Effect of climatic variables and pheromone trapping strategy on the capture of *Cosmopolites sordidus* in banana fallows

Alexis Delaplace [a,c,e,*], Mathieu Coulis [a,c], Gwenaelle Cottin [e], Philippe Tixier [b,c,d]

[a] *CIRAD, UPR GECO, F-97285, Le Lamentin, Martinique, France*
[b] *CIRAD, UPR GECO, F-34398, Montpellier, France*
[c] *GECO, Univ Montpellier, CIRAD, Montpellier, France*
[d] *UPR GECO, CIRAD, Vientiane, Lao People's Democratic Republic*
[e] *Presta'SCIC SARL, Pointe des carrières, BP 1089, F-97209, Fort-de-France Cedex, Martinique, FWI, France*

ARTICLE INFO

ABSTRACT

Cosmopolites sordidus is one of the major pests of bananas. The ban on the use of pesticide products as well as the firmness of public opinion on these products makes it imperative to adopt an alternative method that respects the environment. Pheromone mass trapping is a method that meets these conditions and has demonstrated its effectiveness. However, no study has focused on its use in fallow plots, even though fallowing is recognized as an event that makes plots a source of contamination. Our study compares the effectiveness of two fallow trapping patterns by integrating the effect of climatic variables on the capture rate. Our results showed that the trapping of fallow land ensures a real sanitation of *C. sordidus*. In addition, the internal trapping of fallow land, compared to trapping surrounding the fallow land, cleans up the plots twice as quickly. Furthermore, trapping efficiency is affected by climatic conditions with seasonal variations, the wet season is more favorable to trapping than the dry season. We provide recommendations for the use of trapping considering the effect of climate on the movement of weevils and on the efficiency of pheromone attractivity. Finally, we offer perspectives on the gaps that still need to be filled.

1. Introduction

The black banana weevil, *Cosmopolites sordidus* (Germar, 1824) (Coleoptera: Curculionidae) is one of the main pests of bananas and plantains. This insect, native to the Indo-Malaysian region, has spread to all tropical and subtropical banana-producing regions, mainly those cultivating the genera *Musa* and *Ensete* (Gold et al., 2001). The adult stage of *C. sordidus* is not recognized as being responsible for damages. Larval stages cause damage to the corm of banana plants resulting in yield losses. The larval feeding creates galleries in the banana corm, reducing the absorption of nutrients and weakening the stability of the plant, which can cause the plants to topple over (Gold et al., 2001). According to Rukazambuga et al. (1998), the damage caused by the populations leads to yield losses whose severity increases with the crop cycle. The banana plant completes a 9-month cycle and emits successive suckers according to Tixier et al. (2004), 5% losses in the 1st cycle and up to 44% losses in the 4th cycle. However, the exact contribution of *C. sordidus* in yield losses remains difficult to assess. Most of the literature focuses on estimating the infestation rate of plots using the abundance of imago. However, the current paradigm emphasizes the lack of linearity in the relationship between the abundance of individuals and the damage caused to the plant (Gold et al., 2001; Poeydebat et al., 2017); certainly due of the many environmental factors that merge, e.g. other phytoparasitic species, climatic hazards and cultural practices. In the French West Indies (FWI), the use of insecticides in banana fields largely decreased over the last 20 years (Risède et al., 2019) because of the more strict regulation on pesticides and the adoption of alternative control strategies including sanitation fallows and mass trapping. Most of insecticides registered in banana fields in FWI have been prohibited for environmental and human health reasons. Therefore, it is now important to continue the development and the optimization of sustainable methods to control this pest.

