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Cover cropping reduces the abundance of the banana weevil *Cosmopolites sordidus* but does not reduce its damage to the banana plants

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HIGHLIGHTS

- The cover crop *Paspalum notatum* reduced the abundance of adult weevils.
- The proportion of newly emerged adults was increased by the cover crop.
- The proportion of newly emerged adults was negatively correlated with earwig number.
- Corm damage was higher in cover crop plots than in bare soil plots.
- Fruit biomass was lower in cover crop plots than in bare soil plots.

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ABSTRACT

Diversification of cropping systems raises new questions in the functioning of arthropod communities and biological control of pests. In banana cropping systems, the addition of a cover crop can increase biodiversity in general and the diversity and abundance of arthropod generalist predators in particular. We measured the abundance of a major pest of bananas, the banana weevil *Cosmopolites sordidus*, in plots with a cover crop, *Paspalum notatum*, and in plots with bare soil; all plots had banana plants. We also measured the effect of the cover crop on the damage done to corms by weevil larvae and on banana fruit biomass. The addition of the cover crop reduced numbers of mature *C. sordidus* adults but failed to reduce damage to corms. The proportion of young adults, which reflects survival of eggs and larvae, was higher in cover crop plots than in bare soil plots and was negatively correlated with the abundance of the earwig *Euborellia caraibea*. Fruit biomass was lower in cover crop plots, perhaps because of competition between the banana crop and the cover crop.

1. Introduction

The banana weevil *Cosmopolites sordidus* (Germar) is a major pest of banana crops (Cuillé, 1950; Gold et al., 2001). *C. sordidus* adults are nocturnal and disperse by walking, usually for short distances (Carval et al., 2015; Gold et al., 2001; Vinatier et al., 2010) although Rannestad et al. (2011) showed that the migration potential of *C. sordidus* may be greater in unsuitable environment. The females chew small cavities in the banana corm and pseudostem, where they deposit eggs (Cuillé, 1950). Once the eggs hatch, the larvae bore galleries as they feed on the corm and pseudostem tissues (Cuillé, 1950). The resulting damage can cause yield losses as high as 100% if the damaged banana plants topple before harvest (Gold et al., 2001).

To manage *C. sordidus*, growers apply pesticides, use clean planting material, practice crop sanitation, and trap the adults (Budenberg et al., 1993; Duyck et al., 2012; Gold et al., 2001; Rhino et al., 2010). Since the beginning of the 20th century, however, researchers have studied natural enemies of *C. sordidus*, especially in Indonesia, which is the putative area of origin of this pest (Froggatt, 1924; Jepson, 1914). In a recent survey in Java and Sumatra, Abera-Kalibata et al. (2006) identified several potential predators of the banana weevil. Three of these consumed eggs

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and larvae in a laboratory experiment. However, indigenous natural enemies have been proven to be efficient in pest regulation (Letourneau et al., 2009; Offenberg, 2015) and should be favored over the introduction of predators from the pest's area of origin. Endemic, potential natural enemies of *C. sordidus* have been identified in Africa, Asia, and Latin America (Dassou et al., 2015; Gold et al., 2001) and also in the Caribbean (Mollot et al., 2014, 2012), but little information is available concerning their ability to suppress *C. sordidus* numbers. In Uganda, Koppenhöfer et al. (1992) identified the earwig *Euborellia annulipes* (Lucas) as a predator of the eggs and of the four first instars of larvae of *C. sordidus*. In a controlled experiment, Koppenhöfer (1993) found that *E. annulipes* reduced the number of *C. sordidus* eggs and first instars by 28%. Moreover, this earwig occurs in the same habitat as *C. sordidus*, i.e., on corms, pseudostems, and stumps of banana plants (Koppenhöfer, 1993; Koppenhöfer et al., 1992). Using a metabarcoding approach, Mollot et al. (2014) recently proved that the earwig *Euborellia caraibea* (Hebard) feeds on *C. sordidus* in the French West Indies.

