Agricultural and Forest Entomology

Agricultural and Forest Entomology (2010), DOI: 10.1111/j.1461-9563.2009.00468.x

Effect of fallows on population dynamics of *Cosmopolites sordidus*: toward integrated management of banana fields with pheromone mass trapping

Béatrice Rhino∗, Marc Dorel∗, Philippe Tixier† and Jean-Michel Risède∗

*CIRAD, UPR 103 Hortsys, PRAM - BP 214 - 97285 Lamentin Cedex 2 - Martinique, French West Indies, *CIRAD, UPR 26, Neufchateau, 97130 Capesterre Belle-Eau - Guadeloupe, French West Indies, and †CIRAD, UPR 26, PRAM - BP 214 - 97285 Lamentin Cedex 2 - Martinique, French West Indies, France*

Abstract

1 The banana weevil *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae) is the most serious pest of banana and plantain in most production areas, including the West Indies.

2 During a period of 2 years, we assessed the efficacy of a pheromone mass-trapping control strategy of *C. sordidus* in field conditions in Guadeloupe at different cropping stages, both in sanitation fallows and in different ratoon banana crops.

3 In the fallows, catches peaked 3 months after beginning trapping and then decreased to zero after 9 months. By contrast, for the new plantations, the catches of *C. sordidus* increased after the 11th month and, in the older banana fields, there was no decrease in *C. sordidus* catches. The *C. sordidus* catches increased in the neighbouring banana plots, whereas they decreased in the fallows, and these catches decreased with the distance from fallow.

4 In conclusion, mass trapping with synergized pheromone traps within fallows should allow better sanitation of banana plantations. Yet, within the farms, fallows must not be located next to new plantations to avoid massive damage to the young plants. More generally, the present study emphasizes that the control of this insect should be managed at the farm scale and not at the field scale, with special attention being paid to the location of fallows.

Keywords Black weevil, Curculionidae, IPM, *Musa*, sanitation fallow, West Indies.

Introduction

The banana weevil *Cosmopolites sordidus* Germar (Coleoptera: Curculionidae) is the most serious insect pest of banana and plantain (*Musa* sp.) in most production areas, including the West Indies (Castrillón Arias, 2004). *Cosmopolites sordidus* adults have a maximal life span that varies between 1 (Froggatt, 1925) and 4 years (Rukazambuga *et al*., 1998). The average lifespan in field conditions is often reduced by predation (Abera-Kalibata *et al*., 2008). Females lay an average of three eggs per week in the rhizome (Koppenhöfer, 1993). Larvae bore galleries in the rhizome to feed, reducing nutrient uptake and weakening the stability of the plant (Gold *et al*., 2001). *Cosmopolites sordidus* adults usually disperse by crawling on the soil at night (Gold *et al*., 2001). They are usually patchily distributed in the field (Treverrow *et al*., 1992) and they are able to move a distance of 35 m in 3 days and 60 m in 5 months (Gold *et al*., 2001). They are often found at the base of the banana plant or in crop residues. After harvest, they survive in the residual corm in the field (Padmanaban & Kansasamy, 2003) or in pieces of pseudostem (Gold *et al*., 1999). Traditionally, pseudostem pieces are put on the soil to trap and control populations of *C. sordidus* adults (Gold *et al*., 2001). However, this method is moderately efficient because it depends on the variability of the age and the location of the trap (Mestre & Rhino, 1997). Moreover, this method allows only a small proportion of *C. sordidus* populations to be caught (Gold *et al*., 2001).

In 1993, Budenberg *et al*. (1993b) identified the aggregation pheromone emitted by *C. sordidus* males, and Beauhaire *et al*. (1995) further developed the equivalent synthetic pheromone called 'Sordidine'. Subsequent to 1999, traps with Sordidine,

Correspondence: Béatrice Rhino. Tel: +596 (0) 596 42 30 74; fax: +596 (0) 596 42 30 01; e-mail: beatrice.rhino@cirad.fr

formulated by ChemTica International (Costa Rica), have been tested under field conditions in Costa Rica (Alpizar *et al*., 1999), Uganda (Tinzaara *et al*., 1999) and South Africa (De Graaf *et al*., 2005). The pheromone traps are more effective than pseudostem traps. In Costa Rica, pheromone mass trapping allowed the successful control of *C. sordidus*; damage to banana and plantain was reduced by 70% after 5 months of trapping. In Uganda, an 18-fold greater number of *C. sordidus* were caught in pheromone pitfalls than in pseudostem traps. In South Africa, the pheromone trap catches caught a higher proportion of females than the pseudostem trap catches. Studies on other weevil species have reported the efficiency of similar pheromone traps and the impact of mass trapping on weevil population densities in different crops: sweet potato (Smit *et al*., 2001), American palm (Oehlschlager *et al*., 1995) and sugar cane (Oehlschlager *et al*., 2002).

In the French West Indies, the burrowing nematode *Radopholus similis* is the other major pest of banana. There is an increasing use of fallows and clean planting material to control this plant-parasitic nematode (Chabrier & Quénéhervé, 2003). This banana-fallow system includes 1 year of fallow after the banana plants are killed by the injection of herbicides. To our knowledge, no study has evaluated the effect of these fallows on *C. sordidus* and on its spatial epidemiology.

Several factors, mostly climatic, may affect the efficiency of pheromone and other traps. Honek (1988) showed a positive correlation between catches of Carabidae and temperature. Sappington and Spurgeon (2000) showed that wind speed affects pheromone trap catches of boll weevil *Anthonomus grandis*, a flying insect. By contrast, Tinzaara *et al*. (2005b) showed that only relative humidity had an effect on the pheromone trap catches of *C. sordidus*, which moves mostly by crawling. The other key points for effective control of insects by mass trapping are the number of traps and their spatial distribution. Inter-trap spacing influences the catches of pheromone traps (Wedding *et al*., 1995, Blackshaw & Vernon, 2008). Pheromone trap catches of moths are greater in the periphery of plots than in the centre of plots (Athanassiou *et al*., 2004). In addition to climatic factors, vegetation structure affects pheromone trap effectiveness; Spurgeon and Raulston (2006) showed that more boll weevils are caught in prominent erect vegetation than in sparse vegetation.

