, and sunflower grew taller at full maturity. Therefore, during this period, the time spent on each sampled plant was doubled (2 min/plant) to visually observe the presence of all the target insects. The cumulative number of target insects in all sampling methods was used to analyze the data for treatment performance. The phenological stages of the host plants were recorded through senescence of each plant species.

Statistical analysis

In all seasons, repeated measures multivariate analysis of variance was first used to establish whether treatment, sampling date, and the interaction of treatment and sampling date were significant. The two main factors (sampling date and treatment) were analyzed with time as a repeated measures factor (Ott & Longnecker, 2001; Norman & Streiner, 2008; Frank *et al.*, 2011). When no significant interaction of sampling date and treatment was observed, the data were pooled and a one-way analysis of variance (ANOVA) was used to determine the treatment effect. Also, where the interaction of treatment and sampling date was significant, data were analyzed for each sampling date using one-way ANOVA. To determine which treatment (trap crop species) attracted the most insects, one-way ANOVA was performed on seasonal total number of all target species collected on each treatment. If a seasonal mean of target species differed significantly among treatments, multiple comparisons of the means were carried out using a Tukey–Kramer honestly significant difference comparison test ($P < 0.05$) (JMP, version 7.0.1; SAS Institute, 2007).

Results

Seasonal observations and performance of leaffooted, brown and green stink bugs on host plants during winter seasons

In winter 2011, repeated measures ANOVA showed no significant differences among treatments (Wilk's $\lambda = 0.90$; $P = 0.0863$) and the treatment × sampling date interaction (Wilk's $\lambda = 0.58$; $P = 0.0787$) for all target insect species. However, there was a significant effect of sampling date (Wilk's $\lambda = 0.48$; $P < 0.0001$). One-way ANOVA of the pooled data showed no significant differences among treatments for leaffooted bugs ($F = 1.74$; d.f. = 6,242; $P = 0.1128$), brown stink bug ($F = 0.68$; d.f. = 6,242; $P = 0.6677$) and green stink bug ($F = 0.55$; d.f. = 6,242; $P = 0.7678$). However, when all the target species were combined across all sampling dates, the result showed significant differences among treatments ($F = 4.73$; d.f. = 3,27; $P = 0.0047$). The average number of target species recorded on wheat was significantly higher than triticale, rye, pea and the control (unplanted plot with weeds). Although wheat hosted the highest densities of leaffooted and stink bugs, followed by hairy vetch and oat, they were not significantly different from each other (Fig. 2).

During winter 2012 when fewer treatments were tested, repeated measures ANOVA showed significant differences among treatments (Wilk's $\lambda = 0.52$; $P < 0.0001$), sampling dates (Wilk's $\lambda = 0.12$; $P < 0.0001$) and the treatment × sampling date interaction (Wilk's $\lambda = 0.17$; $P < 0.0001$) for all species. One-way ANOVA for each sampling date showed significant differences among treatments for leaffooted bugs on 28 March

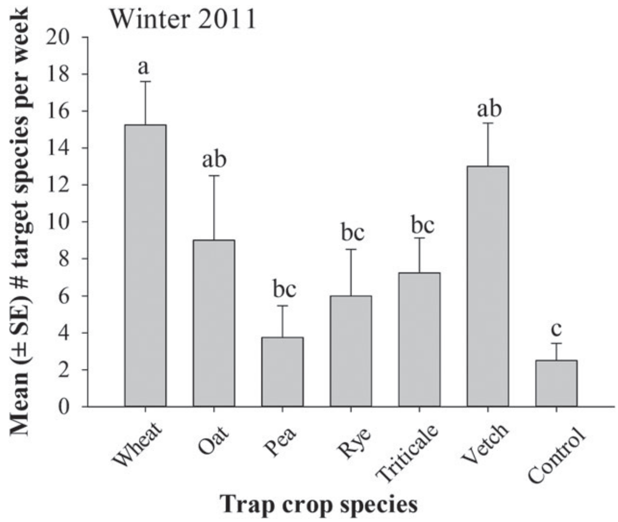

Figure 2 Mean ± SE total number of all target insects recorded in different potential trap crop species during winter 2011. Means indicated by the same lowercase letters are not significantly different from each other ($P = 0.05$). Sampling data were collected once every week, although the data shown are the average densities of target insect species totalled across the season.

