

Pheromone-mediated mating disruption in the millet stem borer, *Coniesta ignefusalis* (Lepidoptera: Pyralidae)

Ousmane Youm^{a,b,*}, Yacouba Maliki^b, David R. Hall^c, Dudley I. Farman^c, John E. Foster^a

^a Department of Entomology, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 103 Entomology Hall, PO Box 830816, Lincoln, NE 68583-0816, USA

^b Formerly, ICRISAT Sahelian Centre, BP 12404, Niamey, Niger

^c Natural Resources Institute, University of Greenwich, Chatham Maritime, Kent ME4 4TB, UK

ARTICLE INFO

Article history:

Received 11 February 2011

Received in revised form

6 September 2011

Accepted 11 September 2011

Keywords:

Coniesta ignefusalis

Mating disruption

Sex pheromone

Pearl millet

ABSTRACT

The millet stem borer, *Coniesta ignefusalis* Hampson (Lepidoptera: Pyralidae), is a major pest of pearl millet in the Sahelian region of Africa. The female sex pheromone has been identified and synthesised, and previous research had shown that the synthetic pheromone could cause high levels of reproductive communication disruption in small plots when released at rates of 640 mg/ha/day, using PVC resin formulation renewed every seven days to maintain efficiency. In the present research, in experiments in farmers' fields in Niger, 86.8% (SE = 2.6%) communication disruption was achieved when polyethylene vials loaded with 0.5 mg pheromone at 400 dispensers/ha were used and replaced every 21 days. Polyethylene vials loaded with 80 mg pheromone gave uniform, zero-order release at approximately 0.05 mg/day at 27 °C. Experiments carried out on replicated 0.5 ha plots in farmers' fields in Niger using a single application of these dispensers at 400 dispensers/ha resulted in at least 99% suppression of pheromone trap catches of male *C. ignefusalis* moths in treated plots relative to numbers in untreated plots for up to 3 months. However, sampling the central portions of these plots before and after harvest showed no significant differences in infestation, damage or yield loss between plots treated with pheromone and untreated plots. This may have been because of small plot size and the immigration of mated female moths into the treated plots which negated any reduction of mating of females within the treated plots. Comparisons of numbers of male *C. ignefusalis* moths in traps baited with the standard 0.5 mg monitoring lures and those baited with the 80 mg disruption dispensers showed catches in the latter were only 10–20% of those in the former; indicating high level communication disruptions in traps with high dose dispensers. Implications of using insect synthetic pheromones in the development of integrated management of *C. ignefusalis* in pearl millet cropping systems in the Sahel are discussed.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

The millet stem borer, *Coniesta ignefusalis* Hampson (Lepidoptera: Noctuidae), is a key pest of pearl millet throughout the West African Sahelian and Sudanian zones (Harris, 1962; N'doye et al., 1984; N'doye and Gahukar, 1987; Youm et al., 1996). First generation larvae cause dead hearts and stand-loss, while the second and third generations cause lodging, disruption of the vascular system and inhibition of grain formation (Harris, 1962). In sub-Saharan Africa, where pearl millet is a major staple crop grown by subsistence farmers, yield losses due to attack by *C. ignefusalis* range from 15% to total crop failure (Harris, 1962; Ajayi, 1990), and in Niger,

more than 90% of stem borer infestation and damage on millet is caused by *C. ignefusalis* (Youm and Gilstrap, 1993, 1994).

Control by chemical means has not been very effective, and repeated applications are not sustainable in subsistence agriculture systems in the Sahel (Youm, 1990). Destruction of alternative hosts and crop residues is difficult to enforce because of the importance of these materials for construction, decoration and animal bedding in the region (Harris, 1962). Manipulation of planting dates (Vercambre, 1978; Guevremont, 1983; Youm, 1990), field sanitation (Nwanze and Muller, 1989) and burning of stalks (Guevremont, 1983; Maiga, 1984) have given inconsistent results. Although some tolerance has been reported in varieties due to production of a sticky secretion in stem tunnels (N'doye, 1977) or due to increased tillering (Nwanze, 1985), there are no varieties showing useful levels of resistance. Natural enemies of *C. ignefusalis* have been described (Youm et al., 1996), but significant parasitism develops too late in the growing season (Youm, 1990).

* Corresponding author. Department of Entomology, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln, 103 Entomology Hall, PO Box 830816, Lincoln, NE 68583-0816, USA. Tel.: +1 402 4727016; fax: +1 402 4724687.
E-mail address: oyoum2@unl.edu (O. Youm).

Female *C. ignefusalis* moths were shown to produce a sex pheromone that attracts males (Bako, 1977; ICRISAT, 1989) and this was isolated, identified and synthesized (Beevor et al., 1999). Synthetic lures were subsequently optimised and an effective, locally-made trap developed (Youm et al., 1993; Youm and Beevor, 1995). Some reduction in damage by *C. ignefusalis* was reported with mass trapping around village granaries with 25 traps/ha (ICRISAT, 1994; 1995), and initial results on use of the synthetic pheromone for control of *C. ignefusalis* by mating disruption were reported. Using a PVC resin formulation of the pheromone components, Beevor et al. (1996) showed that the attractive pheromone blend was more disruptive than two “inhibitor” compounds which only reduce the attractiveness of the attractive blend, and essentially complete communication disruption was achieved with release rates of 640 mg/ha/day. The main limiting factor was a lack of a suitable formulation, as the PVC resin had a half-life of only a few days under field conditions, frequent replacement was necessary.

This paper describes further work conducted on mating disruption of *C. ignefusalis* and the development of a longer-lasting formulation for application to stem borer management.

2. Methods and materials

2.1. Experimental sites

Experiments were carried out on-station at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center, Sadore, Niger and in nearby farmers' fields in the villages of Deybon and Bellare.