The present study describes the use of pheromone mass trapping of *C. sordidus* with pitfall traps containing Sordidine (Cosmotrack®, N.P.P Calliope, France) in field conditions in Guadeloupe (French West Indies). We hypothesized that the dispersion of *C. sordidus* is related to the agronomic stage of fields, especially for fallows where the lack of resource may promote dispersion to neighbouring fields. To test this hypothesis, we evaluated: (i) the temporal dynamics of *C. sordidus* in pheromone traps in banana plots at different agronomic stages, including fallow and banana fields of different ages and (ii) the effect of fallows on *C. sordidus* catches in neighbouring banana plots. To identify the optimum conditions for mass trapping, we evaluated the effect of climatic factors on catches.

Materials and methods

The present study was conducted in Neufchâteau, Guadeloupe (16°15′N, 61°32′W) at the experimental banana farm of CIRAD over 2 years, from October 2004 to October 2006. This farm is 250 m above sea level. The area has a tropical humid climate with a mean annual rainfall of 3850 mm and a rainy period from June to October with a mean daily temperature in the range 21–25°C. This experimental farm cultivates *Musa* spp. (AAA, cv. Grande naine, Cavendish subgroup) bananas. To preserve soil fertility, every year, 20% of plots are replanted after a 1-year fallow without any banana. Banana is a semi-perennial herb that produces succeeding generations of ratoon crops: the ratoon is the sucker succeeding the harvested plant. In the present study, the new plantation is the first crop after planting; and the first and second ratoon crops are the cropping periods after the harvest of the first crop and after the harvest of the first ratoon crop, respectively.

We used 130 pheromone traps placed 25 m apart, over the 10 ha of the farm, including tracks (Fig. 1). The density of the traps varied from nine to 16 traps/ha depending on plot design. This regular pattern corresponds to that used in mass trapping. We assumed that the variation in density of traps did not affect the catches because the distance between traps remained constant. Tinzaara *et al*. (2005a, b) showed that there were no

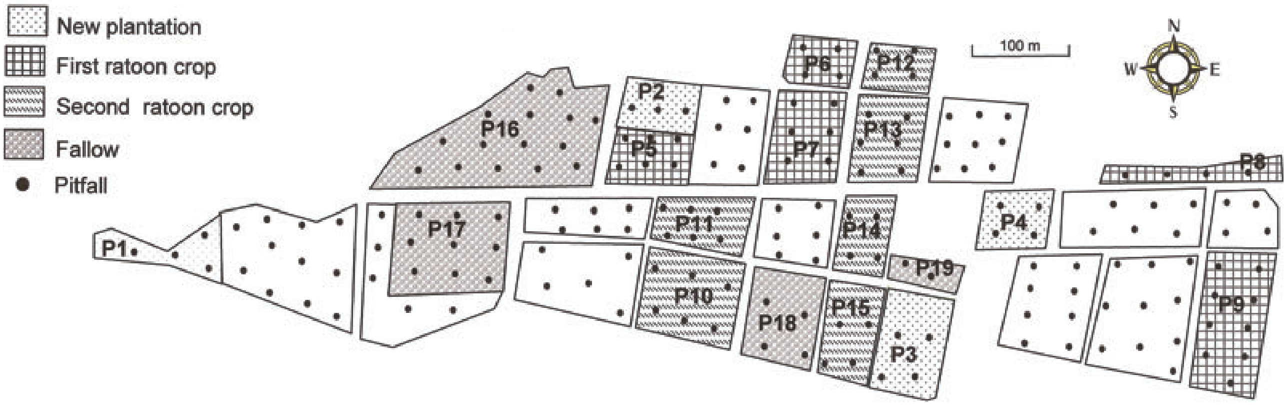

Figure 1 The spatial distribution of pheromone pitfall traps within the banana plots and fallows.

significant differences in numbers of adult *C. sordidus* caught per hectare when the density of pheromone traps doubled, but *C. sordidus* catches in pheromone traps were influenced by the distance from the trap. We used Cosmotrack® (Calliope) pitfall traps made of cylindrical containers with a pheromone diffuser suspended in their upper part; their lower part is buried. The diffuser was made of a polyethylene terephthalate bottle with a wick containing 45 mg of sordidine synergized at a release rate of 0.5 mg per day. The pheromone was changed monthly. Soapy water was used in the bottom of the pitfalls to kill banana weevils. Every 2 weeks, *C. sordidus* adults were removed from the traps and counted.

Temporal dynamics of *C. sordidus* catches in pheromone traps at different agronomic stages

We investigated only 19 banana plots because the other plots were included in other experimental trials (Fig. 1). In these plots, we observed populations of *C. sordidus* caught in pheromone traps at four stages of the banana/fallow cropping system: four plots of new plantations (S1; P1–P4); five plots of first ratoon crop (S2; P5–P9); six plots of second ratoon crop (S3; P10–P15); and four plots of fallows (S4; P16–P19). Fallows are prepared by destroying bananas plants by injection of herbicides (glyphosate), and then a spading machine is used to plow the field (Chabrier & Quénéhervé, 2003). In the fallows, mass trapping lasted 78 weeks after soil tillage (i.e. 2 months after the chemical destruction and 18 weeks after the beginning of mass trapping in the other plots).

Because the area of plots varied, to compare the banana weevil adults collected in different agronomic stages, we calculated *C. sordidus* density, for each plot, per hectare per 2 weeks, over 78 weeks of mass trapping. This density is the ratio between the total of number *C. sordidus* caught in the plot and the area of the plot. Cumulative densities were further analysed by general linear models, after log transformation ($\log x$), and the means were compared by Tukey's test.

