Agricultural and Forest Entomology

Agricultural and Forest Entomology (2014), **16**, 426–433 DOI: 10.1111/afe.12072

Potential of pigeon pea as a trap crop for control of fruit worm infestation and damage to okra

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Abstract

1 The potential of perimeter trap cropping, using short and extra-short duration pigeon pea (SD PP and ESD PP), sorghum and cotton, was evaluated in Niger as an agroecological alternative to pesticide application on okra for the management of the tomato fruit worm (TFW) *Helicoverpa armigera* (Hübner).

2 In 2008, infestation by TFW and damage by fruit worms of unsprayed okra with SD PP borders was intermediate between cypermethrin-sprayed and unsprayed pure okra crops.

3 In 2009, the cypermethrin-sprayed okra was significantly less damaged by fruit worms than in the unsprayed pure okra, as well as in the unsprayed okra crops with SD PP, sorghum and cotton borders.

4 In 2010, the pure okra crop sprayed with cypermethrin was significantly less infested by TFW than the unsprayed pure okra crop and the unsprayed okra crop with SD PP borders. The unsprayed okra crop with ESD PP borders was intermediate between cypermethrin-sprayed and unsprayed pure okra crops.

5 The slightly lower TFW infestation of the unsprayed okra crop with ESD PP borders was a result of increased top-down regulation by predator spiders, whose colonization was significantly higher on the unsprayed okra crop with ESD PP borders than on both (sprayed and unsprayed) pure okra crops.

Keywords *Abelmoschus esculentus*, *Cajanus cajan*, *Helicoverpa armigera*, leafhoppers, Niger, perimeter trap cropping, spiders.

Introduction

Okra *Abelmoschus* spp. (Malvaceae), particularly the common okra *Abelmoschus esculentus*, is a highly nutritious traditional vegetable crop in West and Central Africa, where large areas are under cultivation (Kumar *et al.*, 2010). The crop has huge socio-economic potential in the Sahel. It is particularly profitable for women, notably in the Bioreclamation of Degraded Lands system (Pasternak *et al.*, 2009).

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Although okra is considered to be a robust crop, the yield is adversely affected by several biotic stresses. The main biotic stress of okra in West and Central Africa is leaf curl disease caused by a begomovirus (*Okra leaf curl virus*), as transmitted by the whitefly *Bemisia tabaci* (Gennadius), followed by root-knot nematodes (*Meloidogyne* spp.). In Niger, fruit worms [the tomato fruit worm (TFW) *Helicoverpa armigera* (Hübner) and the spiny bollworm *Earias biplaga* (Walker)] are considered to be the most destructive pests of okra. However, there is no information in the literature about the extent of losses induced by these pests. Although synthetic chemical-based control methods are available and effective over the short term, such methods are not sustainable as a result of pesticide resistance, particularly in *H. armigera*, as well as human hazard risks and adverse effects on the environment, especially on beneficial organisms, in addition to their cost (including that of application).

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Trap cropping is a pest control strategy that complies with the concepts of agroecological crop protection or ecological engineering for pest management, with minimal reliance on pesticides (Hokkanen, 1991; Shelton & Badenes-Perez, 2006). In this system, trap plants attract the pests and consequently divert them away from the main crops (Shelton & Badenes-Perez, 2006). Trap cropping can regulate pest populations and/or limit the damage caused to the crop through the pest diversion process combined with other pathways. Such pathways are bottom-up in the case of 'dead-end' trap plants or top-down in the case of increased control by natural enemies, either on the trap plant itself or via colonization of the crop by natural enemies that come from the trap plant (Ratnadass *et al.*, 2012). Perimeter trap cropping (PTC) (i.e. the planting of trap crop to encircle the main crop) (Boucher *et al.*, 2003) is particularly efficient in the case of pests that show active flight and egg-laying site-seeking behaviour, such as Lepidoptera pests (Potting *et al.*, 2005; Shelton & Badenes-Perez, 2006). Synchronization of the plant phenological stages that are attractive for pests between a main crop and a trap crop is crucial for effective trap cropping (Srinivasan *et al.*, 1994). TFW larvae attack most crops after flowering because TFW adult moths are attracted by floral organs to lay their eggs. Thus, in trap cropping pest control strategies, flowering in the trap crop should be synchronized with flowering in the main crop.