Diversification of cropping systems will likely alter arthropod communities and the biological control of arthropod pests. Scherber et al. (2010) showed that the abundance of all trophic groups except pests and invaders increases with plant diversity. Diversification of cropping systems generally enhances pest regulation (Letourneau et al., 2011; Symondson et al., 2002) but may reduce yield (Letourneau et al., 2011). In banana cropping systems, the addition of a cover crop alters the trophic position of predators, leading to a decrease in intraguild predation and potentially to an increase in pest regulation by generalist predators (Duyck et al., 2011; Tixier et al., 2013). The abundance of the fire ant *Solenopsis geminata* and its predation on bait eggs of *C. sordidus* were greater in banana plots with a cover crop than with bare soil (Mollot et al., 2012).

Although valuable, these previous studies did not measure the effect of the cover crop on *C. sordidus* abundance, or on the damage that this pest causes to the banana crop. To be economically efficient, biological control by generalist predators should reduce pest abundance and pest damage and maintain crop yield. Here, we studied how the introduction of a cover crop, *Paspalum notatum* (Poaceae), affects the abundances of the earwig *E. caraibea* and *C. sordidus*, corm damage, and the weight of banana bunches. We tested the following hypothesis regarding the effects of the added cover crop: (i) the abundance of *C. sordidus* will be smaller because the new basal resource will support a diverse herbivore community that provides alternative prey to generalist predators; (ii) the abundance of *E. caraibea* will be greater because of increase in alternative prey and because of a decrease in intraguild predation; (iii) damage caused by *C. sordidus* to the banana crop will be reduced; and (iv) the banana bunches will have reduced mass because of competition with the cover crop.

2. Materials and methods

2.1. Study site and experimental design

The experiment was conducted in Martinique (French West Indies) between January 2014 and April 2015 on an experimental farm in Rivière-Lézarde (14°39′45.04″N; 60°59′59.08″W) in an area initially free from weevil. Six plots were established, each with an area of 361 m^2 and with 49 banana plants (Cavendish Grande Naine cultivar). The banana plants were planted on 24 July 2012. The cover crop *Paspalum notatum* was planted in three of the plots on 11 June 2012, while the other three plots were maintained with bare soil. The plots with the cover crop and with bare soil are hereafter referred to as CCP and BSP, respectively. The plots were arranged as presented in Fig. 1. On 30 October 2012, 70 banana weevils (sex ratio 1:1) were added to each plot. Each month, banana plants were uniformly fertilized, the cover crop was cut back and weeds were controlled with herbicide (glyphosate) in BSP.

2.2. Sampling of banana weevils and earwigs

Banana weevil and earwig abundances were estimated with pseudostem traps once each month in April, June, August, and November of 2014 and in April of 2015. The pseudostem traps, which were 30 cm long, were deposited at the bottom of each banana plant (new traps were deployed for each of the five sampling dates), and weevils and earwigs found in the traps 1 week later were counted (Dassou et al., 2016; Gold et al., 2001; Koppenhöfer et al., 1992). We discriminated between newly emerged adult weevils (hereafter called teneral adults) and older weevils (hereafter called mature adults) based on exoskeleton color (Gold et al., 2001).

2.3. Corm damage caused by C. sordidus

Banana cropping systems can be maintained multiple cycles. A cycle consists in four steps: vegetative growth, flowering, sucker appearance and harvest of the bunch. Data presented here were issued from the second and the third cycles of culture. For each cycle and for each banana plant, at the harvest, bunch was weighed and damage was assessed by removing 2 cm of the corm surface from 10 cm above to 10 cm below the soil surface over the entire circumference of the corm. A 0–100 scale was used to score the damage on each corm (Vilardebo, 1973): 0 = no damage; 5 = 1 or 2 galleries; and 10, 30, 40, 60, and 100 = 10, 25, 50, 75, and 100%, respectively, of the corm circumference damaged. This method