Effect of fallows on *C. sordidus* catches in neighbouring banana plots

We observed 19 traps in four banana plots neighbouring two fallows. The distance of the traps from the nearest boundary of fallow fields was in the range 12–67 m. We performed regression analysis between the distance from the fallows and trap catches. For each plot, we compared the dynamics of trap catches. P2 was a new banana plantation (S1) and P5 was a first ratoon banana crop (S2); they were adjacent and near the same fallow (P16). P10 and P15 were second ratoon banana crops (S3) and they were near the same fallow (P18) but at opposite sides.

Effect of climatic factors on *C. sordidus* catches

Wind speed, temperature, rainfall and relative humidity were recorded daily using an automated weather instrument on the experimental farm (Campbell Scientific™, U.K.). We calculated average temperature, wind speed, humidity and rainfall for 2-week periods, corresponding trapping periods. For the 15 banana fields, we analysed the effect of these climatic factors on *C. sordidus* densities, after log transformation ($\log x$), by analysis of covariance with abiotic factors as covariates and the dates of removal of *C. sordidus* as replicates.

Results

Temporal dynamics of *C. sordidus* catches in pheromone traps at different agronomic stages

Table 1 shows the cumulative density of *C. sordidus* for different agronomic stages over 78 weeks. In the new banana plantations, the cumulative density was significantly lower than in other plots ($F_{3,19} = 7{,}48$, $P < 0.01$) with 7784, 23 679, 16 314, and 36 109 *C. sordidus* caught per hectare in 2 weeks in S1, S2, S3 and S4, respectively. The cumulative density of catches in fallow was similar to those of first and second ratoon banana crops.

Cosmopolites sordidus catches differed between agronomic stages. In the fallow (Fig. 2a), at week 12, the catch reached a peak density of 8237 per hectare over 2 weeks. Thereafter, the catch declined and, after week 34, the mean density was less than 100. In the new plantation (Fig. 2b), the mean catch was less than 200 until week 44, and then increased to 400. In the first ratoon banana crop (Fig. 2c), at week 6, the catch reached a peak density of 1742, and then declined to less than 1000 after week 14. In the second ratoon banana crop (Fig. 2d), the catch was consistently lower than 1000.

Effect of fallow location on *C. sordidus* catches of neighbouring banana plots

Figure 3 shows that, over the 78 weeks of the study, *C. sordidus* catches decreased with distance from fallow. The linear

Table 1 Mean ± SD cumulative number of *Cosmopolites sordidus* caught in pheromone traps per hectare, in the sanitation fallows and the different stages of banana field over 78 weeks

	Number of weeks after beginning of mass trapping			
Agronomic stage	2	12	34	78
Sanitation fallow (S4)	4443 ± 1334^{a}	22 626 ± 8 370^{a}	34 780 ± 14 296^{a}	36 109 ± 14 873^{a}
New plantation (S1)	190 ± 73^{c}	536 ± 122^{b}	1634 ± 157^{b}	7784 ± 634^{b}
First ratoon crop (S2)	2318 ± 1076^{a,b}	9908 ± 4786^{a}	13 610 ± 6835^{a}	23 679 ± 8260^{a}
Second ratoon crop (S3)	465 ± 108^{b}	3033 ± 513^{a}	6497 ± 899^{a}	16 314 ± 1908^{a}

For each date, means followed by the same superscript letter are not significantly different (analysis of variance + Tukey's test; log transformed data).

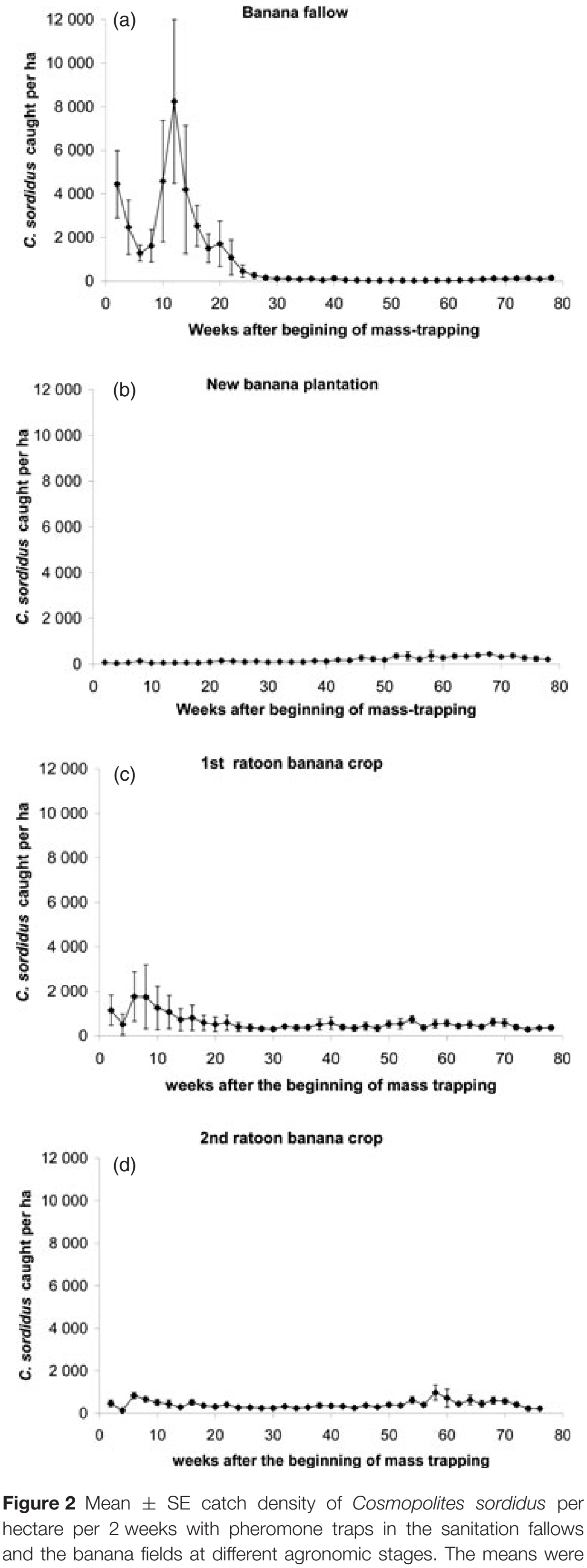

Figure 2 Mean ± SE catch density of *Cosmopolites sordidus* per hectare per 2 weeks with pheromone traps in the sanitation fallows and the banana fields at different agronomic stages. The means were calculated with four new plantations [S1 (b); P1–4], five first ratoon crops [S2 (c); P5–9], six second ratoon crops [S3 (d); P10–P15], and four sanitation fallows [S4 (a); P16–P19].