Trap cropping has a high potential to reduce infestation of Malvaceous crops by *Helicoverpa* spp., fruit worms or bollworms. Crop infestation by these worms has been successfully reduced on cotton (*Gossypium* spp.) in the U.S.A. using grain sorghum (*Sorghum bicolor*) as a trap crop (Tillman & Mullinix, 2004) and on okra in Kenya using pigeon pea (*Cajanus cajan*) as a trap crop (Virk *et al.*, 2004; Youm *et al.*, 2005). However, no studies have been conducted on the use of trap crops to control TFW to protect rainfed okra in West Africa. Hence, from a very limited choice of rainfed trap crops adapted to the Sahelian climate, we evaluated the potential of short and extra-short duration pigeon pea cultivars along with sorghum and cotton as perimeter trap crops to regulate TFW infestation and limit damage to okra in Sahelian West Africa. The effect of these trap crops on homopteran pests (whitefly and leafhoppers) was also assessed.

Materials and methods

A series of field experiments were conducted in three consecutive years (2008–2010) at the research station of the National Institute of Agronomical Research of Niger (INRAN) at Birni N'Konni (13°47′N, 5°15′E, 270 m a.s.l.) in the Sahelian zone of Niger.

Experiment in 2008

Okra (cv Konni) was planted in a randomized complete block design (RCBD) with four treatments (Fig. 1 and Table 1; all of the experimental plots were cropped with okra, only the borders changed along with insecticide protection of okra): Treatment 1 (T1), an unsprayed pure okra crop as a control; Treatment 2 (T2), a sprayed pure okra crop; Treatment 3 (T3), an unsprayed okra crop with short duration pigeon pea borders; and Treatment 4 (T4), an unsprayed okra crop with sorghum borders. In T2, the okra crop was sprayed with cypermethrin insecticide [Cyperforce® 10 EC (Jubaili Agrotec, Nigeria) in four applications of 100 mL a.i/ha] at weekly intervals starting on 22 August 22 (i.e. 10 days after flowering initiation in the okra crop). Because this was a first year preliminary experiment, each treatment was repeated only twice. The experimental plot measured $9.6 \times 9.6\ m^2$ (13 rows of okra) with a border measuring $1.6 \times 9.6\ m^2$ (two rows, either of okra or of the trap crops) to match the small size of okra farmers' fields in Niger. Plots were in a staggered configuration, interspersed with $12.8 \times 12.8\ m^2$ plots of cowpea (cv TN 35-78). Experimental plots were thus separated from each other to minimize interference among treatments but the interspersed plots of cowpea did not hamper the movements of flying insects because cowpea TN 35-78 is a creeping plant. Cowpea also served as a homogenizing crop preceding okra in the experiments conducted in 2009 and 2010.

The time of flower initiation of all crops was recorded. TFW larvae were counted weekly by visual observation of the whole plants in four subplots (each consisting of six hills of okra) located within each plot. Each week, a new set of four observation subplots (out of a total of 32 predetermined subplots) were randomly selected within each experimental plot. In addition, four fixed randomly-selected subplots were devoted to fruit harvest. In each of the harvest subplots, fruits were harvested twice a week (between September 5 and October 3) at the horticultural maturity stage. The fruits were then divided into three categories: undamaged and marketable fruits; fruits damaged by fruit worms; and fruits damaged or unmarketable for other reasons. Fruits in each category were counted and weighed.

A yellow sticky trap was also set up at the centre of each outside row of the main okra plots (i.e. four traps per plot), facing outwards, according to the four cardinal points. At each observation, the height of the traps was adjusted to just above the canopy. Whitefly catches were recorded twice a week for 6 weeks.

Experiment in 2009

The RCBD was modified and extended to test short duration pigeon pea and sorghum as perimeter trap crops, along with a local cotton cultivar. The trial was planted with five treatments replicated three times, named T1–T4 as in 2008 (with five insecticide sprays in the T2 treatment), plus a new treatment, named T5, which was an unsprayed okra crop with cotton borders (Fig. 1 and Table 1). Each treatment was replicated three times. The plots cropped with cowpea in 2008 were used for okra in the experiment in 2009; in addition, other cowpea plots that had previously been interspersed with sorghum plots as part of another trial, were also used. Plot and border sizes were the same as in 2008 and the same observations were recorded when the fruits were harvested and visual counts were made of fruit worms (and predators on borders only) and of whiteflies caught on the sticky traps. The date of flower initiation was recorded only for okra.