2.2. Pheromone traps

Pheromone traps used for the experiments consisted of locally-constructed water-oil traps with a lid and positioned 0.5 m above the ground as described by Youm and Beevor (1995). Numbers of male *C. ignefusalis* were recorded daily and discarded and trap lures were renewed every 21 days.

2.3. Pheromone dispensers

Pheromone dispensers used in field experiments were either sealed polyethylene vials (32 × 15 × 2 mm thick; Agrisense, UK) impregnated with 0.5 mg of the pheromone blend or sealed polyethylene vials (20 × 9 × 1.5 mm thick; Just Plastics, UK) containing 100 µl (80 mg) of the pheromone blend. The lids on the latter were sealed by heating or with Ethylene-vinyl acetate (EVA) hot-melt “glue-gun”. Lures loaded with 0.5 mg pheromone were designed for use in monitoring traps, and the 80 mg lures were developed for use in mating disruption. The pheromone blend contained (Z)-7-dodecenol, (Z)-5-decenol and (Z)-7-dodecenal in a 100:5:3 mixture. Compounds were prepared at the Natural Resources Institute (NRI) as described by Beevor et al. (1999).

2.4. Mating disruption experiment 1996

Experiments were conducted in 1996 at the ICRISAT Sadore station on 40 m × 40 m plots sown with pearl millet varieties Sadore-Local and ICMV-IS-89305 on June 6 with 1 m and 0.75 m spacing between and within rows, respectively. Plots were weeded twice, manually with hoes. The experiment comprised three treatments including pheromone, insecticide and untreated (check); replicated with each variety in four randomised blocks. The pheromone treatment consisted of standard monitoring lures (0.5 mg loading) attached to metal stakes at 0.5 m above ground

level with 5 m spacing (equivalent to 400/ha, 200 mg a.i./ha). The treatment began 21 days after sowing (DAS), and dispensers were renewed every 21 days. The insecticide plots were treated with the synthetic pyrethroid Decis® (Deltamethrin) at 21 DAS, flag leaf stage and at one third panicle exertion.

A pheromone trap with standard monitoring lure (0.5 mg loading) was placed at the centre of each plot, and numbers of male *C. ignefusalis* male moths counted and recorded daily from June 21 to September 26, then traps cleaned and moths discarded. At 40 DAS and 75 DAS, the percentage of infested hills and number of dead hearts were recorded from the 10 m × 10 m central portion of each plot. After harvest, the number of stem borer entry and exit holes and larvae were recorded from 10 randomly selected stems from each plot.

2.5. Mating disruption experiment 1997

The experiments in 1997 used a total of eight plots in farmers' fields at Sadore. Four of these of 0.5 ha area were treated with pheromone and four (0.25 ha) were untreated (check plots). Treated and untreated plots were separated by at least 500 m. All plots were planted with millet variety ICMV-IS-92222 with 1 m × 1 m spacing between hills. After emergence, hills were thinned to three plants, and two weeding operations were carried out.

In the treated plots, pheromone dispensers (80 mg loading) were placed on wire stakes at 0.5 m above ground level with 5 m spacing, to give an application rate of 400 sources/ha (32 g a.i./ha). The sources were not replaced during the season from 4 July–14 October.

A pheromone trap was placed at the centre of each plot, and numbers of male *C. ignefusalis* caught were counted each day and discarded. In the treated plots, traps were baited with the 80 mg dispensers used for mating disruption. In the untreated plots, standard monitoring lures loaded with 0.5 mg pheromone blend were used 4 July–4 August 1997, but these were then replaced by the 80 mg dispensers for the remainder of the experiment. All trap lures were renewed every 21 days.

At 40 and 75 DAS, the percentage of infested hills and number of dead hearts were recorded from the central portion of each plot (10 m × 10 m). After harvest, the number of exit holes and number of larvae were recorded from 50 stems randomly selected from the central portion of each plot (5 from each row).

2.6. Mating disruption experiment 1998

The 1998 experiments were carried out in farmers' fields at Sadore with five plots (0.5 ha) treated with pheromone and five (0.25 ha) untreated. Treated and untreated plots were separated by at least 500 m. In the treated plots, dispensers (80 mg loading) were placed on wire stakes at 0.5 m above ground level, with 5 m spacing to give an application rate of 400 sources/ha (32 g a.i./ha). The sources were not replaced during the season from 4 July–1 October 1998. A pheromone trap baited with the same 80 mg dispenser used for mating disruption and renewed every 21 days was placed at the centre of each plot, and numbers of male *C. ignefusalis* were counted each day and discarded. At 70 and 90 DAS, the numbers of hills, tillers, infested hills and dead hearts were recorded from the central portion of each plot (10 m × 10 m). At harvest, the number of exit holes and number of larvae were recorded from one stem randomly selected from each hill in the central portion of each plot.

2.7. Data analysis

The number of infested hills was expressed as a percentage of the number of hills and the number of dead hearts as a percentage