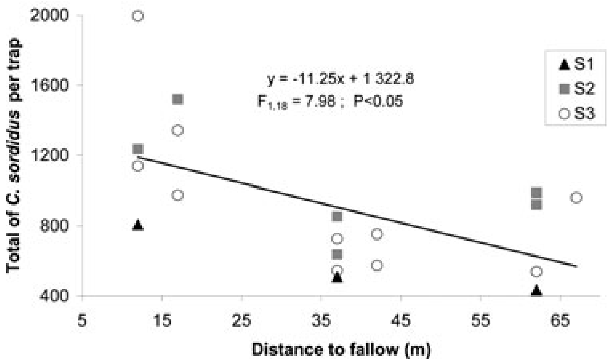

Figure 3 Total *Cosmopolites sordidus* caught per trap per 2 weeks, over 78 weeks of mass trapping, in relation to the distance of the trap from the fallow.

equation was: catches $= -11.25 \times$ distance $+ 1322.8$) ($F_{1,18} = 7.98$, $P < 0.05$). The *C. sordidus* catch increased in the neighbouring banana plots, whereas it decreased in the fallows; increases were greater for the traps 12 and 17 m from the fallow than those farther. In all plots (Fig. 4a–d), a first peak of captures was observed in fallows 8–20 weeks after the beginning of mass trapping; subsequently, in neighbouring banana plots, a second peak of captures appeared within 30–50 weeks after the beginning of mass trapping.

Effect of climatic factors on *C. sordidus* catches

Temperature had a significant effect on the catches in the banana fields; this impact was related to the agronomic stage of the plot ($F_{8,662} = 2.36$, $P < 0.05$). In the first and second ratoon banana crops, when temperatures were higher than 23°C, the catches decreased (Fig. 5a). Wind speed had a significant effect on the catches in the banana fields; this impact was related to the agronomic stage of the plot ($F_{8,662} = 2.15$, $P < 0.05$). In the new plantations, the catches decreased when the wind speed increased. By contrast, in the first and second ratoon banana crops, the catches increased with wind speed but they decreased when the wind speed was greater than 5 km/h (Fig. 5b). Relative humidity had a significant effect on the catches in the banana fields whatever the agronomic stage of the plot ($F_{3,662} = 7.44$, $P < 0.001$). The catches decreased as relative humidity increased (Fig. 5c). Rainfall had no effect on catches in the banana fields ($F_{5,662} = 1.85$, not significant).

The results obtained show that the number of *C. sordidus* caught varied according to the agronomic stage of banana field, and fields were always ranked in the same order: S1, S3 and S2, respectively, from the lowest to the greatest catches.

Discussion

The results obtained in the present study show that, in the fallow, although the *C. sordidus* catches were as large as in the old banana field, populations decreased 4 months after the beginning of mass trapping and remained at almost zero until 9 months after the beginning of mass trapping. We propose that, in fallows, mass trapping with pheromone traps catch a

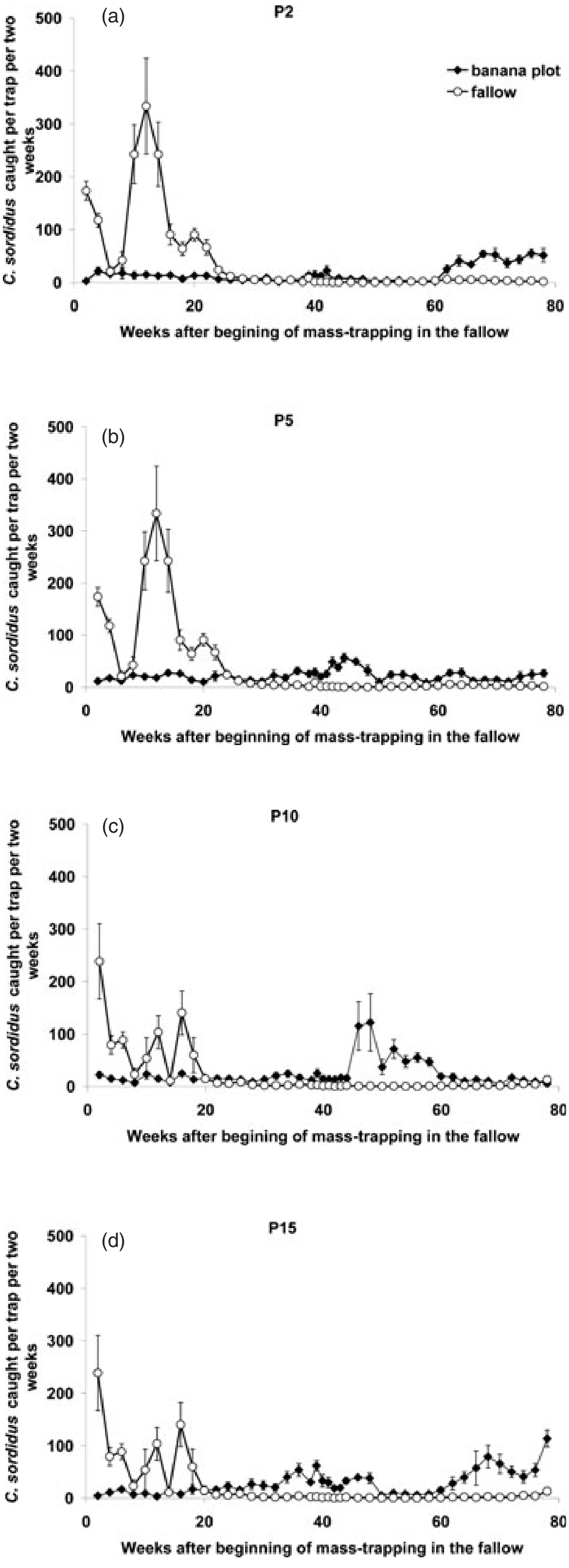

Figure 4 Mean ± SE *Cosmopolites sordidus* caught per trap and per 2 weeks in the four neighbouring fallows. P2 (a) was in a new banana plantation (S1), P5 (b) was in first crop cycle (S2), and P10 (c) and P15 (d) were in second crop cycle (S3).