Experiment in 2010

The RCBD was further modified to test short and extra-short duration pigeon pea as perimeter trap crops. The trial was planted

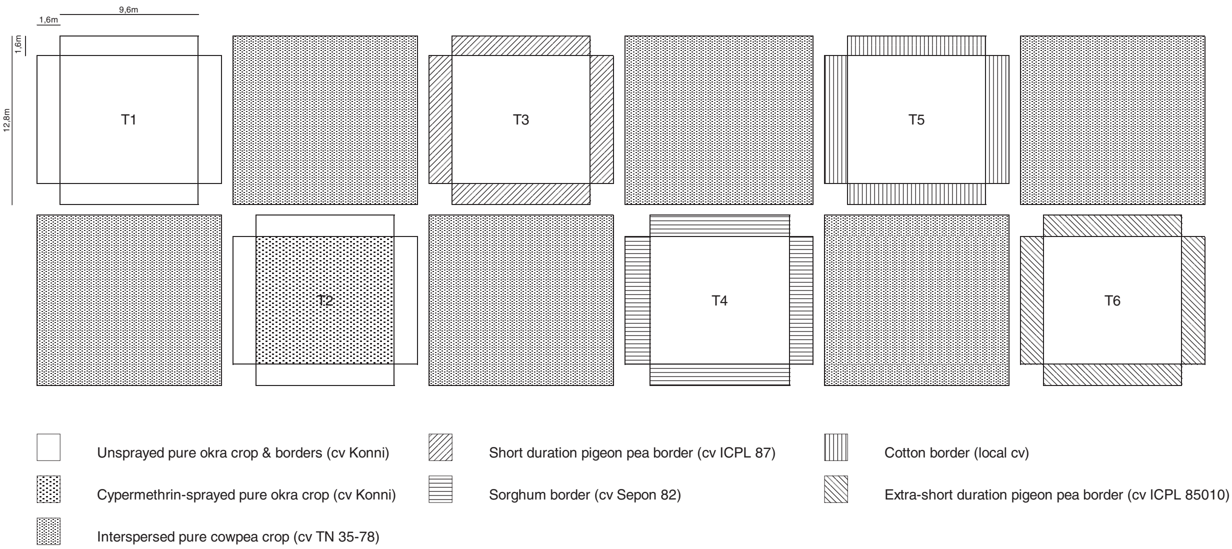

Figure 1 Diagrammatic representation of a replication in the experimental design (scattered plots interspersed with cowpea plots) with all six experimental treatments (T1 to T6) tested over the 3 years (for information on the treatments that were actually compared each year, see Table 1).

Table 1 Details of the six experimental treatments

Treatment code/name	Trap crop (cv) in the plot borders	Spraying of the main and trap crops	Years
T1 = unsprayed pure okra crop	Okra (cv Konni)	No	2008; 2009; 2010
T2 = cypermethrin-sprayed pure okra crop	Okra (cv Konni)	Yes	2008; 2009; 2010
T3 = unsprayed okra crop with short duration pigeon pea borders	Pigeon pea (short duration cv ICPL 87)	No	2008; 2009; 2010
T4 = unsprayed okra crop with sorghum borders	Sorghum (cv Sepon-82)	No	2008; 2009
T5 = unsprayed okra crop with cotton borders	Cotton (local cv)	No	2009
T6 = unsprayed okra crop with extra-short duration pigeon pea borders	Pigeon pea (extra-short duration cv ICPL 85010)	No	2010

with four treatments replicated four times, named T1–T3 as in 2008 (with three insecticide sprays applied at 2-week intervals in the T2 treatment), and a new treatment, T6, which was an unsprayed okra crop with extra-short duration pigeon pea borders (Fig. 1 and Table 1). The size of the plots and borders were the same as in 2008. Similar observations were recorded when the fruits were harvested in two fixed subplots (one external and one internal) and when fruit worms and predators were counted visually, in one subplot in the border, and three subplots in the main plot, corresponding to the distance from the border of the plot: external subplots being 0.8–1.6 m from the border, intermediate subplots being 2.4–3.2 m from the border and internal subplots being 4.0–4.8 m from the border.