($F = 5.05$; d.f. = 3,9; $P = 0.0253$), 5 April ($F = 18.28$; d.f. = 3,9; $P = 0.0004$) and 26 April ($F = 5.05$; d.f. = 3,9; $P = 0.0253$) (Fig. 3A). Similarly, significant differences were recorded among treatments for brown stink bugs on 5 April ($F = 9.58$; d.f. = 3,9; $P = 0.0302$), 19 April ($F = 8.25$; d.f. = 3,9; $P = 0.0060$) and 26 April ($F = 9.00$; d.f. = 3,9; $P = 0.0045$) (Fig. 3B). Also, significant differences were obtained among treatments for green stink bugs on 5 April ($F = 5.67$; d.f. = 3,9; $P = 0.0185$) and 19 April ($F = 9.00$; d.f. = 3,9; $P = 0.0045$) (Fig. 3C). Wheat had significantly higher seasonal populations of leaffooted bugs, brown stink bugs and green stink bugs than any other potential trap crop species evaluated in the winter.

During winter 2013, repeated measures ANOVA showed no significant differences among treatments (Wilk's $\lambda = 0.83$; $P = 0.0715$), sampling dates (Wilk's $\lambda = 0.83$; $P = 0.5659$) and the treatment × sampling date interaction (Wilk's $\lambda = 0.61$; $P = 0.7387$). One-way ANOVA showed a significant difference in the number of leaffooted bugs ($F = 2.55$; d.f. = 3,90; $P = 0.0506$) (Fig. 4A) and green stink bugs ($F = 5.76$; d.f. = 3,90; $P = 0.0012$) (Fig. 4C), although there were no significant differences in the number of brown stink bugs ($F = 1.88$; d.f. = 3,90; $P = 0.1392$) (Fig. 4B). Similarly, wheat hosted significantly higher populations of leaffooted bugs and green stink bugs compared with the control.

In general, though the numbers recorded were not always significantly different from other treatments, higher numbers of leaffooted bugs, brown stink bugs and green stink bugs were recorded on wheat compared with other potential trap crop treatments evaluated in the winter trials (Figs 2–4). When the insects sampled were totalled across the season, leaffooted bugs (mainly *L. phyllopus*) dominated the pest complex (79.7%), followed by brown stink bugs (14.9%) and green stink bugs (5.4%).

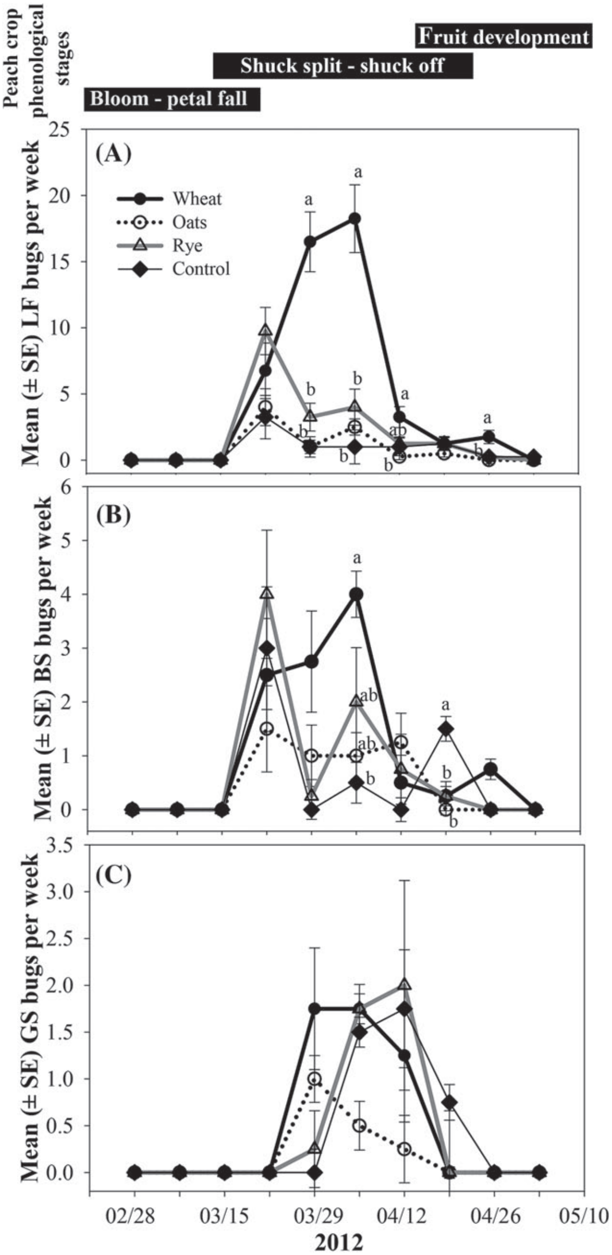

Figure 3 Seasonal mean ± SE per week of number of leaffooted bug (A), brown stink bug (B) and green stink bugs (C) recorded in different potential trap crop species during winter 2012. Means indicated by the same lowercase letters are not significantly different from each other ($P = 0.05$). Sampling data were collected on a weekly basis.