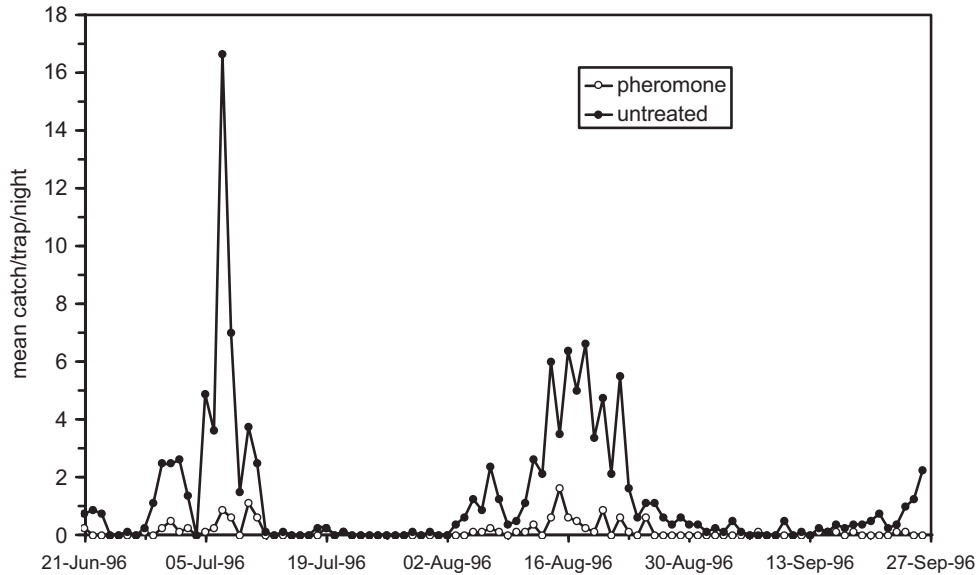


Fig. 1. Mean numbers/trap/night of male *C. ignefusalis* moths in traps during 1996 mating disruption experiment (four replicates on each of two varieties).

of the number of tillers and these data were then arcsine transformed. Counts of larvae and exit holes were square root transformed. Data were then subjected to analysis of variance and differences between means tested for significance ($*P < 0.05$) by the Least Significant Difference test (LSD) (SAS Institute).

2.8. Laboratory assessment of pheromone formulations

Release rates of the pheromone or an analogue, 1-dodecanol, from the polyethylene vials used for mating disruption (80 mg loading) were measured at the Natural Resources Institute (NRI). Release rates from polyethylene sachets (2.5 cm × 2.5 cm × 120 μ thick; International Pheromone Systems Ltd., Wirral, UK) containing 1-dodecanol (80 mg) were also tested. Duplicate samples of the formulation were maintained in a laboratory wind tunnel (27 °C, 8 km/h wind speed) and release measured as weight loss by weighing the dispensers at regular intervals.

2.9. Analysis of dispensers from field

During the mating disruption experiments in 1997, two dispensers were collected each week, wrapped in aluminium foil and returned to NRI at the end of the season. The pheromone remaining in the individual dispensers was extracted with hexane (5 ml) containing dodecyl acetate (12:Ac, 5 mg) overnight at room temperature. The resulting solution was analysed by gas chromatography (GC) using a fused silica capillary column (25 m × 0.32 mm i.d.) coated with CPWax 57CB (Carbowax equivalent; Chrompack, UK), temperature programmed from 60 °C for 2 min, then at 6 °C/

min to 230 °C. Amounts of pheromone components were calculated by comparison of peak areas with those of the 12:Ac internal standard.

2.10. Trapping experiments

Three experiments were carried out to compare numbers of male caught in water traps baited with standard 0.5 mg monitoring lures to those in similar traps baited with the 80 mg dispensers used for mating disruption. In all three experiments, lures were renewed every 21 days.

In the first experiment, two traps of each type were placed at opposite corners of a 35 m square on the ICRISAT station, and male moth numbers caught were monitored daily from 16 July - 30 October 1997 (106 nights). The second experiment was run over the same period, using three replicates of the two traps 30–35 m apart in three different farmers' fields. In the third experiment, two traps of each type were placed at opposite corners of a 100 m square on-station, and male moth numbers were monitored from 5 September - 30 October 1997 (56 nights).

3. Results

3.1. Mating disruption experiments

Results from the 1996 experiment, showed that the pheromone dispensers caused a significant reduction in the number of moths caught in the pheromone trap in the treated plots relative to those in the untreated plots (Fig. 1). The mean percentage reduction in catch

Table 1
Mean and standard error (SE) number of dead hearts and percentage infested hills at 40 and 75 DAS and mean number of larvae, entry and exit holes in 1996 mating disruption experiment.

Treatment	Dead heart count				% Infested hill				Mean number of Larvae, entry holes and exit holes					
	40 DAS		75 DAS		40 DAS		75 DAS		Larvae		Entry holes		Exit holes	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Pheromone	1.62	0.94	2.87	1.24	0.65	0.24	1.23	0.34	0.01	0.00	0.15	0.04	0.01	0.01
Insecticide	0.87	0.51	2.12	1.00	0.56	0.33	0.81	0.36	0.08	0.07	0.53	0.32	0.09	0.06
Untreated	1.25	0.67	2.25	0.83	0.49	0.23	1.07	0.35	0.03	0.01	0.16	0.06	0.03	0.01

over the season across the eight replicates (four blocks with two varieties) was 86.8% (SE = 2.6%) (untransformed data). However, damage assessments showed no consistent or significant differences ($*P < 0.05$) between dead heart counts, percent infestation, entry and exit holes or larval counts in pheromone, insecticide or untreated plots (Table 1). There were no significant differences between the performances of the two varieties (data not shown).

Results from the 1997 experiment indicated a high level of trap catch shut down in the treated plots relative to the untreated plots (Fig. 2, Table 2). Traps in the treated plots were baited with the 80 mg lures throughout, whereas those in the untreated plots were baited with 0.5 mg lures from 4 July - 4 August, 1997, with the 80 mg lures thereafter. As shown later, male moths caught with the 80 mg lures are much lower than with the 0.5 mg lures, so catches in treated and untreated plots during 4 July - 4 August cannot really be compared. However, during the subsequent period when traps in treated and untreated plots were baited with identical 80 mg lures, trap catches in the treated plots remained at zero when catches in the untreated plots increased significantly at the end of August, more than 8 weeks after the mating disruption dispensers were first deployed (Fig. 2, Table 2). Estimates of damage by *C. ignefusalis* showed lower numbers of dead hearts and infested hills in the plots treated with pheromone relative to those in the untreated plots, although these differences were not significant at the 5% level (Table 3). After harvest, counts of larvae and exit holes were significantly lower ($*P < 0.05$) in the pheromone-treated plots than in the untreated plots, although damage levels were low throughout (Table 3).