In addition to the use of fallows and mass trapping, different biological control approaches have been tested to control *C. sordidus* populations. The conservation of predatory species has been extensively studied due to the many arthropod species identified as natural enemies
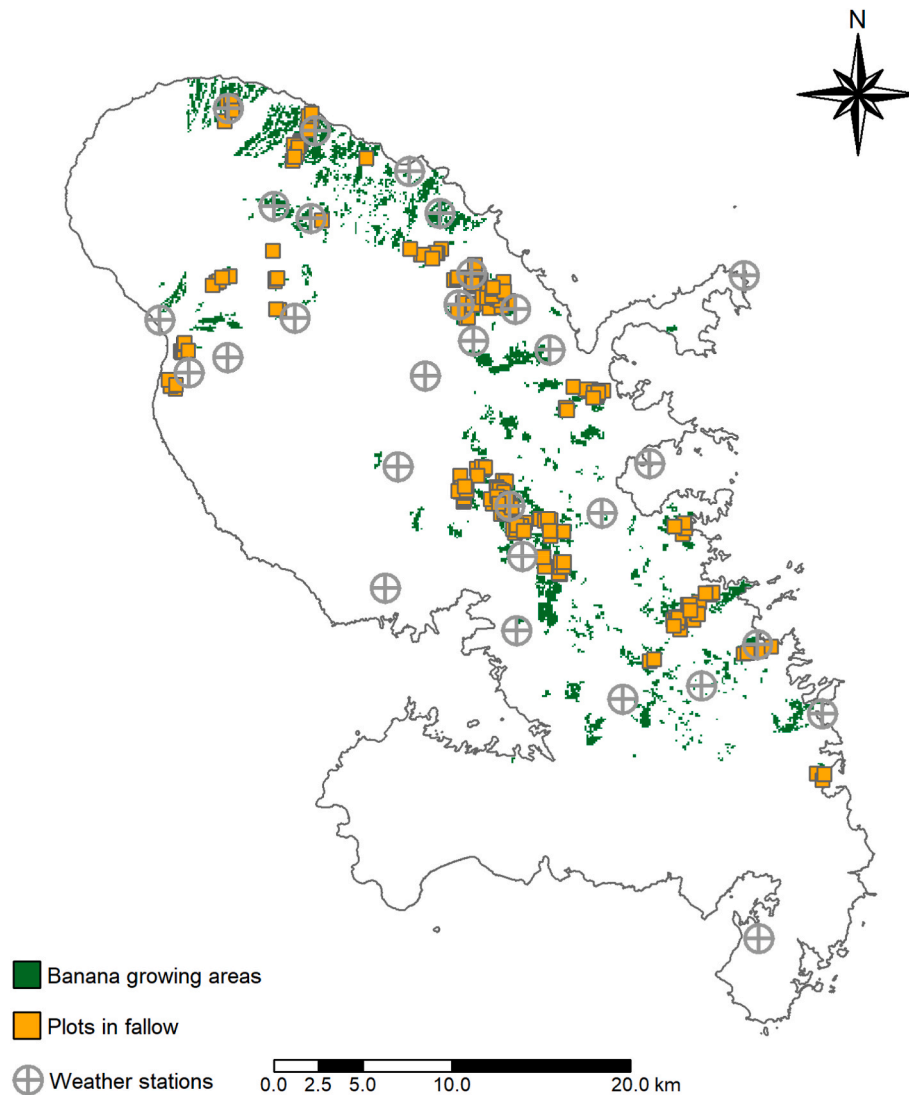

Fig. 1. Location of the banana growing areas and the 228 sampled fallow plots over the years 2012–2019. Green polygons locate the banana growing areas and orange squares locate the plots in fallow investigated in the present work. Grey solar crosses locate the 30 weather stations used to generate the following climatic variables: rainfall, temperature, wind speed, relative air humidity and global radiation.

of different stages of *C. sordidus* (Tresson et al., 2021). The use of natural enemies is relevant when their presence reduces crop damage. Such a relationship has been demonstrated by Poeydebat et al. (2017) between the abundance of generalist predators and *C. sordidus* damage. However, the negative impact of natural enemies on the target pest is not systematic; a significant number of cases show no effect, or even a positive effect. As the results from the prey-predator interaction are context dependent, it is necessary to precisely characterize the trophic relationships of the study environment before integrating practices favoring natural enemies (Rusch et al., 2010). Another avenue explored is the introduction of species, in particular entomopathogenic. Species like *Beauveria bassiana* or *Metarhizium anisopliae* are the two main candidates that have been studied for the management of *C. sordidus*. If the results under laboratory conditions suggest a strong potential (Akello et al., 2007; Lopes et al., 2011), the results under field conditions had been unsatisfactory (Lopes et al., 2014; Negrete González et al., 2018; Tinzaara et al., 2007). A probable cause of the failure of entomopathogenic fungi in the field undoubtedly comes from the volatile compounds they emit which have a repellent effect on *C. sordidus* (Lozano-Soria et al., 2020). The introduction of other antagonist species has also been attempted, without more convincing results (see Tresson et al., 2021).

Cosmopolites sordidus is characterized by a life cycle with a type K demographic strategy: i.e. a long lifespan, ranging from 1 to 4 years and a low reproduction rate, approximately 1–4 eggs per week (Gold and Messiaen, 2000). It is an insect living in the soil litter, with cryptic behaviour and a specific diet limited to the *Musa* genus (Gold et al., 2001). *Cosmopolites sordidus* are marked by gregarious behaviour catalysed by the emission of a pheromone, produced by adult males, attractive to both males and females (Budenberg et al., 1993). *Cosmopolites sordidus* have strong hygrotropism, and negative phototropism (Gold et al., 2001). The period of activity of adults is mainly nocturnal (Carval et al., 2015; Cuillé, 1950; Uzakah, 1995). As *C. sordidus* is very sensitive to the conditions of its habitat, it is important to integrate the climate as a key factor in defining control strategies for this pest.