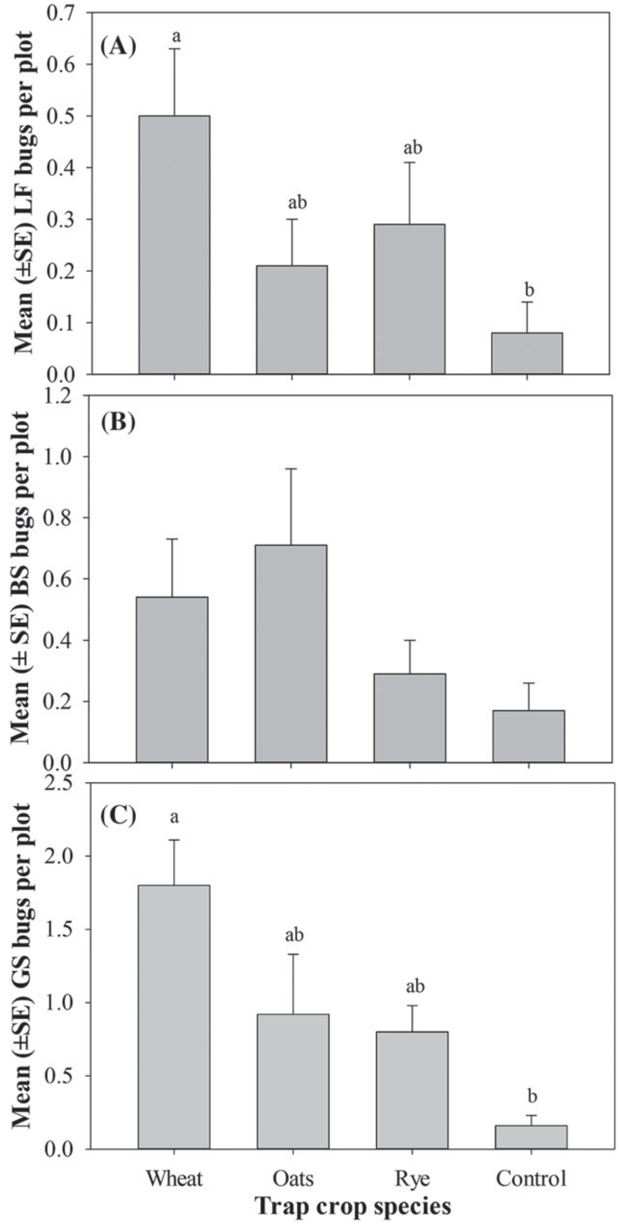

Figure 4 Seasonal mean ± SE number of leaffooted bug (A), brown stink bug (B) and green stink bugs (C) recorded in different potential trap crop species during winter 2013. Means indicated by the same letters are not significantly different from each other ($P = 0.05$). Sampling data were collected once every week.

Seasonal observations and performance of leaffooted, brown and green stink bugs on host plants during summer seasons

During summer 2012, repeated measures ANOVA showed significant differences among treatments (Wilk's $\lambda = 0.51$; $P < 0.0001$), sampling dates (Wilk's $\lambda = 0.38$; $P < 0.0001$) and the treatment × sampling date interaction (Wilk's $\lambda = 0.09$; $P < 0.0001$). When the data were analyzed for each sampling date, the results showed significant differences among the potential trap crop treatments for leaffooted bugs on 14 July ($F = 4.10$; d.f. = 6,18; $P = 0.0091$), 21 July ($F = 4.11$; d.f. = 6,18; $P = 0.0090$), 28 July ($F = 2.92$; d.f. = 6,18; $P = 0.0362$), 4 August ($F = 3.08$; d.f. = 6,18; $P = 0.0296$), 11 August ($F = 2.69$; d.f. = 6,18; $P = 0.0481$), 18 August ($F = 5.23$; d.f. = 6,18; $P = 0.0028$), 25 August ($F = 20.93$; d.f. = 6,18; $P < 0.0001$) and 2 September ($F = 9.26$; d.f. = 6,18; $P = 0.0001$) (Fig. 5A). No significant differences were found among treatments for brown stink bugs (Fig. 5B) and green stink bugs (Fig. 5C).