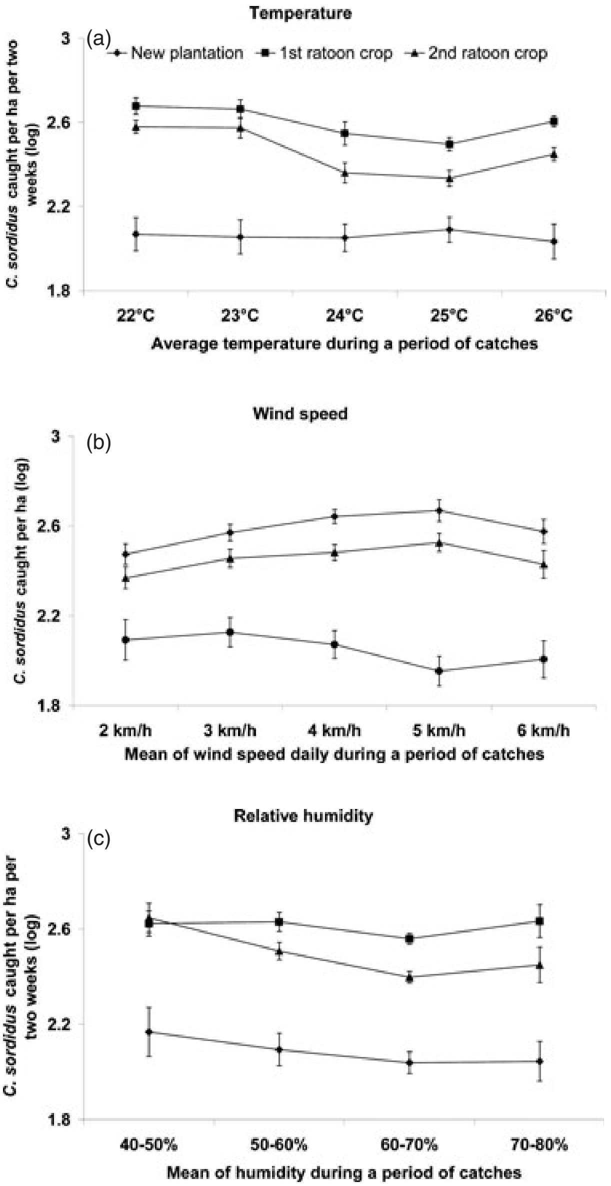

Figure 5 Effect of (a) temperature, (b) wind speed and (c) relative humidity on pheromone trap catches in relation to the agronomic stages of banana fields. The mean ± SE numbers of *Cosmopolites sordidus* caught per hectare per 2 weeks were calculated on four new plantations (S1; P1–4), five first ratoon crops (S2; P5–9), and six second ratoon crops (S3; P10–P15).

large part of the population of *C. sordidus* during the first year after the beginning of the fallow. Mestre and Rhino (1997) showed that *C. sordidus* populations decreased in the fallow after 9 months. In their study, pseudostem traps were used, the density was more than 200 traps/ha, and the greatest rate of capture was lower than 35 *C. sordidus* per trap. In the present study, in the fallow, the number of pheromone traps was lower and the rate of capture was larger. The density of traps varied in the range 9–16 traps/ha, and the greatest capture rate was more than 300 *C. sordidus* per trap.

In the fallows, the capture peak was 3 months after the beginning of mass trapping (i.e. 5 months after the destruction of the banana plants with glyphosate). Decomposing banana plants could be more attractive than pheromone traps: previous research has shown that decaying banana material emits volatile substances that are attractive for *C. sordidus* (Budenberg *et al*., 1993a; Braimah & Van Emden, 1999). Accordingly, *C. sordidus* would move when banana plants are completely decayed and dried, and the traps would be less effective in the banana plots. Nevertheless, there is little evidence that the sanitation effect of fallows results from the elimination of the entire *C. sordidus* population by pheromone traps within fallows. The results obtained in the present study show that the *C. sordidus* catches increased in the neighbouring banana plots, whereas they decreased in the fallows, and these catches decreased with distance from fallow. *Cosmopolites sordidus* probably move from fallows to banana plots because of a lack of resources within a fallow. They are able to move a distance of 35 m in 3 days and 60 m in 5 months (Gold *et al*., 2001). For ground beetles, which disperse by crawling, Duelli *et al*. (1990) showed that they move between natural and cultivated areas. Furthermore, trap location may affect catches, and *C. sordidus* may be caught by the first trap they encounter. Winder *et al*. (2001) showed that barrier pitfall traps can increase the catches of carabid and staphylinid beetles.

The results obtained in the present study show that pheromone trapping did not prevent the infestation of young banana plots because the catches of *C. sordidus* increased 11 months after the beginning of mass trapping. In the first and second ratoon banana crops, the catches were never less than 300 *C. sordidus* per hectare, despite pheromone mass trapping. In a previous study, Tinzaara *et al*. (2005a) caught only 13% of released weevils at a distance of 4 m from the pheromone traps. In future studies, we aim to use mark and recapture techniques to estimate the adult population size attracted. Although we did not use such a technique in the present study, we suggest that one limit of the pheromone mass-trapping method is the low percentage of capture of *C. sordidus.* In the present study, there was little evidence that pheromone mass trapping controlled damage by *C. sordidus* in banana fields. Several studies have reported a poor relationship between *C. sordidus* trap captures and corm damage (Gold *et al*., 2001). Speijer *et al*. (1993) only found a correlation between numbers of male weevils caught with pseudostem trap in a plot and the mean percent of infestation measured in the plot. De Graaf *et al*. (2005) found that less than 20% of the total of pheromone traps catch comprised females with eggs, yet only this category can damage the rhizome.