Some additional observations recorded at the okra vegetative stage began earlier than in the previous years to include foliar pests [particularly leafhoppers (Cicadellidae, subfamily Typhlocybinae): mainly *Empoasca* spp.] and spiders, which are the main leafhopper predators in many agroecosystems (Costello & Daane, 2003). Accordingly, an extra set of sampling subplots was selected for D-Vac (Rincon-Vitova Insectaries, Inc., Ventura, California) sampling (Dietrick, 1961) of flying homoptera at the border of the plot and at three different distances from the border. Four D-Vac samples were taken at weekly intervals. As in previous years, visual observations were made. On the other hand, whitefly populations were not recorded in 2010 because, unlike adult *Empoasca* spp., whiteflies cannot be easily identified/counted using D-Vac sampling, and sticky traps were not set up to avoid interfering with D-Vac sampling.

Statistical analysis

Cumulative data (five counts of TFW and 14 of whiteflies in 2008; seven counts of TFW and 17 of whiteflies in 2009; 11 counts of TFW and spiders and four of leafhoppers in 2010) were analyzed after square root transformation with XLSTAT (Addinsoft, 2011). Analysis of variance with the Student–Newman–Keuls test was used for the comparison of means. Visual counts of flying homoptera in the D-Vac traps were expressed as numbers per six-hill subplot. Whiteflies caught on the yellow sticky traps were expressed as numbers per experimental plot. In 2010, to compare the number of TFW, leafhopper and spider populations among border, external, intermediate and internal subplots, and because the analysis was not run in accordance with the RCBD design, data were analyzed with XLSTAT (Addinsoft, 2011), without transformation, using the nonparametric test module (Kruskal–Wallis test) with Dunn's method for multiple comparison. Correlations among the leafhopper and spider populations were calculated using Pearson's *r* in XLSTAT, using individual experimental plot values (untransformed data). For each year, yields were converted to tons/ha prior to analysis.

Results

Experiment in 2008

Okra cv Konni both as main and trap/border crops started flowering 32 days after sowing (DAS), sorghum cv Sepon 82 as a trap/border crop started flowering 52 DAS, and short duration pigeon pea cv ICPL 87 as a trap/border crop started flowering 66 DAS. In 2008, the population of TFW (*H. armigera*) largely dominated (92.6 ± 8.0%; $n = 2$) the only other fruit boring species (*Earias* spp.) found in the experimental plots.

Significant differences were detected in TFW larval populations among treatments ($F_{3,4} = 7.497$, $P = 0.041$) (Table 2). Significant differences were also detected in the extent of damage to okra fruits caused by fruit worms ($F_{3,4} = 38.285$, $P = 0.002$) (Table 2). TFW infestation was significantly reduced in the sprayed pure okra crop (T2) compared with the unsprayed pure okra crop (T1) and compared with the unsprayed okra crop with sorghum borders (T4) (Table 2) and, in terms of damage to okra fruits, compared with the unsprayed pure okra crop (T1) (Table 2). Infestation by TFW and damage by fruit worms of unsprayed okra crop with short duration pigeon pea borders (T3) was intermediate between sprayed (T2) and unsprayed (T1) pure okra (Table 2).

On the other hand, as a result of their flowering dates, both sorghum and pigeon pea only started being attractive to *H. armigera* from the end of September, whereas okra was attractive from beginning of September. For this reason, sampling of the border rows was conducted only once, on 26 September, and no differences among treatments were found in the larval population sampled in the border crops (data not shown).

Regarding yellow trap catches, differences among treatments were not significant ($F_{3,4} = 2.261$, $P = 0.223$), with a mean value of 105.3 per plot (square root of cumulated catches). It should be noted that no evidence was found either for actual damage to okra caused by sap-sucking pests or for virus disease potentially transmitted to okra by whiteflies or leafhoppers.

No difference was found among treatments in terms of fresh fruit yield, either total, with a general mean of 14.2 t/ha ($F_{3,4} = 1.931$, $P = 0.266$), or marketable, with a general mean of 11.2 t/ha ($F_{3,4} = 0.214$, $P = 0.254$).