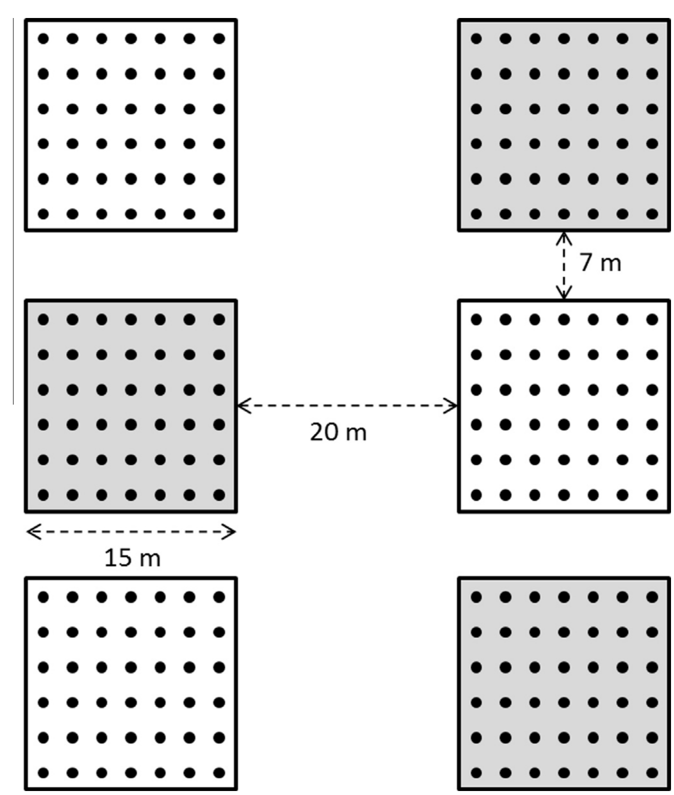

Fig. 1. Spatial arrangement of the experimental plots. White squares: bare soil plots. Gray squares: cover crop plots. Black points: banana plants.

has been proven to be representative of the true corm damage (Dassou et al., 2015).

2.4. Statistical analysis

We first used Kruskal-Wallis tests to analyze the variation in the mean abundance across dates of *C. sordidus* adults (total number of adults, number of mature adults, and number of teneral adults), earwigs, and the proportion of teneral adults relative to total adults. If significant variation was detected, we added sampling date as a random intercept effect in Poisson generalized mixed models (GLMMs; see next paragraph).

Poisson generalized linear models (GLMs) were used to analyze the effect of the soil cover on the abundance of *C. sordidus* adults (total number, number of mature adults, and number of teneral adults), and GLMMs were used to analyze the effect of the soil cover on the abundance of earwigs with sampling date as a random intercept effect. The statistical unit was the plot, and abundance corresponded to the sum of *C. sordidus* weevils or earwigs at each sampling date. The effect of soil cover was tested against a null model using a Likelihood Ratio Test (LRT) (Bolker et al., 2009).

GLMMs were used to analyze the effect of soil cover on the damage scores. The statistical unit was the damage score of each banana plant. Banana plants that were related (i.e., mother plant in cycle 2 and its successive suckers of cycles 3) were identified by an individual number that was used as a random intercept effect. The effect of soil cover was tested against a null model using an LRT.

Linear models (LMs) were used to analyze the relationship between (i) the weight of the bunches and the damage scores and (ii) the weight of the bunches and the soil cover. The statistical unit was the bunch weight of each banana plant. Each model was compared to a null model using an LRT.

A binomial GLM was used to analyze the effect of the abundance of earwigs on the proportion of teneral adults relative to all *C. sordidus* adults on each sampling date. The statistical unit was the plot. The effect of earwig abundance was tested against a null model using an LRT.

All LMs, GLMs and GLMMs were estimated using the 'lme4' package (Bates et al., 2011), in which the maximum likelihood of parameters is approximated by the Laplace method (Bolker et al., 2009). Means and confidence interval were calculated using the 'simpleboot' package (Peng, 2008). All statistical analyses were performed with R 3.2.2 (R Development Core Team, 2015) and with an alpha level of 0.05.