In the 1998 experiment, the number of moths caught/trap/night in the pheromone-treated plots (mean of five replicates 0.08 (SE = 0.03) moths/trap/night) were greatly reduced relative to those in the untreated plots (mean was 13.15 (SE = 4.33) moths/trap/night), giving a mean level of communication disruption of 99.4% (SE = 0.2%) (calculated on untransformed data) (Fig. 3). Damage caused by *C. ignefusalis* was high. Differences in numbers of dead hearts and infested hills between pheromone-treated and untreated plots were small and inconsistent (Table 4). However, after harvest, the numbers of larvae and exit holes in stems from the plots treated with pheromone were much greater than those in stems from the untreated plots (Table 4).

Table 2

Pheromone trap catch data for 1997 mating disruption experiment (across four replicates pheromone-treated and untreated for period indicated; % disruption untransformed).

Dates	No. Nights	Mean catch/trap/night and SE					
		Pheromone		Untreated		% Disruption and SE	
		Mean	SE	Mean	SE	Mean	SE
4 Jul–4 Aug	31	0.19	0.04	79.47	20.51	99.7	0.1
4 Aug–14 Oct	70	0.02	0.01	3.26	0.87	99.0	0.5
4 Jul–14 Oct	101	0.07	0.02	26.65	6.67	99.7	0.1

3.2. Dispenser evaluation

The release rates of 1-dodecanol and the *C. ignefusalis* pheromone blend from a polyethylene sachet or polyethylene vial were constant (zero-order) over the periods of measurement (32 d) in the laboratory wind tunnel at 27 °C and 8 km/h wind speed. Release rates were 2.58 mg/d for 1-dodecanol from the sachet and 0.13 mg/d and 0.11 mg/d for 1-dodecanol and the pheromone blend respectively from the vial, equivalent to 1032 mg/d/ha, 52 mg/d/ha and 44 mg/d/ha respectively for 400 dispensers/ha. Shade temperatures for Sadore (1996 data) were mean maximum of 35.1 °C, mean minimum 23.7 °C and overall average 29.4 °C.

Disruption dispensers returned from the field during the 1997 experiment still contained 70% of the initial loading of pheromone after 10 weeks in the field. Fig. 4 shows the proportions of the minor pheromone components, Z7-12:Ald and Z5-10:OH, relative to the major component, Z7-12:OH, remaining in the dispensers after ten weeks. The proportion of the relatively more volatile Z5-10:OH remained remarkably constant, although that of the Z7-12:Ald declined. This was probably due to both a higher release rate and degradation of the more labile aldehyde.

3.3. Trapping experiments

In all three trapping experiments, catches in traps baited with the 0.5 mg lures were much higher than those in traps baited with the 80 mg lures. Representative data for the on-farm experiment

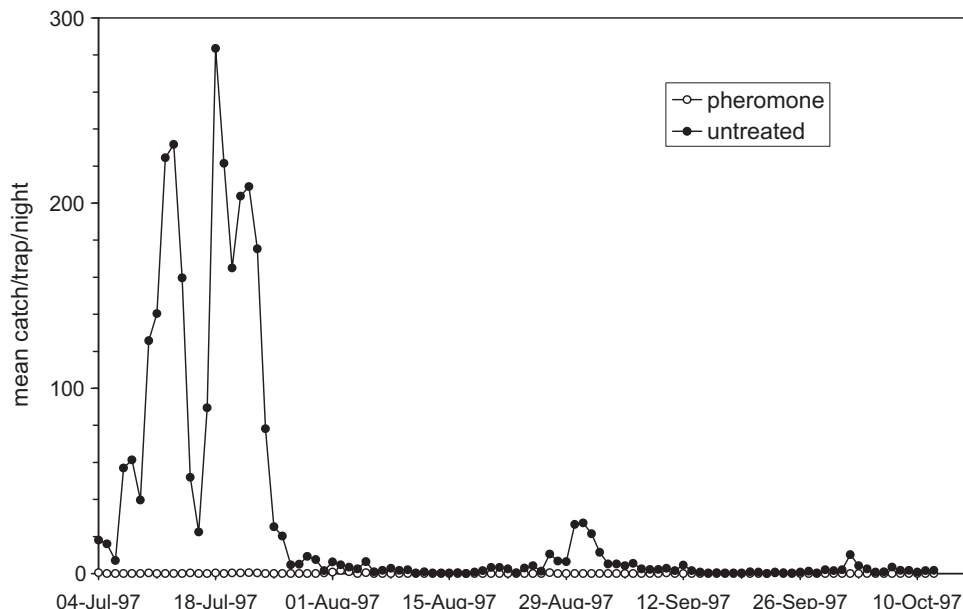


Fig. 2. Mean numbers/trap/night of male *C. ignefusalis* moths in treated and untreated areas during mating disruption 1997 experiment (mean of four replicates).

Table 3
Mean and standard error (SE) percent dead hearts and infested hills at 40 and 75 DAS and mean numbers of larvae and exit holes in 1997 mating disruption experiment (means followed by different letter in a column are significantly different at 5% level).

Treatment	% Dead hearts				% Infested hills				Larvae and Exit holes			
	40 DAS		75 DAS		40 DAS		75 DAS		Larvae		Exit holes	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Pheromone	0.45a	0.30	5.37a	4.51	1.35a	0.90	13.91a	0.91	2.28a	0.22	1.79a	0.15
Untreated	0.93a	0.32	7.08a	2.34	2.04a	0.84	18.81a	7.40	2.88b	0.02	2.30b	0.13

are shown in Fig. 5 and mean male moth catches across the replicates are summarised in Table 5. In all three experiments, differences between means were highly significant (** $P < 0.01$) by simple t tests on untransformed data.