In Martinique, banana cultivation is generally established after a fallow period for plot sanitation purposes, i.e. in order to reduce the populations of plant parasitic nematodes (especially *Radopholus similis* Cobb, 1893) and *C. sordidus* (Côte et al., 2009). After fallow, plots are planted using healthy *in vitro* plant material which is recognized as effective on nematodes (Chabrier et al., 2010). Nevertheless, fallow alone seems to be less effective in controlling *C. sordidus*, probably because of its long lifespan and cryptic lifestyle. After the destruction of the banana plant, *C. sordidus* can survive and remain hidden in the fallows, due to their great capacity for survival when food runs out, 3–6

months with the absence of banana plants and residues on the plot (Gold et al., 2001). Therefore, without trapping if decaying pieces of banana plants remain, a significant part of *C. sordidus* population may survive in fallow plots, dampening the benefit of the planting healthy materials. Sanitation fallows are generally installed after five to ten years of production.

Another issue in sanitation of fallows is that a part of *C. sordidus* population flees the fallow plot, becoming a source of contamination for surrounding banana fields. Mass-trapping of *C. sordidus* is thus essential to effectively control this pest at the farm scale (Rhino et al., 2010). Consequently, it is essential to optimize the trapping strategy to achieve effective sanitation and to reduce contamination of neighbouring plots. In 1995, Beauhaire et al. succeeded in synthesizing the sordidin aggregation pheromone emitted by the *C. sordidus*. The effectiveness of pitfall traps using this pheromone as attractant during the growth of Cavendish bananas has been demonstrated (Alpizar et al., 2012; Fu et al., 2019). However, the efficiency of the trapping strategy during the fallow period remains largely unknown. The work of Rhino et al. (2010) showed that pheromone trapping during sanitizing fallows leads to a peak of captures between two and four months after the beginning of fallows. In that study, authors did not investigate the role of the climate in the trapping efficiency. In a work conducted on a larger scale (the entire island of Martinique), Duyck et al. (2012) investigated the effectiveness of mass pheromone trapping inside banana fields (not fallows). This study concluded that air temperature, wind speed and relative humidity have a negative effect on catches, whereas precipitations had no effect. To improve the trapping strategies, it is necessary to evaluate the efficiency of different trapping patterns in controlling *C. sordidus* and to contextualize the strategies according to climatic conditions.

The position of the traps on the plot is an essential aspect. For example, it has been shown that trapping fruit flies (*Rhagoletis pomonella*) is more effective when traps are positioned at the edge of the plot than in the center.(Rull and Prokopy, 2003). On the other hand, for boll weevil (*Anthonomus grandis)*, the use of trapping has shown that the infestation is not limited to plot edges. In addition, early infestations suggest that part of the population remains active within the plots even out of season, implying the need for homogeneous and regular control (Arruda et al., 2020). Phytosanitary treatments applied at the edge of fields against *A. grandis grandis* have proven to be ineffective in preventing the colonization of Cotton crops (Arruda et al., 2020). These examples show that the efficacy of biological control applied in the belt or in the field can depend on the pest species, but this has never been studied for *C. sordidus*, which is one of the aims of this study. In addition to their position, the density of the traps is an important criterion. For the control of *Halyomorpha halys*, it is preferable to use a single trap for small farms (<2.5ha); too many traps lead to competition between them, affecting their capture performance (Schumm et al., 2021).

In this study, we analysed a large dataset of mass trapping in banana fallow plots in Martinique to understand i) the efficiency of two contrasted trapping strategies (belt and internal trapping) and ii) the effect of climate variables on *C. sordidus* captures. Our dataset included 54 170 observations, covering the diversity of the conditions of banana production in Martinique.

2. Materials and methods

2.1. Collection of field data

We analysed a data set of *C. sordidus* trapping resulting from the mass-trapping carried out by Presta'SCIC, the company that provides a trapping service to farmers in Martinique. The data used for this work were only collected in fallow plots after banana production. Trapping data covers a period of seven years (from 2012 to 2019), on 33 banana farms from Martinique, leading to a total of 228 fallow fields and for a total of 410 ha. Studied fields were located all over Martinique (Fig. 1), covering a large range of soil and climate conditions. *Cosmopolites*

Fig. 2. Photos of a pitfall trap in field condition, with and without its upper part (left and right respectively).