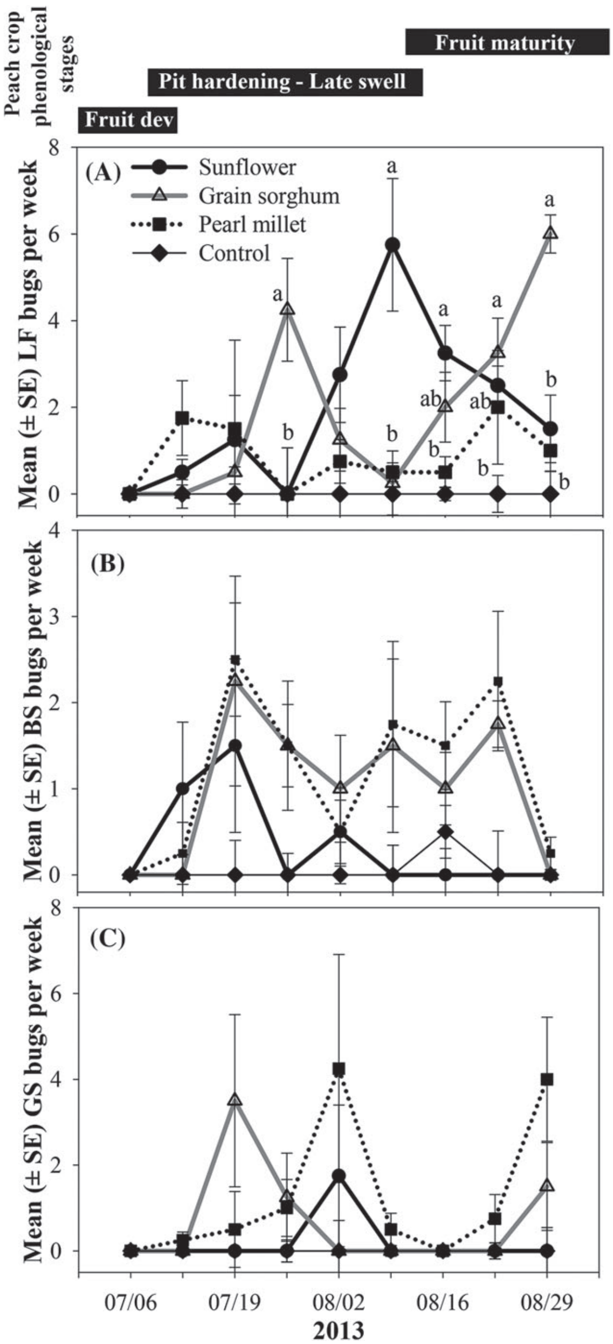

Figure 5 Seasonal mean ± SE number of leaffooted bug (A), brown stink bug (B) and green stink bugs (C) recorded in different potential trap crop species during summer 2012. Means indicated by the same lowercase letters are not significantly different from each other ($P = 0.05$). Sampling data were collected on a weekly basis.

During summer 2013, when the treatments were reduced to three, repeated measures ANOVA showed no significant differences among treatments (Wilk's $\lambda = 0.90$; $P = 0.0584$) or sampling dates (Wilk's $\lambda = 0.81$; $P = 0.0861$). However, the treatment × sampling date interaction was significant (Wilk's $\lambda = 0.52$; $P = 0.0048$). When the data were analyzed for each

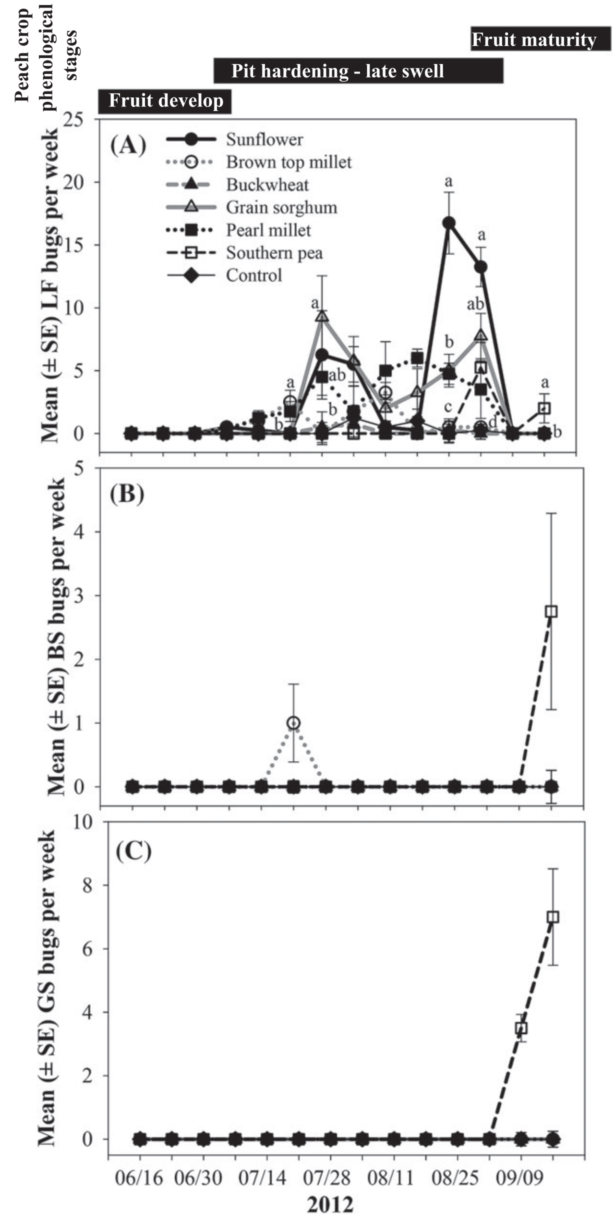

Figure 6 Seasonal mean ± SE number of leaffooted bug (A), brown stink bug (B) and green stink bugs (C) recorded in different potential trap crop species during summer 2013. Means indicated by the same lowercase letters are not significantly different from each other ($P = 0.05$). Sampling data were collected on a weekly basis.