3. Results

Sampling date did not significantly affect the abundance of adults (total number, number of mature adult, or number of teneral adults: $\chi^2 = 5.22$, d.f. = 4, P = 0.27; $\chi^2 = 5.51$, d.f. = 4, P = 0.24; and $\chi^2 = 6.85$, d.f. = 4, P = 0.14, respectively) (see Figs. 1 and 2 in Carval et al., in press) or the proportion of teneral adults ($\chi^2 = 6.73$, d.f. = 4, P = 0.15) (see Fig. 3 in Carval et al., in press). Sampling date did significantly affect the abundance of earwigs ($\chi^2 = 9.73$, d.f. = 4, P = 0.046) (see Fig. 4 in Carval et al., in press).

3.1. Effect of soil cover on the abundance of C. sordidus adults

C. sordidus adults were significantly more abundant in BSP than in CCP (Fig. 2A, Table 1). Mature adults were significantly more abundant in BSP than in CCP (Table 1), with means [95% CI] of 43.5 individuals [34.3–57.8] and 21.4 individuals [17.5–27.5], respectively. Teneral adults, in contrast, were less abundant in BSP than in CCP (Table 1), with means of 9.6 individuals [6.5–15.5] and 13.5 individuals [10.1–17.3], respectively.

3.2. Proportion of teneral weevils

The proportion of teneral adults relative to all *C. sordidus* adults was greater in CCP than in BSP (Fig. 2B) and was negatively correlated with the abundance of *E. caraibea* (LRT = 6.5, p-value = 0.01, df = 1).

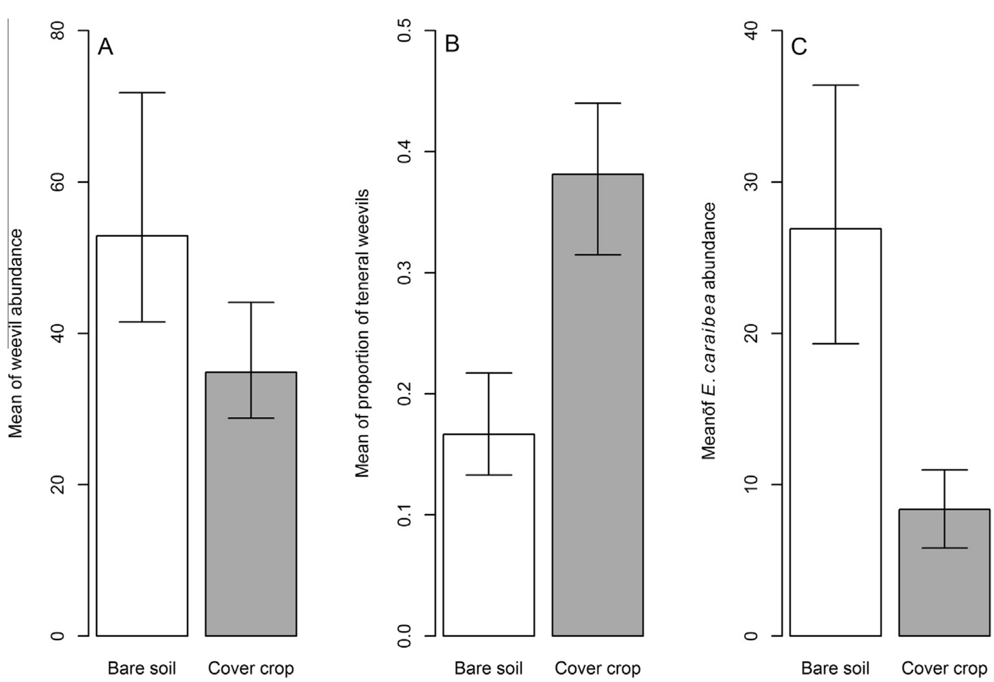

Fig. 2. Effect of soil cover on (A) the abundance of all *C. sordidus* adults (teneral and mature), (B) the abundance of earwigs, and (C) the proportion of teneral adults relative to all *C. sordidus* adults. Values are means ± 95% CI per plot averaged across all sampling dates.