Table 1
Description of explanatory climatic variables used in the GLMM model.

Variable name	Description	Unit
Rainfall	Daily rainfall height	mm
Air temperature	Daily measure by averaging minimal and maximal temperature under shelter	C°
Wind speed	Daily measure of the maximum wind speed averaged over 10 min	m.s^{-1}
Relative air humidity	Daily average relative air humidity	%
Global radiation	Daily global radiation	J. cm^{-2}
Elevation	Modelling of the relief of Martinique	m
Nebulosity	Cloud cover in Martinique	%

TN: minimal temperature under shelter.
TX: maximal temperature under shelter.

sordidus were captured by pitfall traps (yellow colour, 216 mm high, including 100 mm buried and an upper outer diameter of 185 mm and an inner diameter of 148 mm, Fig. 2) baited with the sordidin aggregation pheromone (Cosmoplus®, Scyll'Agro, Hastingues, France). The pheromone was changed every three months according to the supplier's recommendations. The traps were installed according to two trapping patterns, belt trapping and internal trapping. The belt trapping pattern consisted in installing a trap every 10 m around the fallow plot. The internal trapping pattern consisted in installing traps regularly inside the fallow plots at a density of 16 traps per hectare. In total 12 148 traps were monitored during this period. The trapped *C. sordidus* were collected and counted every month for each trap (54 170 observations in all). Our study focused on plots in fallows, but we also compared our fallow plot catch levels to those in banana production plots using the raw data from the Duyck et al. (2012) study from the period 2006 to 2008 (for a total of 78 783 observations in all, Supplementary 1). In our study and in the one of Duyck et al. (2012) no insecticides were used during the trapping periods.

2.2. Weather variables

To understand the role of weather variables on the number of *C. sordidus* captured, a wide range of variables was collected (Table 1). Rainfall, air temperature, wind strength, relative humidity and global radiation variables were collected using the daily measures of the meteorological stations of Météo-France Martinique (grey solar cross in Fig. 1). To each trap we assigned the measured value of the nearest climate station to the corresponding trapped plot (≤430 m). As each trap was collected monthly, we integrated climatic variables over this same time intervals. During this period of integration, all variables were averaged, except the rainfall that was cumulated. Additionally, to weather stations, the nebulosity came from MODIS (Moderate Resolution Imaging Spectroradiometer) measured by the Terra satellite from 1999 and by the Aqua satellite from 2002. The nebulosity is usually expressed in octa, in our case it has been normalized to vary from 0 to 100. This makes it possible to integrate the stationary bioclimate.
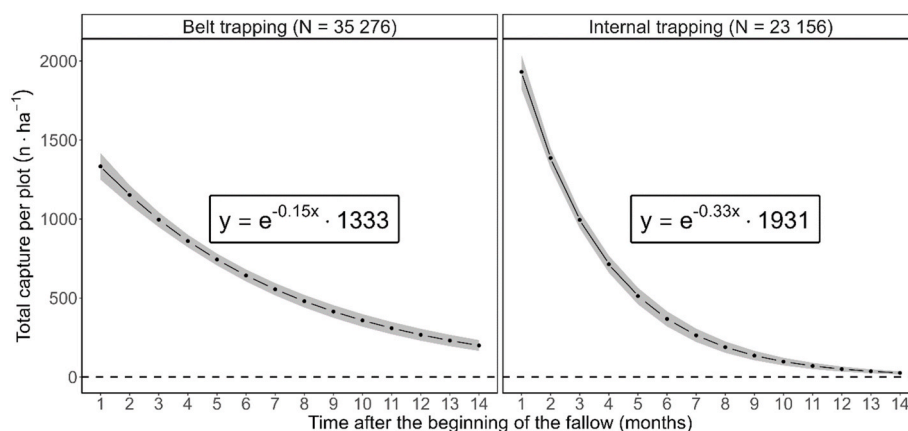
Fig. 3. Total capture of *C. sordidus* per plot and per hectare according to the time after the beginning of the fallow (in months). The left panel presents the results of belt trapping pattern and the right panel presents the results of internal trapping pattern. The black lines with dots represent estimations from the negative exponential model. The black dashed lines represent an asymptote of zero. Grey areas represent the standard error.

Eventually, the elevation comes from a modelling of the relief in the form of a 25 × 25 m grid provided by the IGN (French national institute for geographical and forestry information, Paris, France).