In the French West Indies, crop residues are not removed from banana fields and increase over time. These residues are mainly harvested residues such as leaves and pseudostem cut at harvest. These residues may alter the living conditions of *C. sordidus*, affecting their dispersion and reproduction. Although Gold *et al*. (1999) showed that activity and trivial movement of *C. sordidus* were greater in mulched rather than unmulched plots and Tinzaara *et al*. (2008) showed that mulching has no effect on weevil catches in pheromone traps, we suggest that *C. sordidus* would be more attracted by banana crop residues than by pheromone traps. All residues increase soil moisture, which is favourable to the development of *C. sordidus*. Masanza *et al*. (2005) showed that female oviposition depends on moisture. In the case of stemborers, sorghum crop residues represent a livestock feed and an important overwintering sites for larvae (Van den Berg & Ebenebe, 2001). In a previous study in Uganda, Gold *et al*. (2004) found 35% of adults in or under cut residues. The lower catches in the second ratoon crop compared with the first ratoon crop might be explained by banana harvesting dynamic. After the second ratoon, the banana plant population is unsynchronized and harvested throughout the year, whereas, for new plantations and the first ratoon, crop harvest is synchronized and occurs in 1 or 2 months (Tixier *et al*., 2004). We suggest that *C. sordidus* can remain in harvest residues, which are present throughout the year in the second ratoon banana crop, but persist for only 1–2 months in the first banana crop.

The results obtained in the present study show that abiotic factors such as temperature, relative humidity and wind affect *C. sordidus* catches. We also observed that these effects depended on the cropping stage. The microclimate created by the height of banana plants and residues would enhance the effects of weather on the movement of the banana weevil and pheromone trapping efficacy. In the first and second banana crops, *C. sordidus* catches decreased when the daily temperature was greater than 23°C. Uzakah (1995) found weevil activity in the laboratory to be negatively correlated with temperature. We suggest that *C. sordidus* move less at such temperatures and stay under the crop residues. Henderson and Roitberg (2006) showed that *Exophthalmus jekelianus* (Coleoptera: Curculionidae) prefer a shaded microhabitat when the temperature increases. Temperature could also have an effect on the release rate of the pheromone. Leonhardt *et al*. (1988) showed that pheromone release rates increased by 13-fold as the temperature was raised from 28 to 62°C. Van der Kraan and Ebbers (1990) showed that, when the temperature increased from 15 to 25°C, the release rates doubled. In the present study, however, the temperature range (22–26°C) was more restricted. During their study, with a mean ± SD temperature of 19.5 ± 1.8°C, Tinzaara *et al*. (2005b) also found no correlation between temperature and *C. sordidus* catches. In line with Tinzaara *et al*. (2005b), the results of the present study showed no relationship between rainfall and *C. sordidus* catches. In new plantations, catches in pheromone traps decreased when the wind speed increased. We propose, similar to Suckling *et al*. (1999), that the concentration of pheromone in the air decreases when the wind increases. Moreover, the effect of the wind may be partly explained by the low vegetation, which does not restrict it. In the first and second ratoon banana crops, the results differed from those in new plantations: the catches decreased when the wind speed was greater than 5 km/h. We suggest that the effect of wind would be minor in these banana plots because of the prominent erect vegetation. *Cosmopolites sordidus* catches decreased when the relative humidity increased. By contrast, Tinzaara *et al*. (2005b) found a positive correlation between relative humidity and *C. sordidus* catches. We propose that, when relative humidity increases, *C. sordidus* move less. In a laboratory study, Roth and Willis (1963) showed that *C. sordidus* tended to aggregate at higher humidities.

In conclusion, mass trapping with synergized pheromone traps within fallows should allow better sanitation of banana plantations, preventing a large part of the *C. sordidus* population from moving from fallows to other banana plots. Yet, within each farm, the fallows must not be located next to new plantations in an effort to avoid massive damage to young plants. Pheromone traps could be of value in new banana plantations, particularly if they are in the perimeter of the plot, hence limiting the arrival of *C. sordidus* from neighbouring fields. The efficacy of pheromone traps would be better if the traps were established during periods of moderate wind. To prevent the build-up of *C. sordidus* populations in banana fields, mass trapping must be associated with a high level of field sanitation. To optimize the pheromone trap catches, harvested residues must be destroyed and removed from the banana fields. More generally, the present study emphasizes that the control of this insect should be managed at the farm scale and not at the field scale, with special attention being paid to the location of fallows. The adoption of this approach to *C. sordidus* management, including fallows and mass trapping, is appropriate for the French West Indies, where farms are generally larger than 10 ha. The economic performance of cropping systems, however, is highly dependent on labour cost (Blazy *et al*., 2009). In this context, the planning of fallows and new plantations may be established according to the findings reported in the present study. The moderate labour necessary for pest management with pheromone trap compared with pseudostem traps makes it a promising technique for use in industrial banana farms. The integration of this innovative pest management strategy in cropping systems would be facilitated by using simulation models, such as the COSMOS model developed for *C. sordidus* (Vinatier *et al*., 2009), which can be used alone or linked to a farm-scale cropping system model, such as the SIMBA model developed for banana (Tixier *et al*., 2008). This would help optimize the temporal and spatial location of pheromone traps on the entire farm. Mass-trapping practices can contribute to the development of global integrated and environmentally friendly agriculture, to meet the high societal demand for food in places such as the French West Indies.