sampling date, the results showed significant differences among treatments for leaffooted bugs on 9 August ($F = 6.8$; d.f. = 3,9; $P = 0.0109$), 16 August ($F = 5.39$; d.f. = 3,9; $P = 0.0212$) and 23 August ($F = 16.14$; d.f. = 3,9; $P = 0.0006$) (Fig. 6A). No significant differences were found for brown stink bugs (Fig. 6B) and green stink bugs (Fig. 6C).

In general, sunflower, pearl millet and sorghum recorded significantly higher seasonal populations of leaffooted, brown and green stink bugs compared with the other trap crops evaluated in summer trials (Figs 5 and 6). When all the insects sampled

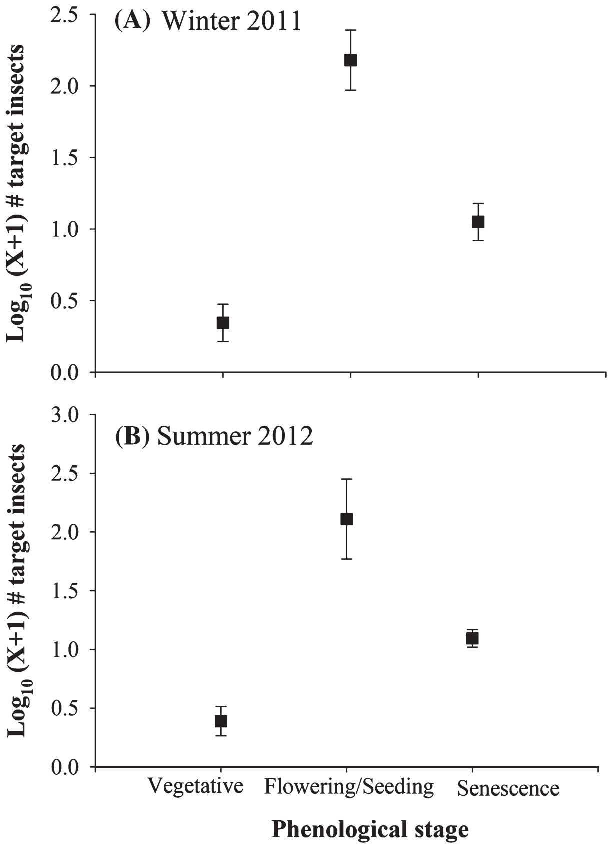

Figure 7 Log_{10} $(x + 1)$ mean ± SE total number of all target species in potential trap crop species by plant phenological stage in winter 2011 (A) and summer 2012 (B).

were totalled across the season, leaffooted bugs (mainly *L. phyllopus*) dominated the pest complex (80%), followed by brown stink bugs (12.9%) and green stink bugs (8.1%).

Incidence of target insects during plant phenological stages

When the data were combined for all target insects during each phenological stage (vegetative, flowering/seeding and senescence) of trap crops across the season, the results showed that the target insects colonized the trap crops mainly during the flowering/seeding (reproductive) stage and continued until maturity in winter 2011 (Fig. 7A) and summer (2012) (Fig. 7B). Similar results were obtained for the other seasons (data not shown).

Discussion

The present study aimed to identify attractive host plants (either single species or combination of species) that could serve as potential trap crops for season-long management of leaffooted bugs and stink bugs in peaches. Data from the six field seasons demonstrated a clear host preference of leaffooted bugs (mainly *L. phyllopus*) and phytophagous stink bugs [green (*A. hilare*) and brown (mainly *E. servus*) stink bugs] for certain trap crop species evaluated in the study. The relative attractiveness of stink bugs to selected potential trap crops was more prominent when the pest population level was high in 2012 compared with 2011 and 2013 when pest densities were relatively low. Wheat was the most attractive of all crop species evaluated in winter, whereas sunflower was found to be a highly attractive summer trap crop, followed by grain sorghum and pearl millet. Seasonal average densities of all leaffooted and stink bug species were two- to 3.5-fold higher on wheat than other winter trap crops and 0.5 to ten-fold higher on sunflower than other summer trap crops in 2012. Leaffooted and stink bug densities were initially high on rye but moved to wheat as rye started to mature (grains harden). Overall, rye and wheat together provided a 4-week attraction period that coincides with the period of early migration (mid-March to April) of overwintering populations of leaffooted and stink bugs. Similarly, grain sorghum and sunflower together provided a 6-week attraction period (mid-July to August) for late season populations that may move into peaches from other adjacent crops. Furthermore, plant phenology was found to influence the attraction of target insect pests to host plants. For example, the bugs predominantly colonized the winter trap crops during the reproductive stages (early April). During this period, the peach fruit had developed to an average size of approximately 10 mm, which is typically the time that most damage begins in the orchard. In all seasons, leaffooted bugs (mainly *L. phyllopus* L.) were the most abundant (>70% of total insects sampled), followed by brown stink bugs (mainly *E. servus*) and green *(A. hilare*) or southern green (*N. viridula*) stink bugs.