2.3. Statistical analysis

In order to characterize the slope of the decrease of the *C. sordidus* captured in traps after the beginning of the fallow, we fitted a negative exponential curve, according to the formula: $y = e^{-a} + b$. The parameter a of the fitted curves indicates the slope of the decrease and parameter b indicates the intercept. This function was fitted using the 'nls' function from R software.

A generalized linear mixed-effects model (GLMM) was used to examine the relation between *C. sordidus* abundance captured in pitfall traps with the time after the beginning of the fallow period, if there was a pheromone replacement (i.e. every three months), the climatic variables corresponding to each trapping period and the trapping pattern (in belt or inside the fallow field) (Bolker et al., 2009). We also included the quadratic values of predictors except for air temperature, relative humidity, pheromone replacement and for trapping pattern. It allowed us to deal with non-linear effects of these variables. Moreover, we added an interaction between rainfall and air temperature since the effect of temperature is expected to be highly dependent of the level of rainfall. We performed a variance inflation factor VIF (Montgomery and Peck, 1992) to check that there was no collinearity between all predictors. A variographic analysis of the model residuals was performed, to check that data did not present spatial autocorrelation (Supplementary 2). In all, the database included 54 170 observations. Overdispersion of these abundance data was taken into account by using a negative binomial distribution (Venables and Ripley, 2002). In order to consider potential effects associated to the cultural practices between farms, we included the farm identity as a random factor on the intercept in the model. The inclusion of random effects allowed us to account for the effect of factors that create variance but that are not important to be tested. Moreover, we added an offset term based on the trap density in order to weight the number of captures. We carried out a backward selection of the predictors of the model. We standardized climatic variables in order to make them easily comparable on a same "scale" while preserving the
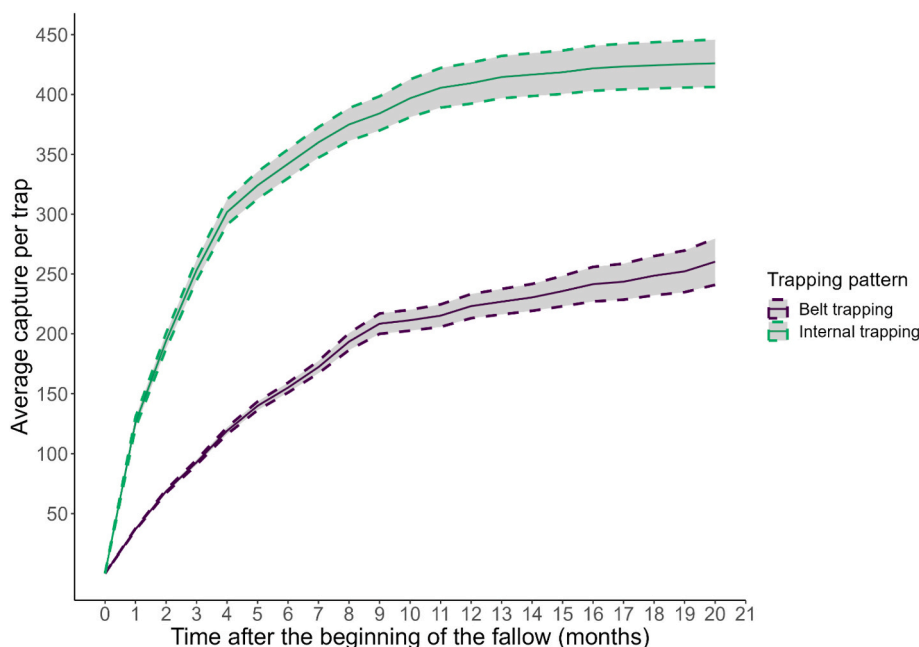

Fig. 4. Average capture per trap over time after the beginning of the fallow according to the type of trap installed in the fallow. The solid lines represent the average and dashed lines represent the standard errors.
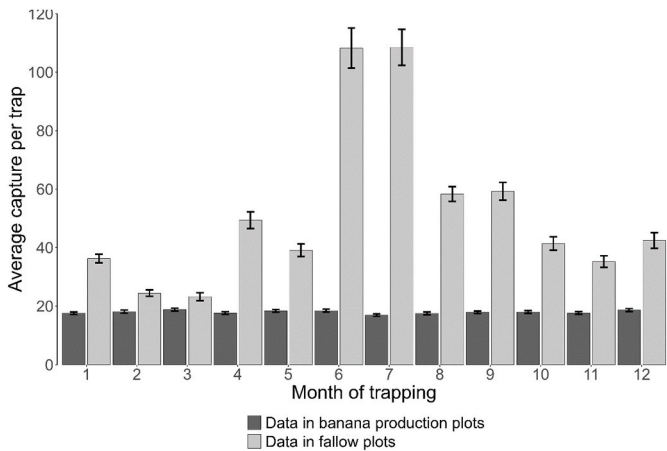
Fig. 5. Average number of *C. sordidus* captured per trap according to the month of trapping. Light grey bars represent captures in plots in fallow from Presta'SCIC data and dark grey bars represent captures in plots in banana production from Duyck et al. (2012). The error bars represent the standard error.