Experiment in 2009

Main and trap/border crops of okra started flowering 42 DAS (the flowering dates of other crops were not recorded). Treatments tested in 2009 did not differ significantly with respect to TFW infestation ($F_{4,10} = 0.947$, $P = 0.476$). Unlike in 2008, TFW infestation was very low. *Helicoverpa armigera* represented only 27.0 ± 10.6% ($n = 3$) of fruit boring species. *Earias biplaga* was the dominant species. It was the only fruit worm species to be recovered on borders (a total of 11 specimens in cotton borders and four in okra borders in treatment T1; none on either sorghum or pigeon pea). On the other hand, no TFW was observed on any of the species used as border crops.

Table 2 Infestation of okra (cv Konni) fruit by tomato fruit worm (TFW) and damage caused by fruit worms in 2008

Treatments	TFW infestation[a, b]	Damage by fruit worms (%)[a]
T1 = unsprayed pure okra crop	4.45 ± 0.05a	15.15 ± 1.33a
T2 = cypermethrin-sprayed pure okra crop	1.93 ± 0.15b	2.49 ± 0.76b
T3 = unsprayed okra crop with short duration pigeon pea borders	3.50 ± 0.04ab	10.87 ± 0.68ab
T4 = unsprayed okra crop with sorghum borders	4.17 ± 0.25a	11.27 ± 1.77ab
P-value (*F*-test)	0.041	0.002

[a]Data are the mean ± SE.
[b]Cumulative number of worms per six-hill subplot, after square root transformation.
Means with the same lowercase letters in a column are not significantly different ($P < 0.05$) according to the Student–Newman–Keuls test.

Table 3 Extent of damage to okra (cv Konni) fruit by fruit worms in 2009

Treatments	Damage by fruit worms (%)[a]
T1 = unsprayed pure okra crop	21.27 ± 4.47a
T2 = cypermethrin-sprayed pure okra crop	7.66 ± 1.86b
T3 = unsprayed okra crop with short duration pigeon pea borders	19.53 ± 3.76a
T4 = unsprayed okra crop with sorghum borders	18.27 ± 6.53a
T5 = unsprayed okra crop with cotton borders	20.98 ± 0.72a
P-value (*F*-test)	0.010

[a]Data are the mean ± SE.
Means with the same lowercase letters are not significantly different ($P < 0.05$) according to the Student–Newman–Keuls test.

The only significant effect was on the percentage of worm-damaged fruits ($F_{4,10} = 5.933$, $P = 0.010$) (Table 3): the cypermethrin-sprayed okra was significantly less damaged than in the other three treatments. Regarding yellow trap catches, differences among treatments were not significant ($F_{4,10} = 3.061$, $P = 0.069$), with a mean of 66.25 per plot (square root of cumulated catches).

Potential predators of the TFW collected by sampling the borders belonged to the groups: spiders (Arachnida; Araneae), pirate bugs (Insecta; Hemiptera: Anthocoridae), praying mantis (Insecta; Mantodea: Mantidae) and earwigs (Insecta; Dermaptera: Forficulidae) (Table 4). The first group was almost evenly distributed across the four border species, whereas the second group, although the most abundant, was restricted to sorghum, and the other two groups were marginal.

In terms of fresh fruit yield, no differences were found among treatments, either in total yield, with a general mean of 5.0 t/ha ($F_{4,10} = 2.140$, $P = 0.150$), or in marketable yield, with a general mean of 4.2 t/ha ($F_{4,10} = 3.055$, $P = 0.069$).

Table 4 Potential predators of *Helicoverpa armigera* collected on borders of okra plots in 2009

Predator groupBorder (treatment)	Spiders[a]	Pirate bugs[a]	Mantis[a]	Earwigs[a]
Okra (T1)	1.28 ± 0.24a	0b	0.47 ± 0.41a	0a
Pigeon pea (T3)	1.27 ± 0.29a	0b	0a	0a
Sorghum (T4)	1.86 ± 0.55a	7.15 ± 2.40a	0a	0.47 ± 0.41a
Cotton (T5)	2.23 ± 0.56a	0b	0.24 ± 0.41a	0a
P-value (*F*-test)	0.070	0.000	0.219	0.052

[a]Cumulative number of arthropods per six-hill subplot, after square root transformation. Data are the mean ± SE.
Means with the same lowercase letters in a column are not significantly different ($P < 0.05$) according to the Student–Newman–Keuls test.