Our data corroborated with previous study reported by Mizell *et al.* (2008) where sorghum and sunflower were identified as potential trap crops for *E. servus*, *Chinavia hilaris* (Say) and *N. viridula* in Florida. Endemic stink bugs such as *E. servus*, the rice stink bug *Oebalus pugnax* (F.), *N. viridula* and the red shouldered stink bug *Thyanta custator* (F.) were observed to be the main phytophagous stink bugs in wheat in South Carolina (Reay-Jones, 2010, 2014) and Georgia (Buntin & Greene, 2004). Moreover, wheat was also found to be the most preferred crop for the initial build-up of most stink bugs before moving to other susceptible crops such as corn early in the season (Buntin & Greene, 2004; Tillman *et al.*, 2009; Reay-Jones, 2010, 2014). Sorghum was also shown to be an effective trap crop for *N. viridula* in cotton (Tillman, 2006) and *L. phyllopus* in tomato (Majumdar, 2012) in the Southern U.S.A. Recently, Nielsen *et al.* (2016) found that sorghum and sunflower were highly attractive to both invasive *H. halys* and endemic stink bug species and they suggested the use of sorghum and sunflower as trap crops for managing *H. halys* and other endemic stink bug species in the mid-Atlantic U.S.A.

Although the use of annual trap crops to manage pests of perennial fruit crops such as peaches has not been investigated fully, the results from the present study support the notion that the technique is promising. It was shown that, if wheat and oat are planted around a peach orchard in autumn followed by sunflower, pearl millet and sorghum in the spring, they can serve as potential trap crops for season-long attraction of leaffooted bugs, brown stink bugs and green stink bugs. For example, when planted during October to December, the reproductive stages of wheat and oat will coincide with the blooming period of peach. During this period (early March/April), temperatures will be warming up and most of the insects, including leaffooted and stink bugs, will migrate from their overwintering sites in search of food. Therefore, wheat and oat planted around the borders of peach orchards may potentially intercept and prevent the migration of leaffooted and stink bugs as they migrate into the peach orchards.

Because there is no single, practically reliable way to monitor leaffooted and stink bug species in peach orchards, the attractive host plants identified in the present study could be used to detect the damaging populations of leaffooted and stink bugs in the field. This basic information is critical for precise timing of insecticide sprays and also to avoid unnecessary calendar-based sprays for stink bug management in peaches.

Although host-specific semiochemical odours play a key role in mediating host preference in phytophagous insects in general, a part of the observed host preference in the present study could also be attributed to host plant height, which made some of the plants more apparent than others. The plants that attracted the highest number of the bugs were the tallest and the height of potential trap crops is an area of further study.

In summary, the results obtained in the present study showed that winter and summer annual crops can serve as a trap crops for monitoring and perhaps managing leaffooted and stink bugs in peaches. In particular, wheat and oat could be used to detect and manage the early migration of overwintering populations, whereas sunflower and sorghum could be used to manage first-generation adults by intercepting their movement into peach orchards from neighbouring crops. To the best of our knowledge, we have demonstrated, for the first time, the host preference of leaffooted and stink bugs in a perennial orchard system. Further studies are needed to determine whether the attractive host plants identified in the present study could be used as trap crops for managing leaffooted and stink bugs in peaches. Ultimately, this is expected to lead to the development of environmentally sound integrated pest management practices that replace or complement the calendar-based insecticide application currently used to manage stink bugs in peaches

Acknowledgements

We thank Jason Burkett and his associates at the E. V. Smith Extension Research Station for assisting with crop production and field maintenance. This work was funded in part by the Alabama Department of Agriculture and Industries through a grant given to Henry Y. Fadamiro.

References

Akotsen-Mensah, C., Boozer, R. & Fadamiro, H.Y. (2011) Field evaluation of reduced insecticide spray programs for managing plum curculio, *Conotrachelus nenuphar* (Coleoptera: Curculionidae) in Alabama peaches. *Pest Management Science*, **67**, 626–632.

Allen, R.C. (1969) A revision of the genus *Leptoglossus* Guerin (Hemiptera: Coreidae). *Entomologica Americana*, **45**, 35–140.