Acknowledgements

This research was supported by European Network for the Durable Exploitation of Crop Protection Strategies (ENDURE).

References

Abera-Kalibata, A.M., Gold, C.S. & Van Driesche, R. (2008) Experimental evaluation of the impacts of two ant species on banana weevil in Uganda. *Biological Control*, **46**, 147–157.

Alpizar, D., Fallas, D., Oehlschlager, O.C., Gonzalez, L.M. & Jayaraman, S. (1999) Pheromone-based mass trapping of the banana weevil, *Cosmopolites sordidus* (Germar) and the West Indian sugarcane weevil *Metamasius hemipterus* L. (Coleoptera: Curculionidae) in banana and plantain. *Memorias XIII Reunion ACORBAT*, pp. 515–538, 23–27 November 1998. Guayaquil, Ecuador.

Athanassiou, C.G., Kavallieratos, N.G. & Mazomenos, B.E. (2004) Effect of trap type, trap color, trapping location, and pheromone dispenser on captures of male *Palpita unionalis* (Lepidoptera: Pyralidae). *Journal of Economic Entomology*, **97**, 321–329.

Beauhaire, J., Ducrot, D.G., Malosse, C., Rochat, D., Ndiege, I.O. & Otieno, D.O. (1995) Identification and synthesis of sordidin, a male pheromone emitted by *Cosmopolites sordidus*. *Tetrahedron Letters*, **36**, 1043–1046.

Blackshaw, R.P. & Vernon, R.S. (2008) Spatial relationships between two *Agriotes* click-beetle species and wireworms in agricultural fields. *Agricultural and Forest Entomology*, **10**, 1–11.

Blazy, J.M., Dorel, M., Salmon, F., Ozier-Lafontaine, H., Wery, J. & Tixier, P. (2009) Model-based assessment of technological innovation in banana cropping systems contextualized by farm types in Guadeloupe. *European Journal of Agronomy*, **31**, 10–19.

Braimah, H. & Van Emden, H.F. (1999) Evidence for the presence of chemicals attractive to the banana weevil, *Cosmopolites sordidus* (Coleoptera: Curculionidae) in dead banana leaves. *Bulletin of Entomological Research*, **89**, 485–491.

Budenberg, W.J., Ndiege, I.O., Karago, F.W. & Hansson, B.S. (1993a) Behavioral and electrophysiological responses of the banana weevil *Cosmopolites sordidus* to host plant volatiles. *Journal of Chemical Ecology*. **19**, 267–277.

Budenberg, W.J., Ndiege, I.O. & Karago, F.W. (1993b) Evidence for volatile male-produced pheromone in banana weevil *Cosmopolites sordidus*. *Journal of Chemical Ecology*, **19**, 1905–1915.

Castrillón Arias, C. (2004) Situación actual del picudo negro del banano (*Cosmopolites sordidus* Germar) (Coleóptera: Curculionadae) en el mundo. *Actas del Taller 'Manejo convencional y alternativo de la Sigatoka negra, nematodos y otras plagas asociadas al cultivo de Musáceas'*, pp. 125–138, 11–13 August 2003. INIBAP, Guayaquil, Ecuador.

Chabrier, C. & Quénéhervé, P. (2003) Control of the burrowing nematode (*Radopholus similis* Cobb) on banana: impact of the banana field destruction method on the efficiency of the following fallow. *Crop Protection*, **22**, 121–127.

De Graaf, J., Govender, P., Schoeman, A. & Viljoen, A. (2005) Efficacy of pseudostem and pheromone seasonal trapping of the banana weevil *Cosmopolites sordidus* in South Africa. *International Journal of Pest Management*, **51**, 209–218.

Duelli, P., Studer, M., Marchland, I. & Jakob, S. (1990) Population movements of arthropods between natural and cultivated areas. *Biological Conservation*, **54**, 193–207.

Froggatt, J.L. (1925) The banana weevil borer (*Cosmopolites sordidus*). *Queensland Agricultural Journal*, **24**, 558–593.

Gold, C.S., Rukazambuga, N.D.M., Karamura, E.B., Nemeye, P. & Night, G. (1999) Recent advances in banana weevil biology, population dynamics and pest status with emphasis on East Africa. Mobilizing IPM for sustainable banana production in Africa. *Proceedings of a workshop on banana IPM*, pp. 35–50, 23–28 November 1998. INIBAP, Nelspruit, South Africa.

Gold, C.S., Pena, J.E. & Karamura, E.B. (2001) Biology and integrated pest management for the banana weevil *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae). *Integrated Pest Management Reviews*, **6**, 79–155.

Gold, C.S., Night, G., Ragama, P.E., Kagezi, G.H., Tinzaara, W. & Abera, A.M.K. (2004) Field distribution of banana weevil (*Cosmopolites sordidus* Germar) adults in cooking banana stands in Uganda. *Insect Science and its Applications*, **24**, 242–248.

Henderson, A.E. & Roitberg, B.D. (2006) Microhabitat Location of Exophthalmus jekelianus (White) (Coleoptera: Curculionidae): is there a preference for shade-grown coffee? *Environmental Entomology*, **35**, 1603–1609.

Honek, A. (1988) The effect of crop density and microclimate on pitfall catches of Carabidae, Staphylinidae (Coleoptera) and Lycosidae (Araneae) in cereal fields. *Pedobiologia*, **32**, 233–242.

Koppenhöfer, A.M. (1993) Observations on egg-laying behaviour of the banana weevil, *Cosmopolites sordidus* (Germar). *Entomologia Experimentalis et Applicata*, **68**, 187–192.

Leonhardt, B.A., Dickerson, W.A., Ridgway, R.L. & Devilbiss, E.E. (1988) Laboratory and field evaluation of controlled release dispensers containing grandlure, the pheromone of the boll weevil

(Coleoptera: Curculionidae). *Journal of Economic Entomology*. **81**, 937–943.

Masanza, M., Gold, C.S. & Van Huis, A. (2005) Distribution, timing of attack, and oviposition of the banana weevil, *Cosmopolites sordidus*, on banana crop residues in Uganda. *Entomologia Expeimentalis et Applicata*, **117**, 119–126.