Experiment in 2010

Okra cv Konni both as main and trap/border crops started flowering 38 DAS, extra-short duration pigeon pea cv ICPL 85010 as a trap/border crop started flowering 49 DAS, and short duration pigeon pea cv ICPL 87 as a trap/border crop started flowering 61 DAS. As in 2008, in 2010, infestation of okra fruit was mainly by TFW *H. armigera*, which represented 96.2 ± 1.7% ($n = 4$) of fruit worm species. Significant differences in infestation by TFW larvae were detected among treatments ($F_{3,12} = 4.243$, $P = 0.029$) (Table 5). By contrast, no significant differences were found among treatments in the percentage of worm-damaged fruits ($F_{3,12} = 2.196$, $P = 0.141$), with a general mean of 8.7% and a value of 10.1% for the control (T1). The sprayed pure okra crop (T2) was significantly less infested by fruit worms than both the unsprayed pure okra crop (T1) and the unsprayed okra crop with short duration pigeon pea borders (T3). However, it was not significantly less infested than the unsprayed okra crop with extra-short duration pigeon pea borders (T6) (Table 5).

Concerning infestation by leafhoppers, significant differences were found among treatments (determined by D-Vac sampling) ($F_{3,12} = 4.257$, $P = 0.029$) (Table 5). Infestation of the unsprayed okra crop with extra-short duration pigeon pea borders by leafhoppers was significantly higher than infestation of the sprayed pure okra crop and of the unsprayed okra crop with short duration pigeon pea borders (Table 5).

The unsprayed okra plots with extra-short duration pigeon pea borders were also significantly more colonized by predator spiders than both the sprayed and unsprayed pure okra crops ($F_{3,12} = 5.123$, $P = 0.016$) (Table 5). In 2010, there was a significant positive Pearson's correlation coefficient between leafhopper and spider populations ($r = 0.649$, $P = 0.007$, d.f. = 14).

Although extra-short duration pigeon pea borders became attractive to TFW slightly later than okra borders and okra main crops, general infestation by TFW started at the onset of flowering of each crop. Still, infestation of pigeon pea borders remained significantly lower than that of the main okra crop (Table 6). Regarding spider colonization, although differences were not significant, a tendency appeared at the $P = 0.06$ threshold, with the lowest spider population recorded on the pigeon pea border. No such trend was observed for leafhoppers (Table 6).

There was no significant difference in total fresh fruit yield among treatments ($F_{3,3} = 3.281$, $P = 0.059$). However, a tendency appeared at the $P = 0.06$ threshold, with the highest yield recorded in the unsprayed pure okra crop with extra-short duration pigeon pea borders. The mean yield of fresh okra fruit was 13.0 t/ha.

Discussion

The present study highlighted a mean level of damage caused by fruit worms to unsprayed control plots of 15.5% over a 3-year period. There was no evidence of either whitefly- or leafhopper-transmitted viral disease. Among fruit worms, *H. armigera* was the dominant species in 2008 and 2010. In 2009, okra infestation by the Malvacean-specialist species *E. biplaga* was much higher than that of the generalist species *H. armigera.* The overall higher incidence of *E. biplaga* in 2009 can be partly ascribed to lower rainfall than in 2008 and 2010. Total precipitation was 603.8 mm in 2008 and 603.5 mm in 2010, the highest two in the decade, compared with only 370.1 mm in 2009, the second lowest in the decade at the experimental site (INS, 2011). Kadam Jijabrao and Khaire (1995) reported the adverse effect of high relative humidity and rainfall on *Earias vitella* larvae on okra in India, whereas the relationship is less straightforward in *H. armigera* (Khan *et al.*, 2003). Indeed, in a test conducted in Niamey in 2011, a year with very low and erratic rainfall (total of 346.2 mm), okra was not infested by *H. armigera*, although it was to a certain extent by *Earias* spp. (I. K. Harouna *et al*., unpublished data). The lower yield of rainfed okra in 2009 compared with 2008 and 2010 can also be ascribed to erratic rainfall and resulting poor water availability for plant growth.