Table 2

GLMM β estimates for each predictor with standard error associated. When the β value is positive, it has a positive effect on the number of *C. sordidus* captured and it is the contrary when the β value is negative.

Model	Df	Estimate	Std. Error	z value	Pr(>|z|)
Intercept	1	−0.340	0.193	−1.765	0.07750
Time	1	−0.212	0.007	−30.658	<0.00001
(Time)²	1	−0.004	0.001	−5.775	<0.00001
Internal trapping	1	1.010	0.023	43.983	<0.00001
Pheromone replacement	1	0.116	0.014	8.554	<0.00001
Rainfall	1	0.160	0.011	15.143	<0.00001
(Rainfall)²	1	−0.049	0.004	−11.807	<0.00001
Air temperature	1	0.178	0.009	20.450	<0.00001
Wind strength	1	0.088	0.016	5.527	<0.00001
(Wind strength)²	1	−0.075	0.008	−9.358	<0.00001
Relative air humidity	1	−0.063	0.012	−5.426	<0.00001
Global radiation	1	0.236	0.008	29.266	<0.00001
(Global radiation)²	1	−0.045	0.006	−7.673	<0.00001
Elevation	1	0.743	0.030	25.070	<0.00001
(Elevation)²	1	−0.076	0.012	−6.279	<0.00001
Nebulosity	1	−0.660	0.038	−17.460	<0.00001
(Nebulosity)²	1	0.313	0.015	20.670	<0.00001
Rainfall x Air temperature	1	0.048	0.007	6.741	<0.00001

shape of their distribution. We graphically checked the normality of the residuals of the model. The relative importance of each predictor was assessed by their contribution to reduce the AIC (Akaike information criterion) (Akaike, 1974; Sakamoto et al., 1986). The GLMM were fitted by the Laplace approximation using the 'glmer' function in 'lme4' (Bates et al., 2015) and initializing via theta.ml from 'MASS' (Venables and Ripley, 2002) in the statistical programme R 4.2.0 (R Core Team, 2022) and with an alpha level of 0.05.

3. Results

The fallow plots sampled were distributed all over the banana production area in Martinique (Fig. 1) and overall, 1 667 977 *C. sordidus* were captured. The total captured *C. sordidus* decreased with the time after the beginning of fallow with two contrasted dynamics of capture between the trapping patterns (Fig. 3). First, the intercept of the negative exponential curve fitted for the belt trapping pattern was lower for the internal trapping pattern than for the belt trapping pattern (1333 and 1931, respectively). The internal trapping pattern presented a greater decrease compared to the belt trapping pattern with slopes of

Table 3

Part of the AIC explained by each predictor in the generalized linear mixed effect model that predict the number of *C. sordidus* captured. The Δ AIC. corresponds to the variation of AIC with and without the predictors included in the model.

Model	AIC	deltaAIC	percentAIC
Null Model	455889	22514	100.0
−Time	441030	7655	34.0
−Pheromone replacement	435143	1768	7.9
−Trapping pattern	435083	1708	7.6
−Global radiation	434189	814	3.6
−Elevation	434009	634	2.8
−Nebulosity	433843	467	2.1
−Air temperature	433750	375	1.7
−Rainfall	433702	327	1.5
−Wind strength	433452	77	0.3
−Relative air humidity	433398	23	0.1
Global Model	433375	0	0.0
−Random effect	440854	7479	33.2

−0.33 and −0.15, respectively. The captured *C. sordidus* density, at the end of the first month of sanitation, was 59% greater for the internal trapping pattern compared to the belt trapping pattern (2100 ± 278 versus 1323 ± 167). Interestingly, the cumulated captures per trap after 14 months was about 2-times bigger for the internal trapping pattern (409 ± 17) compared to the belt trapping pattern (223 ± 10) (Fig. 4). The total number of *C. sordidus* captured according to the month in the production plots presented a clear difference with those in fallow. The number of *C. sordidus* captured on average per trap in production ranged between 16.9 (±0.4) and 18.8 (±0.5) (in July and March, respectively), while it ranged between 23.2 (±1.3) and 108.0 (±6.2) over all the plots in fallow (in March and July, respectively) (Fig. 5).