4. Discussion

4.1. Pheromone dispensers

In previous work on mating disruption of *C. ignefusalis* (Beevor et al., 1996), a PVC resin formulation developed at NRI (Cork et al., 1989) and commercialised by Agrisense-BCS was used. This has been used successfully with the pheromones of several other pests, e.g. pink bollworm, *Pectinophora gossypiella* (Saunders) on cotton (Minks and Cardé, 1995) and yellow stem borer, *Scirpophaga incertulas* (Walker) on rice (Cork et al., 1998). However, the components of the pheromone of *C. ignefusalis* are significantly more volatile than those of these other pests, and the formulation was very short-lived, requiring replacement every seven days under field conditions in Niger. Nevertheless, as judged by the reduction of trap catches of male moths and suppression of mating of tethered virgin female moths in plots treated with pheromone, these dispensers gave high levels of mating disruption at a release rate of 640 mg/ha/day (Beevor et al., 1996).

A main objective of this work was to develop better dispensers that had a longer field life, preferably lasting for the whole millet-growing season of approximately three months, therefore more practical to prepare and apply in the field. Polyethylene sachets and

polyethylene vials loaded with 80–100 mg of pheromone were examined. These "reservoir" dispensers showed constant, zero-order release rates, in contrast to the "monolithic" PVC dispensers, which showed first-order release rates decreasing as the pheromone content decreased. Release from polyethylene sachets was too rapid. Considering temperature data from Niger, it was estimated that release of pheromone from the vials was the most applicable, approaching 400 mg/d/ha at an application rate of 400 dispensers/ha in full sun, and an 80 mg loading giving a field life of at least 3 months.

These vials are commercially available, and filling could easily be automated. Sealing the filled vials presented some problems: heat-sealing, or use of hot-melt EVA glue, was tedious and not always totally effective. Application in the field required fastening to sticks but was relatively straightforward.

4.2. Mating disruption experiments

In initial experiments of mating disruption in *C. ignefusalis* carried out at ICRISAT Sahelian Centre, Niger, in 1996, standard polyethylene vial dispensers containing 0.5 mg of pheromone for use in traps were used and replaced every 21 days. As measured by reduction of catches of male *C. ignefusalis* moths in pheromone traps in treated plots relative to those in untreated plots, significant communication disruption was observed in 0.16 ha plots with 400 dispensers/ha, equivalent to a remarkably low 200 mg pheromone/ha/application or 800 mg/ha/season.

Experiments in 1997 and 1998 used the mating disruption polyethylene vials containing 80 mg pheromone at 400 dispensers/

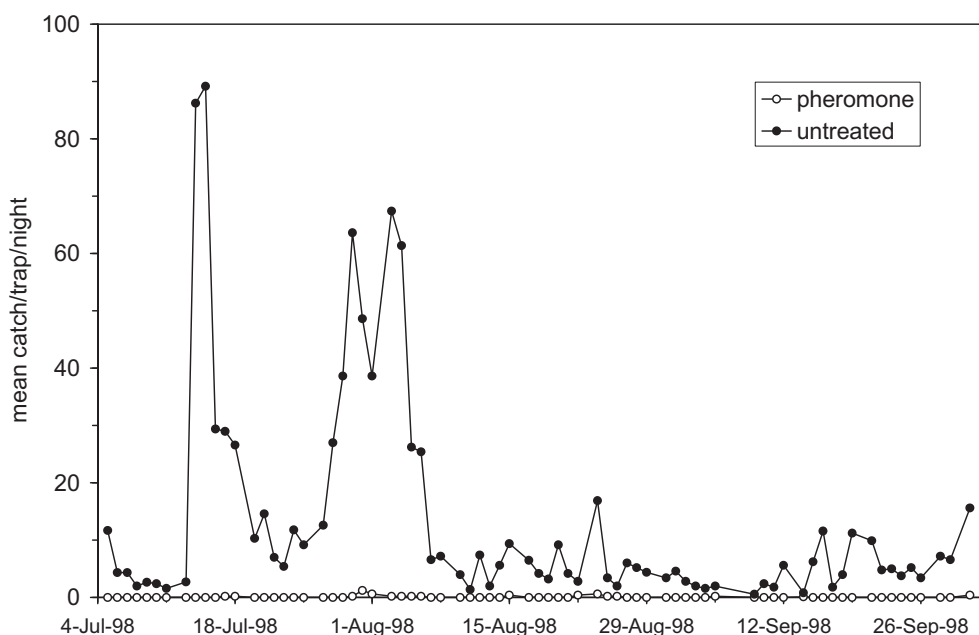


Fig. 3. Mean numbers of male *C. ignefusalis* moths caught in treated and untreated areas during 1998 mating disruption experiment (mean of five replicates).

Table 4

Mean and standard error (SE) percent dead hearts and infested hills at 70 and 90 DAS and mean number of larvae and exit holes in 1998 mating disruption experiment (means followed by different letter in a column are significantly different at 5% level).

Treatment	% Dead hearts				% Infested hills				Larvae and Exit holes			
	70 DAS		90 DAS		70 DAS		90 DAS		Larvae		Exit holes	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Pheromone	1.99a	0.76	4.74a	2.12	9.18a	3.72	34.25a	13.61	14.00a	9.24	31.20a	10.49
Untreated	3.11a	1.27	4.14a	0.92	10.87a	2.84	28.00a	6.92	3.60a	2.11	12.80b	3.72

ha with a single application per season, giving an application rate of 32 g pheromone/ha/season. In replicated 0.5 ha plots in farmers' fields, very high levels of trap catch suppression ($\geq 99\%$) were observed throughout the season. However, estimates of infestation, damage and yield loss due to *C. ignefusalis* during the season and after harvest in the central portions of the experimental areas, showed no significant differences between plots treated with pheromone and untreated plots.