In this context, the insecticide treatment (T2) was the only treatment that provided significant protection against TFW (either in terms of infestation or damage or both) compared with the untreated control (T1) in all three experimental years. However, the protection did not result in any significant gain in yield. PTC treatment with pigeon pea provided partial protection and could thus be of interest in integrated pest management programmes in combination with other partially effective methods, including under higher pest pressure. On the other hand, this partial protection could not be ascribed to the increased attractiveness of the trap crop for ovipositing female TFW moths because, in 2008, pigeon pea cv ICPL 87 started flowering long after the onset of TFW infestation of okra. Similarly, in 2010, although the attractive stage of pigeon pea cv ICPL 85010 was better synchronized with that of okra, this pigeon pea cultivar was less attractive to TFW than the main crop. In studies conducted in Uganda, pigeon pea cv ICPL 85010 was found to be far less attractive to TFW than pigeon pea cv ICPL 87 (Night & Ogenga-Latigo, 1993). Nor could the apparent 'protection' be ascribed to a 'barrier' effect because the pigeon pea cultivars tested (especially ICPL 85010) are characterized by short plant height. In addition, such a barrier effect by pigeon pea could only be effective against an active flyer such as the TFW if

Table 5 Okra (cv Konni) fruit infestation by tomato fruit worm (TFW), whole okra plant infestation by leafhoppers and colonization by spiders in 2010

Treatments	TFW infestation[a]	Leafhopper infestation[a]	Spider colonization[a]
T1 = unsprayed pure okra crop	2.94 ± 0.37a	7.36 ± 1.10ab	2.66 ± 0.36b
T2 = cypermethrin-sprayed pure okra crop	2.13 ± 0.25b	6.41 ± 0.43b	2.38 ± 0.69b
T3 = unsprayed okra crop with short duration pigeon pea borders	2.86 ± 0.31a	6.80 ± 0.80b	2.95 ± 0.20ab
T6 = unsprayed okra crop with extra-short duration pigeon pea borders	2.68 ± 0.45ab	8.23 ± 0.56a	3.55 ± 0.37a
P-value (*F*-test)	0.029	0.029	0.016

[a]Cumulative number of individuals per six-hill subplot, after square root transformation. Data are the mean ± SE.
Means with the same lowercase letters in a column are not significantly different ($P < 0.05$) according to the Student–Newman–Keuls test.

Table 6 Okra fruit and pigeon pea pod infestation by tomato fruit worm (TFW), okra plant infestation by leafhoppers and colonization by spiders in 2010 in treatment T6 (unsprayed okra crop with extra-short duration pigeon pea borders)

Treatments	TFW infestation[a]	Leafhopper infestation[a]	Spider colonization[a]
Border (pigeon pea cv ICPL 85010)	1.0 ± 2.0a	41.8 ± 29.47a	3.1 ± 3.30a
External subplots (okra cv Konni)	7.0 ± 2.58ab	26.0 ± 17.11a	11.5 ± 1.63a
Intermediate subplots (okra cv Konni)	8.3 ± 2.08b	23.3 ± 5.10a	10.6 ± 5.56a
Central subplots (okra cv Konni)	6.5 ± 2.99ab	19.0 ± 14.08a	8.8 ± 2.50a
P-value	0.040	0.619	0.055

[a]Cumulative number of individuals per six-hill subplot. Data are the mean ± SE.
Means with the same lowercase letters in a column are not significantly different ($P < 0.05$) according to Dunn's test.

it prevented the moths from reaching the main crop by being highly attractive, which was not the case.

The effectiveness of pigeon pea was not a result of the higher attractiveness of the border for spiders either, nor to higher predation by spiders on the border plant. Indeed, major taxa of predators including chrysopids, coccinellids, anthocorids and spiders are more common on sorghum than on pigeon pea in sorghum-pigeon pea intercrops (Shanower *et al.*, 1999). Omnivorous pirate bugs (*Orius* spp., Hemiptera: Anthocoridae) attack eggs and first-instar nymphs of *H. armigera* more effectively on sorghum than on pigeon pea (Sigsgaard & Esbjerg, 1997). In the present study, *Orius* spp. were only found in large numbers on flowering sorghum. Spiders, the main potential predators of the TFW larval instars, were more abundant on cotton and sorghum borders than on pigeon pea, although differences were not significant.