Table 1
Effect of soil cover (cover crop vs. bare soil) on *C. sordidus* abundance (all adults, mature adults, and teneral adults), earwig abundance, and corm damage across all sampling dates. Statistics presented here were obtained by comparing null models with models that included the soil cover as an explanatory variable, with bare soil as the reference.

Response variable	AIC	LRT	p-value	Estimate (±se)
Abundance of all *C. sordidus* adults	286.9	57.6	<0.0001	−0.42 (±0.06)
Abundance of *C. sordidus* mature adults	205.9	114.9	<0.0001	−0.71 (±0.07)
Abundance of *C. sordidus* teneral adults	141.1	9.1	0.0026	0.33 (±0.1)
Earwig abundance	358.8	154.0	<0.0001	−1.2 (±0.10)
Corm damage	7526.6	15.9	<0.0001	2.9 (±0.66)
Banana bunch weight	3463.6	809.4	<0.0001	−2.5 (±0.64)

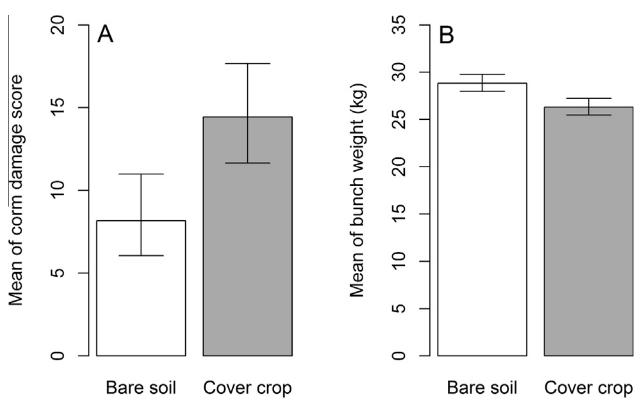

Fig. 3. Effect of soil cover on (A) the corm damage score and (B) the banana bunch weight. Values are means ± 95% CI per plot averaged across all sampling dates.

3.3. Effect of soil cover on earwig abundance

Earwigs were more abundant in CCP than in BSP (Fig. 2C; Table 1).

3.4. Corm damage and bunch weight

Corm damage scores were significantly higher in CCP than in BSP (Fig. 3A, Table 1). Bunch weight was not correlated with corm damage (LRT = 2.92, p-value = 0.09, df = 1) but was significantly lower in CCP than in BSP (Fig. 3B, Table 1).

4. Discussion

4.1. Weevil abundance as affected by the cover crop

In a banana cropping system, we measured the effect of a cover crop on the abundance of *C. sordidus* adults, the damage to corms caused by *C. sordidus*, and crop production. Consistent with previous reports (Letourneau et al., 2011; Scherber et al., 2010; Symondson et al., 2002), we found that the diversification of the cropping systems by the planting of a cover crop reduced pest abundance, i.e., banana weevil abundance. This could be explained by an increase in generalist predator abundance as suggested by previous studies (Letourneau et al., 2011; Mollot et al., 2012; Scherber et al., 2010; Tixier et al., 2013). Meta-analyses have shown that natural enemy abundances were greater in diversified cropping systems than in simple cropping systems in more than half of the studies on this topic (Letourneau et al., 2011; Poveda et al., 2008). In plantain-based cropping systems, (Dassou et al., 2016) recently found that plant diversity was correlated with an increase in the abundance of predator arthropods and a decrease in the abundance of herbivores. Such top-down effects could explain the lower abundance of *C. sordidus* in CCP than in BSP in the current study. Indeed, GLM analysis indicated that the addition of the cover crop *P. notatum* was correlated with the reduction in *C. sordidus* numbers in CCP relative to BSP. Further experiments should be conducted to confirm such top-down effects in CCP.