All the tested predictors included in the GLMM were significant (Table 2). The time spent in fallow was the most significant predictor, explaining 34% of the variance of captured *C. sordidus* (Table 3). Then by decreasing importance, the pheromone replacement and the trapping pattern explained both near 8% of this variance, then, global radiation, elevation, nebulosity, air temperature and rainfall, explained between 1.5% and 3.6% of this variance. On average the model predicted that internal trapping pattern leads to increasing captures by a factor of 2.75 than belt trapping pattern (Fig. 6A). The pheromone replacement enhanced captures by 12% (Fig. 6B). The sum of rainfall presented a positive relationship with the captures up to an optimum reached at 400 mm of rain. Beyond this threshold, rainfall had a negative effect (Fig. 6C). The maximum wind speed averaged (in other words, the wind force) followed the same type of relationship with an optimal threshold near 8.5 m s^{-1} (Fig. 6E). The abundance of the trapped *C. sordidus* responded positively with the average air temperature, global radiation and elevation (Fig. 6D, G, H). There was a dramatic increase of *C. sordidus* captured above 24 °C and 350 m. In the case of global radiation, the increase begins from 1600 J cm^2 until 2500 J cm^2. Inversely, there was a negative response for the relative humidity and nebulosity (Fig. 6F, I). In the case of relative humidity, there was a regular decrease of the captures between 70 and 100%. Finally, for the nebulosity the relationship strongly decreases between 0 (i.e. clear sky) and 10 and nearly null above 20 of nebulosity.

4. Discussion

4.1. Effect of the trapping pattern of C. sordidus catching

This study showed that the sanitation method based on the internal trapping pattern was more effective than the belt trapping pattern (+83.4% of *C. sordidus* trapped over 1 year). Moreover, thanks to the large dataset analysed, and to the diversity of climates and soil types in Martinique, this study allowed a better understanding of the interaction between trapping efficiency and the pedoclimatic context of a farm. After one year of sanitation, only the internal trapping pattern tended to
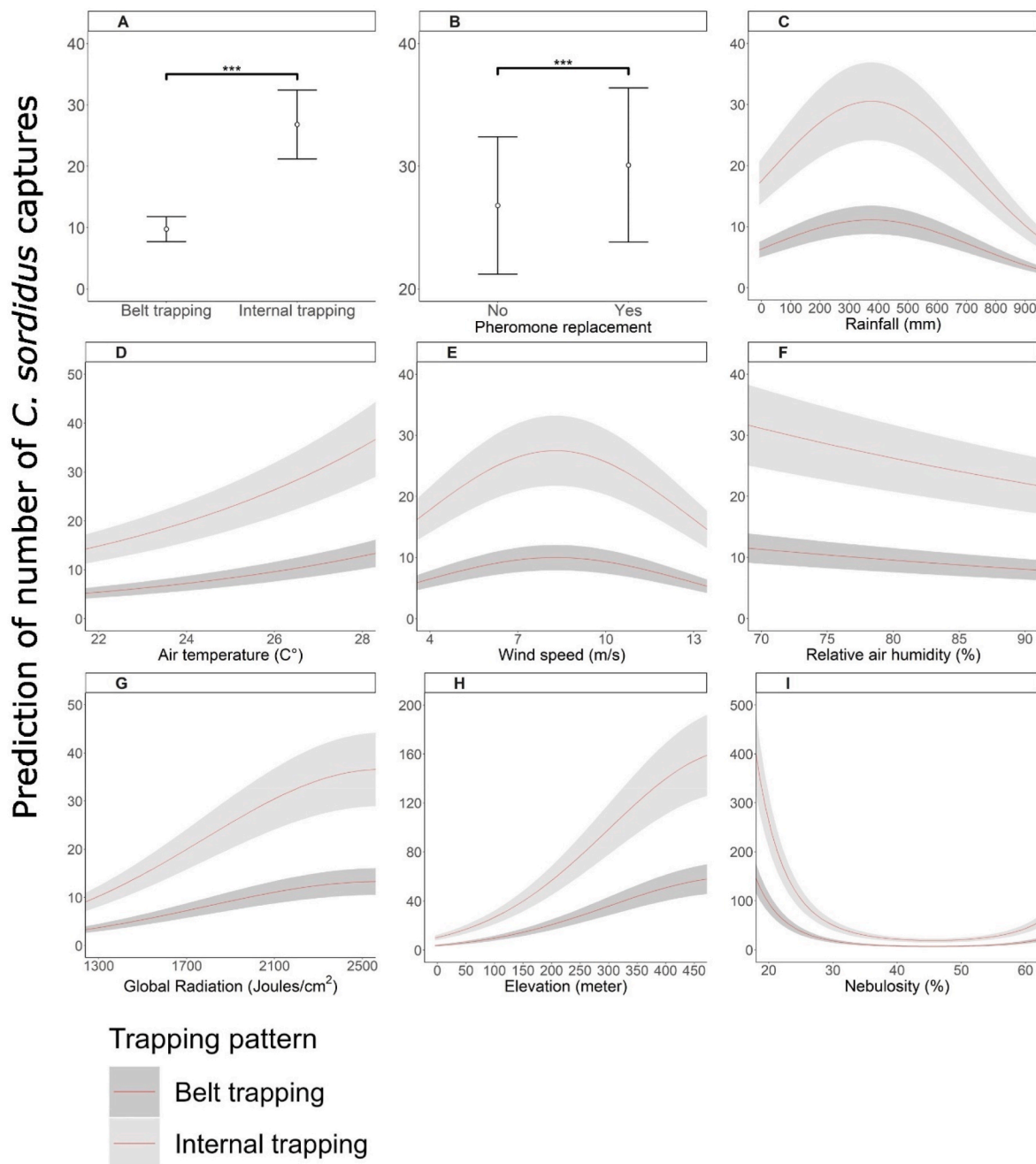
Fig. 6. Predictions of *Cosmopolites sordidus* abundance by the model according to each parameter and each trapping pattern. The grey surfaces show the error associated to the banana farm.