Mestre, J. & Rhino, B. (1997) *Les études sur le charançon des bananiers, Cosmopolites sordidus* (*Germar, 1924*): *Bilan sommaire–Neufchâteau 1995–1997*. 19 p.

Oehlschlager, A.C., McDonald, R.S., Chinchilla, C.M. & Patschke, S.J. (1995) Influence of a pheromone-based mass-trapping system on the distribution of *Rhynchophorus palmarum* (Coleoptera: Curculionidae) in oil palm. *Environmental Entomology*, **24**, 1005–1012.

Oehlschlager, A.C., Gonzalez, L., Gomez, M., Rodriguez, C. & Andrade, R. (2002) Pheromone-based trapping of West Indian sugarcane weevil in a sugarcane plantation. *Journal of Chemical Ecology*, **28**, 1653–1664.

Padmanaban, B. & Kandasamy, M. (2003) Survival of banana weevil borers in banana plant residues. *Indian Journal of Entomology*, **65**, 424–425.

Roth, L.M. & Willis, E.R. (1963) The humidity behavior of *Cosmopolites sordidus* (Coleoptera: Curculionidae). *Annals of the Entomological Society of America*, **56**, 41–52.

Rukazambuga, N.D.T.M., Gold, C.S. & Gowen, S.R. (1998) Yield loss in East African highland banana (Musa spp., AAA-EA group) caused by the banana weevil, *Cosmopolites sordidus* Germar. *Crop Protection*, **17**, 581–589.

Sappington, T.W. & Spurgeon, D.W. (2000) Variation in boll weevil captures in pheromone traps (Coleoptera: Curculionidae) arising from wind speed moderation by brush lines. *Environmental Entomology*, **29**, 807–814.

Smit, N.E.J., Downham, M.C.A., Laboke, P.O., Hall, D.R. & Odongo, B. (2001) Mass-trapping male *Cylas* spp. with sex pheromones: a potential IPM component in sweet potato production in Uganda. *Crop Protection*, **20**, 643–651.

Speijer, P.R., Budenberg, J.W. & Sikora, R.A. (1993) Relationships between nematodes, weevils, banana and plantain cultivars and damage. *Annals of Applied Biology*, **123**, 517–525.

Spurgeon, D.W. & Raulston, J.R. (2006) Captures of boll weevils (Coleoptera: Curculionidae) in traps associated with different habitats. *Journal of Economic Entomology*, **99**, 752–756.

Suckling, D.M., Green, S.R., Gibb, A.R. & Karg, G. (1999) Predicting atmospheric concentration of pheromone in treated apple orchards. *Journal of Chemical Ecology*, **25**, 117–139.

Tinzaara, W., Tushemereirwe, W. & Kashaija, I. (1999) The potential of using pheromone traps for the control of Cosmopolites sordidus Germar in Uganda. Mobilizing IPM for sustainable banana production in Africa. *Proceedings of a Workshop on Banana IPM*, pp. 327–332, 23–28 November 1998. INIBAP, Nelspruit, South Africa.

Tinzaara, W., Gold, C.S., Kagezi, G.H. *et al*. (2005a) Effects of two pheromone trap densities against banana weevil, *Cosmopolites sordidus*, populations and their impact on plant damage in Uganda. *Journal of Applied Entomology*, **129**, 265–271.

Tinzaara, W., Gold, C.S., Dicke, M., Van Huis, A. & Ragama, P. (2005b) Factors influencing pheromone trap effectiveness in attracting the banana weevil, *Cosmopolites sordidus*. *International Journal of Pest Management*, **51**, 281–288.

Tinzaara, W., Gold, C.S., Dicke, M., Huis, Avan. & Ragama, P.E. (2008) Effect of mulching on banana weevil movement relative to pheromone traps. *African Crop Science Journal*, **16**, 59–66.

Tixier, P., Malézieux, E. & Dorel, M. (2004) SIMBA-POP: a cohort population model for long-term simulation of banana crop harvest. *Ecological Modelling*, **180**, 407–417.

Tixier, P., Malézieux, E., Dorel, M. & Wery, J. (2008) SIMBA: a comprehensive model for evaluation and prototyping of banana-based cropping systems. *Agricultural Systems*, **97**, 139–150.

Treverrow, N., Peasley, D. & Ireland, G. (1992) *Banana Weevil Borer, A Pest Management Handbook for Banana Growers*, Banana Industry Committee, New South Wales Agriculture, U.K.

Uzakah, R.P. (1995) *The reproductive biology behaviour and pheromones of the banana weevil, Cosmopolites sordidus (Germar) (Coleopteria: Curculionidae)*. PhD Thesis, University of Ibadan.

Van den Berg, J. & Ebenebe, A.A. (2001) Integrated management of stemborers in Lesotho. *Insect Science and its Applications*, **21**, 389–394.

Van der Kraan, C. & Ebbers, A. (1990) Release rates of tetradecen-1-ol acetates from polymeric formulations in relation to temperature and air velocity. *Journal of Chemical Ecology*, **16**, 1041–1058.

Vinatier, F., Tixier, P., Le Page, C., Duyck, P.F. & Lescourret, F. (2009) COSMOS, a spatially explicit model to simulate the epidemiology of *Cosmopolites sordidus* in banana fields. *Ecological Modelling*, **220**, 2244–2254.

Wedding, R., Anderbrant, O. & Jönsson, P. (1995) Influence of wind conditions and intertrap spacing on pheromone trap catches of male european pine sawfly, *Neodiprion sertifer*. *Entomologia Experimetalis et Applicata*, **77**, 223–232.

Winder, L., Holland, J.M., Perry, J.N., Woolley, C. & Alexander, C.J. (2001) The use of barrier-connected pitfall trapping for sampling beetles and spiders. *Entomologia Experimentalis et Applicata*, **98**, 249–258.

Accepted 12 October 2009