Although earwigs were previously identified as predators of *C. sordidus* eggs and larvae (Koppenhöfer, 1993; Koppenhöfer et al., 1992; Mollot et al., 2014), we found more teneral adults and fewer mature adults of *C. sordidus* in CCP than in BSP. According to the GLMs, the cover crop reduced the numbers of mature adults by almost 50% but increased the numbers of teneral adults by almost 40%. This suggests that the predation on *C. sordidus* eggs larvae was weakened in CCP and that the reduction in total number of *C. sordidus* adults in CCP may have been caused by predation on mature adults.

The proportion of teneral adults relative to all *C. sordidus* adults was negatively correlated with the abundance of the earwig *E. caraibea*, which is consistent with the view that *E. caraibea* is an efficient predator of *C. sordidus* eggs and larvae. However, the lower abundance of *C. sordidus* in CCP cannot be explained by predation by the earwig *E. caraibea* because *E. caraibea* was less abundant in CCP than in BSP, apparently resulting in a higher proportion of teneral adults in CCP than in BSP. We therefore infer that the reduced abundance of *C. sordidus* adults in CCP resulted from mortality factors other than earwigs.

Several studies have reported on the predation of the banana weevil by ants. Abera-Kalibata et al. (2008) reported a reduction in numbers of *C. sordidus* eggs but not of larvae when two ant species were present. Mollot et al. (2012) also demonstrated that the egg predation rate was higher when the abundance of the fire ant *Solenopsis geminata* was higher, but because the eggs were artificially placed on the corms, the results may not reflect the true ability of *S. geminata* to suppress *C. sordidus* numbers. Mollot et al. (2014) identified three predators of *C. sordidus*, two of which were ants. Based on a correlation between corm damage and ant abundance, Dassou et al. (2015) identified ants belonging to the genera *Axinidris*, *Monomorium*, *Pheidole*, and *Tetramorium* as potential predators of the banana weevil. Another explanation of the lower abundance of *C. sordidus* in CCP could be that the pseudostem traps were more effective in attracting weevils in the BSP compared to the CCP. However, Vinatier et al. (2010) found no effect of a cover crop on the movement behavior of the banana weevils. Further experiments will be needed to study this potential bias.

4.2. Corm damage as affected by the cover crop

The damage caused by *C. sordidus* was higher in CCP than in BSP, and we hypothesize that the increased damage in CCP was due to the reduced abundance of earwigs in CCP. Earwigs are predators of *C. sordidus* eggs and larvae (Abera-Kalibata et al., 2007; Koppenhöfer, 1993). A reduced abundance of earwigs would presumably reduce the predation of eggs and larvae and thereby result in an increase in the feeding on corms by larvae. Our finding that addition of a cover crop increased damage to the main crop adds to the list of studies that have reported contradictory effects of diversification on crop damage caused by pests (Letourneau et al., 2011; Poveda et al., 2008; Pumarino et al., 2015).

4.3. Fruit biomass as affected by the cover crop

In this study, the weight of banana bunches was reduced by the addition of the cover crop. However, we found no relationship between the level of corm damage and the weight of bunches. This suggests that the decrease in the bunch weight in CCP was probably due to competition for resources between the banana crop and the cover crop, *P. notatum*. This is consistent with previous studies on banana cropping systems (Ripoche et al., 2012) and with synthetic studies that show that cropping systems diversification often causes yield losses (Letourneau et al., 2011; Quijas et al., 2010) because of competition for nutrients and light between the crop and associated plants.

5. Conclusions

We found that the addition of the cover crop *P. notatum* in a banana cropping system reduced the abundance of *C. sordidus* adults, but failed to reduce damage to corms and decreased the production of banana fruit. Finally, the reduced production of banana fruit may be explained by competition between the banana crop and the cover crop.

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