In the rich vertisols of Birni n'Konni, the association of okra with pigeon pea may have provided a 'luxury' nitrogen input, which made the okra plants (particularly those growing close to the pigeon pea border) more attractive to sap-feeding pests (Jahn *et al.*, 2005; Lu *et al.*, 2007; Stafford *et al.*, 2012). The benefits of intercropping okra with legumes have been demonstrated in India with cowpea (John & Mini, 2005) and pigeon pea (Srinivasulu *et al.*, 2000). Mechanisms of nitrogen transfer between plants have also been described (Malézieux *et al.*, 2009; Pirhofer-Walzl *et al.*, 2012; Jamont *et al.*, 2013). The nitrogen-rich okra plants could thus have attracted more leafhoppers. In Africa, leafhoppers (mainly *Empoasca* spp.) are considered minor pests of okra (Obeng-Ofori & Sackey, 2003; Dabiré-Binso *et al.*, 2009), unlike *Amrasca biguttula biguttula* Ishida in Asia (Jayasimha *et al.*, 2012). *Empoasca* spp. do not cause significant damage to okra because they are attracted at the vegetative stage, when the plant can overcome pest attacks by physiological resistance as a result of better plant nutrition and because they are not vectors of viral diseases.

We recorded a high rate of colonization of okra by spiders, which are key generalist predators for natural pest control in crops (Blake *et al.*, 2013). As expected, the spider population was notably high on unsprayed pure okra plots with extra-short duration pigeon pea borders. Thus, the lower infestation of fruit worm on okra plots could be a result of top-down regulation by spiders, attracted by leafhoppers, rather than to the bottom-up effect of the border trap crops diverting TFW egg laying away from okra. A high positive correlation between sap-sucking pests, particularly leafhoppers and predatory spiders in okra, has been reported in Pakistan (Sahito *et al.*, 2013) and was recorded by our team in Niamey, Niger (I. K. Harouna *et al*., unpublished data).

The results of the present study provide new insights into the benefits of controlling TFW by associating okra with a legume plant, which improves the amount of nitrogen available to the main crop and thus increases its attractiveness (and physiological resistance) to homoptera. Nevertheless, there is a need to improve the efficiency of the system through other partial effects (e.g. via 'assisted push–pull') (Cook *et al.*, 2007). The effectiveness of trap cropping for TFW control could be improved by optimizing trap cropping design by a better match between the attractive stages of the crop and the trap crop for pests. There is not much scope for breeding extra-short duration pigeon pea for higher attractiveness to TFW because the trend is rather towards the reverse (Jadhav *et al.*, 2012). Under rainfed conditions, in an environment where water is a scarce resource before the onset of rains, it is not possible to plant the pigeon pea border earlier and to water it, or to delay planting okra, because the farmers already plant at the earliest possible date to take advantage of the entire (short) rainy season. To find a better match between the attractive stage of the two species, a sorghum cultivar other than Sepon 82 could have been tested. However, highly attractive sorghum cultivars are those with compact panicles (Ratnadass *et al.*, 2009) and those that flower and mature earlier than Sepon 82 are prone to grain molds, which would affect both their attractiveness to

TFW and their ability to yield edible grain (Ratnadass *et al.*, 2003).

Consequently, there is a need to identify the spatial arrangements that optimize both types of pest regulating effects, particularly with the PTC design in case the size of the plot increases. Spatially explicit process-based models are powerful tools for integrating and linking population processes with habitat spatial organization (Bianchi *et al.*, 2007). Individual-based models (i.e. spatially explicit models with a strong emphasis on individual behaviours) have been used to study the pest control efficacy of agro-ecosystem diversification strategies as part of a theoretical approach (Potting *et al.*, 2005; Holden *et al.*, 2012). Individual-based models are suitable research tools for studying the effects of interplay between the spatial distribution of trap plants, crop ecology (e.g. retention, attraction, repulsion rates), and the life history and behavioural ecology of pests on the efficacy of trap cropping. Modelling approaches should help produce guidelines for optimizing trap cropping strategies for the control of TFW. The results of the present study provide a reference point for future research aimed at improving integrated pest management, especially of TFW on okra in the Sahelian zone of West Africa.

Acknowledgements

These studies were funded by CIRAD core-budget (ATP Omega3 Project). We are grateful for the technical and administrative support provided by Mahamane Hamza and Habou Kano, Head and Acting Head of INRAN Konni research station, for making the arrangements to enable us to conduct the field experiments.

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Accepted 21 April 2014
First published online 23 July 2014