Aluja, M., Jimenez, A., Camino, M., Pinero, J., Aldana, L., Caserjon, V. & Valdes, M.E. (1997) Habitat manipulation to reduce papaya fruit fly (Diptera: Tephritidae) damage: orchard design, use of trap crops and border trapping. *Journal of Economic Entomology*, **90**, 1567–1576.

Atanassov, A., Shearer, P.W. & Hamilton, G.C. (2003) Peach pest management programs impact beneficial fauna abundance and *Grapholita molesta* (Lepidoptera: Tortricidae) egg parasitism and predation. *Environmental Entomology*, **32**, 780–788.

Blaauw, B.R., Jones, V.P. & Nielsen, A.L. (2016) Utilizing immunomarking techniques to track *Halyomorpha halys* (Hemiptera: Pentatomidae) movement and distribution within a peach orchard. *PeerJ*, **4**, e1997.

Buntin, G.D. & Greene, J.K. (2004) Abundance and species composition of stink bugs (Heteroptera: Pentatomidae) in Georgia winter wheat. *Journal of Entomological Science*, **39**, 287–290.

Fadamiro, H.Y., Akotsen-Mensah, C., Boozer, R.T. & Jacobi, J. (2009) *Crop Profile for Peaches in Alabama* [WWW document]. URL http://www.ipmcenters.org/cropprofiles/docs/ALpeaches.pdf [accessed on 11 July 2016].

FQPA (Food Quality Protection Act). (1996) *Public Law, 104–170*.

Frank, D.L., Brewster, C.C., Leskey, T.C. & Bergh, J.C. (2011) Factors influencing the temporal and spatial patterns of dogwood borer (Lepidoptera: Sesiidae) infestations in newly planted apple orchards. *Environmental Entomology*, **40**, 173–183.

Grutzmacher, A.D., Zimmermann, O., Yousef, A. & Hassan, S.A. (2004) The side-effects of pesticides used in integrated production of peaches in Brazil on the egg parasitoid *Trichogramma caecoeciae* Marchal (Hym., Trichogrammatidae). *Journal of Applied Entomology*, **128**, 377–383.

Hokkanen, H.M.T. (1991) Trap cropping in pest management. *Annual Review of Entomology*, **36**, 119–138.

Kanga, L.H.B., Pree, D.J., van Lier, J.L. & Walker, G.M. (1999) Monitoring for resistance to organophosphorus, carbamate, and pyrethroid insecticides in the oriental fruit moth (Lepidoptera: Tortricidae). *Canadian Entomologist*, **131**, 441–450.

Majumdar, A. (2010) *Report on Stink Bug and Leaffooted Bugs on Vegetables*. Alabama Cooperative Extension System [WWW document]. URL http://www.aces.edu/timelyinfo/entomology/2010/October/October_%2012.pdf [accessed on July 2016].

Majumdar, A. (2012) *Trap Crops for Leaffooted Bug Management*. Southern SARE Research Update [WWW document].URL http://www.southernsare.org/SARE-in-Your-State/Alabama/State-News/Research-Update-Trap-Crops-for-Leaffooted-Bug-Management [accessed on July 2016].

McPherson, J.E. (1982) *The Pentatomoidea (Hemiptera) of Northeastern North America with Emphasis on the Fauna of Illinois*. Southern Illinois University Press, Carbondale, Illinois.

McPherson, J.E. & McPherson, R.M. (2000) *Stink Bugs of Economic Importance in America North of Mexico*. CRC Press, Boca Raton, Florida.

McPherson, R.M. & Newsom, L.D. (1984) Trap crops for control of stink bugs in soybean. *Journal of the Georgia Entomological Society*, **19**, 470–480.

Medrano, E.G., Esquivel, J., Bell, A. *et al.* (2009) Potential for *Nezara viridula* (Hemiptera: Pentatomidae) to transmit bacterial and fungal pathogens into cotton bolls. *Current Microbiology*, **59**, 405–412.

Mitchell, P.L. (2004) Heteroptera as vectors of plant pathogens. *Neotropical Entomology*, **33**, 519–545.

Mizell, R.F., Tedders, W.L. & Yonce, C.E. (1997) Stink bug monitoring – an update. *Proceedings of Southern Pecan Grower Association*, **90**, 50–52.

Mizell, R.F. & Tedders, W.L. (1995) A new monitoring method for detection of the stink bug complex in pecan orchards. *Proceedings of Southeastern Pecan Growers Association*, **8**, 36–40.

Mizell, R.F. III, Riddle, C.T. & Blount, A.S. (2008) Trap cropping system to suppress stink bugs in the southern coastal plain. *Proceeding of Florida State Horticultural Society*, **121**, 377–382.