Examination of dispensers returned from the field showed that only 30% of the initial loading of pheromone had been released, which correlated with the lower estimates from laboratory release rate data.

4.3. Lures for traps

During the 1997 mating disruption experiments, monitoring traps in the plots treated with pheromone were baited with the dispensers containing 80 mg of pheromone used for mating disruption. The traps in the untreated plots were initially baited with the standard 0.5 mg monitoring lures, but later these were replaced with the 80 mg lures. This was done because it has been reported by Minks and Cardé (1995) that monitoring traps equivalent to "super females" releasing large amounts of pheromone give a more discriminating and valid test of effectiveness in mating disruption experiments. However, subsequent comparisons of catches of male *C. ignefusalis* moths in traps baited with 0.5 mg or 80 mg lures in the absence of mating disruption treatments showed

that numbers with the 80 mg lures were only 10–20% of those with the 0.5 mg lures. The 80 mg lures were used again in the monitoring traps for the 1998 experiments, consistently in treated and non-treated plots throughout, so a valid comparison could be made.

Previous studies (Beevor et al., 1996) indicated that the release rate of pheromone from a fresh 0.5 mg lure was approximately 0.01 mg/day at 27 °C. Under the same conditions, release from the 80 mg dispenser was more than ten times greater at 0.13 mg/day.

Previous results reported by Beevor et al. (1996), showed that a mean rate of 640 mg/ha/day gave effective communication disruption.

Release through polyethylene devices is known to be affected exponentially by temperature doubling for each 6 °C rise in temperature (Torr et al., 1996), irrespective of type of device, and so it was taken for granted that the release of pheromone from the polyethylene sachets would be much more rapid than was required. Release from the vials on the other hand was probably on the slow side. However, allowing for the fact that the above temperatures are shade temperatures, overall release rates might well reach 1 mg/day/dispenser (400 mg/ha/day) which was approaching the target value. Furthermore, dispensers containing 80 mg pheromone would then be predicted to last for up to three months in the field, as required for *C. ignefusalis*. A lower estimate would be 0.3 mg/day/dispenser corresponding to only 30% released during the season.

Witzgall et al. (2008) considered "pheromone-mediated mating disruption" a viable pest management strategy and reported that a rate of 100 g of synthetic codlemone per ha controlled the codling

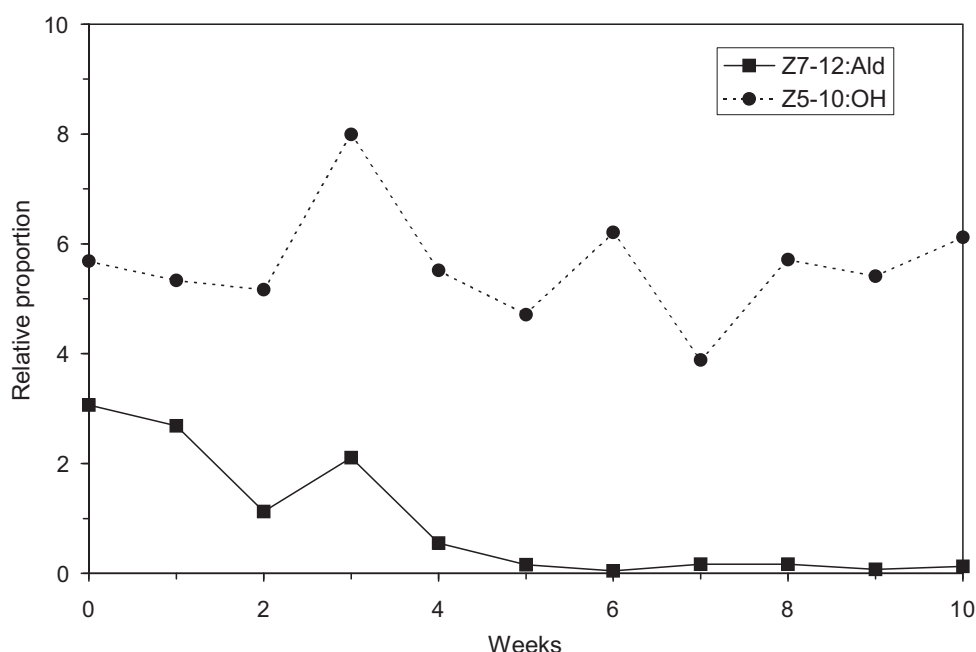


Fig. 4. Relative proportions (Z7-12:OH = 100) of Z5-10:OH and Z7-12:Ald remaining in dispensers used in 1997 mating disruption experiment.

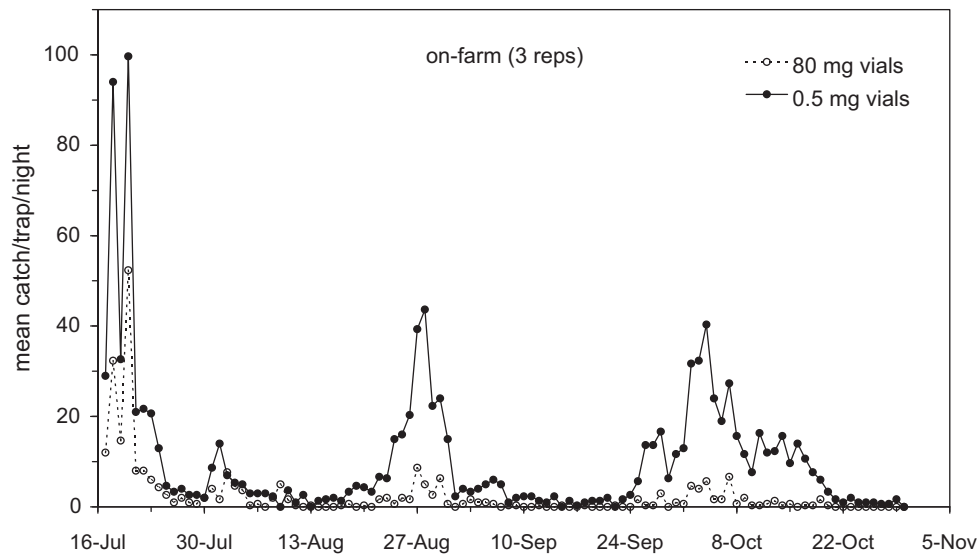


Fig. 5. Numbers of *C. ignefusalis* male moths caught in traps baited with polyethylene vials containing 0.5 mg or 80 mg pheromone in farmers' fields (traps 30–35 m apart; 3 replicates).

moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae) throughout the growing season. Witzgall et al. (2008) also described mechanisms of mating disruption in relation to codling moth which included sensory fatigue, competitive attraction (competition between natural and synthetic pheromone sources), and a less relevant mechanism which is camouflage. Exposure to higher concentrations of synthetic pheromone may desensitize "the olfactory apparatus" of male moths, thus "causing orientational disruption". Rodriguez-Saona et al. (2009) studied ways to optimize pheromone application for "effective mating disruption" of the oriental beetle, *Anomala orientalis* (Waterhouse) (Coleoptera:Scarabaeidae), in blueberries and reported that a rate ≥ 50 dispensers/ha at ≥ 0.1 g active ingredient (a.i.) per dispenser was most effective. They also reported the mechanism of mating disruption as "competitive attraction" because the beetle approached the dispensers throughout the day. In the case of the millet stem borer in our studies, male moth flight was observed during the night when the females are also active. Competitive attraction to pheromone dispensers "virtual females" in place of females and sensory fatigue due to exposure of males to high concentration of pheromone are both relevant mechanisms for the stem borer mating disruption. Stelinski et al. (2005) assessed the effectiveness of using of high densities of wax-drop pheromone dispensers in the oriental fruit moth, *Grapholita molesta* (Busck) mating disruption and reported competitive attraction between "pheromone sources and pheromone females". They also found that application rates of 100 drops per tree (27,300/ha) and 30 drops per tree (8200/ha) resulted in 99.2% and 99.4% "orientational disruption", respectively. Our studies with the millet stem borer (*C. ignefusalis*) using 80 mg

dispensers deployed at the rate of 400 dispensers/ha resulted in at least 99% suppression in trap catches in treated plots.

In conclusion, there is an improvement over previous work in which successful mating disruption of millet stem borer, *C. ignefusalis*, was demonstrated but pheromone dispensers were too short-lived for practical exploitation. Through this study, suitable dispensers have been developed. Sealed polyethylene vials loaded with 80 mg of pheromone were shown to maintain $\geq 99\%$ communication disruption for up to three months in farmers' fields in Niger when applied at 400 dispensers/ha. Approximately 30% of the pheromone was released (110 mg/ha/day), and so the loading of pheromone in the dispensers could safely be reduced to 40 mg/dispenser, so that 400 dispensers/ha would be equivalent to an application rate of 16 g/ha/season.

In the replicated 0.5 ha plots used in these experiments, effective communication disruption did not translate into reduced infestation, damage or yield loss due to *C. ignefusalis*. This may have been because actual reduction in mating was less effective than the reduction in pheromone trap catch would indicate, or because immigration of mated female moths into the treated plots negated any reduction of mating of females within the treated plots. The latter is considered to be more likely (Minks and Cardé, 1995); suggesting the assessment of mating disruption in larger plots to measure its effectiveness in the control of *C. ignefusalis*.

Acknowledgements

The authors thank Idi Saley, Salha Halarou and Amadou Kanguye for their technical support and the farmers in villages of Deybon and Bellare for allowing the use of their fields to carry out experiments. Support from DFID (Department for International Development at UK) for providing funds to undertake this study and to ICRISAT.

References

- Ajayi, O., 1990. Possibilities for integrated control of the millet stem borer, *Coniesta ignefusalis*, Hampson (Lepidoptera: Pyralidae) in Nigeria. *Insect Science and Its Application* 11, 109–117.
- Bako, O., 1977. Etude biologique de *Haimbachia ignefusalis* (Hamps.) (Lepidoptera: Pyralidae, Crambinae) en vue d'une lutte biologique. Thèse de Maitrise. Université Laval, Quebec, Canada.

Table 5
Mean and standard error (SE) number of *C. ignefusalis* male moths caught in traps baited with 0.5 mg or 80 mg lures.

Location	Spacing (m)	No. nights	No. Reps	Mean catch/trap/night and SE			
				0.5 mg lure		80 mg lure	
				Mean	SE	Mean	SE
On-station	30–35	106	2	3.74	0.04	0.56	0.03
On-farm	30–35	106	3	10.25	1.86	2.42	0.19
On-station	100	56	2	12.99	0.35	0.71	0.17