NASS (National Agricultural Statistics Service) USDA (2015) *Noncitrus Fruits and Nuts Summary*. [WWW document]. http://www.agmrc.org/commodities-products/fruits/peaches/ [accessed 2 July 2016].

Nielsen, A.L., Dively, G., Pote, J.M., Zinati, G. & Mathews, C. (2016) Identifying a potential trap crop for a novel insect pest, *Halyomorpha*

halys (*Hemiptera: Pentatomidae*), in organic farms. *Environmental Entomology*, **45**, 472–478.
Norman, G.R. & Streiner, D.L. (2008) *Biostatistics: The Bare Essentials*. B.C. Decker Inc., Canada.
Ott, R.L. & Longnecker, M. (2001) *An Introduction to Statistical Methods and Data Analysis*, 5th edn. Duxbury, Thompson Learning Inc., Pacific Grove, California.
Platt, J.O. (1997) *The use of buckwheat border habitats to attract natural enemies of cucumber beetles in a cucurbit agroecosystem*. MS Thesis, Virginia Polytechnic and State University, Virginia.
Potting, R.P.J., Perry, J.N. & Powell, W. (2005) Insect behavioural ecology and other factors affecting the control efficacy of agro-ecosystem diversification strategies. *Ecological Modelling*, **182**, 199–216.
Prokopy, R.J. (1994) Integration in orchard pest and habitat management: a review. *Agriculture Ecosystems & Environment*, **50**, 1–10.
Rae, J., Wratten, S., Sedcole, R., Cameron, P. & Davis, S. (2002) Trap cropping to manage green vegetable bug *Nezara viridula* (L.) (Heteroptera: Pentatomidae) in sweet corn in New Zealand. *Agricultural and Forest Entomology*, **4**, 101–107.
Reay-Jones, F.P.F. (2010) Spatial and temporal dynamics of stink bugs (Hemiptera: Pentatomidae) in wheat. *Environmental Entomology*, **41**, 1516–1526.
Reay-Jones, F.P.F. (2014) Spatial distribution of stink bugs (Hemiptera: Pentatomidae) in wheat. *Journal of Insect Science*, **14**, 1–22.
Ruberson, J.R. (2011) *Integration of Predators and Parasitoids into Row Crop Agroecosystems* [WWW document]. URL http://www.reeis.usda.gov/web/crisprojectpages/0203491-integration-of-predators-and-parasitoids-into-row-crop-agroecosystems.html [accessed on 9 July 2016].
SAS Institute (2007) *JMP, Version 7.0.1*. Cary, North Carolina.
Shelton, A.M. & Badenes-Perez, F.R. (2006) Concepts and applications of trap cropping in pest management. *Annual Review of Entomology*, **51**, 285–308.
Smaniotto, L.F. & Panizzi, A.R. (2015) Interactions of selected species of stink bugs (Hemiptera: Heteroptera: Pentatomidae) from leguminous crops with plants in the neotropics. *Florida Entomologist*, **98**, 7–17.
Soergel, D., Ostiguy, C.N., Fleischer, S.J., Troyer, R.R., Rajotte, E.G. & Krawczyk, G. (2015) Sunflower as a potential trap crop of *Halyomorpha halys* (Hemiptera: Pentatomidae) in pepper fields. *Environmental Entomology*, **44**, 1581–1589.
Swezey, S.L., Nieto, D.J. & Bryer, J.A. (2007) Control of western tarnished plant bug *Lygus Hesperus* Knight (Hemiptera: Miridae) in California organic strawberries using alfalfa trap crops and tractor-mounted vacuums. *Environmental Entomology*, **36**, 1457–1465.
Tillman, P.G. (2006) Sorghum as a trap crop for *Nezara viridula* L. (Heteroptera: Pentatomidae) in cotton in the Southern United States. *Environmental Entomology*, **35**, 771–783.
Tillman, P.G., Northfield, T.D., Mizell, R.F. & Riddle, T.C. (2009) Spatiotemporal patterns and dispersal of stink bugs (Heteroptera: Pentatomidae) in peanut-cotton farmscapes. *Environmental Entomology*, **38**, 1038–1052.
Todd, J.W. (1989) Ecology and behavior of *Nezara viridula*. *Annual Review of Entomology*, **34**, 273–292.
Todd, J.W. & Schumann, F.W. (1988) Combination of insecticide applications with trap crops of early maturing soybean and southern peas for population management of *Nezara viridula* in soybean (Hemiptera: Pentatomidae). *Journal of Entomological Science*, **23**, 92–99.
Xiao, Y. & Fadamiro, H.Y. (2010) Evaluation of damage to Satsuma mandarin (*Citrus unshiu*) by the leaffooted bug, *Leptoglossus zonatus* (Hemiptera: Coreidae). *Journal of Applied Entomology*, **134**, 694–703.

Accepted 16 December 2016
First published online 27 January 2017