- Beevor, P.S., Cork, A., Farman, D.I., Hall, D.R., McVeigh, L.J., Robinson, R.D., Smith, J.L., 1996. Monitoring and control of insect pests of millet. Final Technical Report on CPP Project R5281.
- Beevor, P.S., Youm, O., Hall, D.R., Cork, A., 1999. Identification and field evaluation of components of the female sex pheromone of the millet stem borer, *Coniesta ignefusalis* Hampson (Lepidoptera: Pyralidae). *Journal of Chemical Ecology* 25, 2643–2664.
- Cork, A., Hall, D.R., Mullings, J.L., Jones, O.T., 1989. A New PVC Resin Formulation for Controlled Release of Insect Pheromones. Proceedings of 16th International Symposium on Controlled Release of Bioactive Materials, Chicago. Controlled Release Society, Inc., Lincolnshire, Illinois, pp. 9–10.
- Cork, A., De Souza, K., Krishnaiah, K., Ashok Reddy, A., Zainullabuddin, S., 1998. Season-long control of yellow stem borer, *Scirpophaga incertulas* (Lepidoptera: Pyralidae) by mating disruption with the natural ratio of pheromone components. *Bulletin of Entomological Research* 88, 109–116.
- Guevremont, H., 1983. Recherches sur l'entomofaune du mil. Rapport Annuel de Recherches, 1982. Centre National de Recherches Agronomiques (CNRA), Tarna (Maradi), Niger, 69 pp.
- Harris, K.M., 1962. Lepidopterous stem borers of cereals in Nigeria. *Bulletin of Entomological Research* 53, 139–171.
- Sahelien Centre ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), 1989. ICRISAT West African Programmes Annual Report, 1988. BP 12404. ICRISAT Sahelien Center, Niamey, Niger.
- ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), Sahelien Centre, 1994. ICRISAT West African Programmes Annual Report, 1988. BP 12404. ICRISAT Sahelien Center, Niamey, Niger.
- ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), Sahelien Centre, 1995. ICRISAT West African Programmes Annual Report, 1988. BP 12404. ICRISAT Sahelien Center, Niamey, Niger.
- Maiga, S.D., 1984. Premier séminaire régional de formation. Project amélioration des mil, sorgho, niébé et maïs, Maradi/Tarna, Niger. 45 pp.
- Minks, A.K., Cardé, R.T., 1995. Control of moth pests by mating disruption. *Annual Reviews of Entomology* 40, 559–585.
- N'doye, M., 1977. Synthèses de quelques résultats sur les insectes foreurs des mils et sorgho au Sénégal. CNRA, Bambey, Sénégal, 15 pp.
- N'doye, M., Gahukar, R.T., 1987. Insect pests of pearl millet in West Africa and their control. In: Proceedings of the International Pearl Millet Workshop, 7–11 April 1986. ICRISAT Center, Patancheru, India AP, pp. 195–205.
- N'doye, M., Gahukar, R.T., Carson, A.G., Selvaraj C., M'baye, D.F., Diallo, S., 1984. Situation of plant protection problems of millet crop in the Sahel, pp 18, in Proceedings of International Seminar: CILSS Pest Management Project, Niamey 6–13 Dec.
- Nwanze, K.F., 1985. Some aspects of pest management and host plant resistance in pearl millet in the Sahel. *Insect Science and Its Application* 6, 461–465.
- Nwanze, K.F., Muller, R.A.E., 1989. Management options for sorghum stemborers for farmers in the semi-arid tropics. In: International Workshop on Sorghum Stem Borers, 17–20 November 1987. ICRISAT Centre, Patancheru 502324, India, pp. 105–116.
- Rodriguez-Saona, C.R., Polk, D.F., Barry, J.D., 2009. Optimization of pheromone deployment for effective mating disruption of oriental beetle (Coleoptera: Scarabaeidae) in commercial blueberries. *Journal of Economic Entomology* 102, 659–669.
- Stelinski, L.L., Gut, L.J., Mallinger, R.E., Epstein, D., Reed, T.P., Miller, J.R., 2005. Small plot trials documenting effective mating disruption of oriental fruit moth by using high densities of wax-drop pheromone dispensers. *Journal of Economic Entomology* 98, 1267–1274.
- Torr, S.J., Mangwiro, T.N.C., Hall, D.R., 1996. Responses of tsetse flies (Diptera: Glossinidae) to synthetic repellents in the field. *Bulletin of Entomological Research* 86, 609–616.
- Vercambre, B., 1978. *Raghuva* spp. et *Masalia* sp. (Lepidoptera: Noctuidae), chenilles des chandelles du mil en zone sahelienne. *Agronomie Tropicale* 33, 62–79.
- Witzgall, P., Stelinski, L., Gut, L., Thomson, D., 2008. Codling moth management and chemical ecology. *Annual Reviews of Entomology* 53, 503–522.
- Youm, O., 1990. Evaluation of natural enemies associated with the millet stalk borer, *Haimbachia ignefusalis* (Hampson) (Lepidoptera: Pyralidae) in Niger. PhD Dissertation, Texas A&M University, College Station, Texas, USA.
- Youm, O., Beevor, P.S., 1995. Evaluation of pheromone-baited traps for *Coniesta ignefusalis* (Lepidoptera: Pyralidae) in Niger. *Journal of Economic Entomology* 88 (1), 65–69.
- Youm, O., Gilstrap, F.E., 1993. Population dynamics and parasitism of *Coniesta (=Haimbachia) ignefusalis*, *Sesamia calamistis* and *Heliocheilus albipunctella* in millet monoculture. *Insect Science and Its Application* 14, 419–426.
- Youm, O., Gilstrap, F.E., 1994. Habitat site selection, crop damage, and oviposition preference by *Coniesta (=Haimbachia) ignefusalis* (Lepidoptera: Pyralidae). *International Journal of Pest Management* 40, 231–236.
- Youm, O., Beevor, P.S., Hall, D.R., 1993. Trap design studies with the pheromone of *Coniesta ignefusalis* (Hampson) (Lepidoptera: Pyralidae) in sub-Saharan Africa. In: Proceedings IOBC/WPRS Working Group "Use of Pheromones and Other Semiochemicals in Integrated Control, vol. 16 (10), pp. 58–63. Chatham, UK, 11–14 May 1993.
- Youm, O., Harris, K.M., Nwanze, K.F., 1996. *Coniesta ignefusalis* (Hampson), the Millet Stem Borer: A Handbook of Information. Information Bulletin No 46. ICRISAT, Patancheru 50234, Andhra Pradesh, India, 60 pp.