zero capture (3 per hectare and per month) while it was above 250 per hectare for the belt trapping pattern. The slow movements of *C. sordidus*, below 1 m per night on average (Vinatier et al., 2010), and the distance at which *C. sordidus* can locate the sordidin pheromone (Rannestad et al., 2011; Tinzaara et al., 2005), probably explain why the *C. sordidus* located at the centre of fallow plots are less likely to enter in the zone of influence of belt traps. On average, the number of traps per hectare was 35.3 in belt trapping pattern against 16.3 in internal trapping pattern (see distribution in Supplementary 1). The higher trap density in the belt trapping pattern could give rise to more competition between traps and, by extension, to a reduction in the number of captures. Another important result is that trapping in fallows leads to much higher captures than in banana production plots as shown by Duyck et al. (2012) (Fig. 5). This contrast between levels of capture suggests that trapping in

production plots captures only a part of the total population while it seems much higher in fallow plots. This demonstrates the key role of fallow trapping in the long-term farm-scale sanitation strategy.

4.2. Effect of climatic variables

4.2.1. Relation between climatic variables and the biology of C. sordidus

An essential aspect is that the catches of *C. sordidus* are not stable over time. The variability of capture levels over the year shows the importance of taking climatic factors into consideration in order to better understand the effectiveness of trapping. The average air temperature was positively correlated with the number of *C. sordidus* caught. Temperature is known to affect the biological activity of adults and larvae of insects (Birch, 1948; Mellanby, 1939). High temperatures

accelerate the development of *C. sordidus* larvae to the imago stage, reducing hatch times and larval development stages (Schmitt, 1993; Traore et al., 1993, 1996). Moreover, temperature is also known to be a determining factor in the survival and distribution of insects (Chown and Nicolson, 2004). Rainfall is strongly linked to triggering the movement of *C. sordidus* due to its hydrophilic behaviour (Gold et al., 2001). Our results have made it possible to refine the understanding of the relationship between precipitation and number of catches by showing that this relationship is bell-shaped, meaning that if low rainfall had a negative effect on catches, excessive rainfall also had negative effect on catch rates. There was a similar trend for humidity, the higher the humidity, the lower the number of captures. It can be explained by the behaviour of the *C. sordidus*, which tend to become sedentary as the relative humidity of the air increases (Roth and Willis, 1963). The effect of air humidity on the diffusion of the pheromone is also probably at play (see § 4.2.2). We can hypothesize that the positive effect of radiation is consistent with the light avoidance behaviour of the *C. sordidus*, more radiation leading to more movement and therefore more capture (Cuillé, 1950).

In our dataset, captures were achieved at a monthly time step. In future studies, it would be interesting to collect the traps with a smaller time step in order to detect the key moments of movement of *C. sordidus* according to the instantaneous climate.

4.2.2. Relation between climatic variables and the aggregation pheromone
Air humidity and temperature are known to alter the emission rate of the pheromones used in mass trapping of insects (Howse et al., 1998). For example, Leonhardt et al. (1988) showed that the rate of pheromone emission from different commercial products increased with higher temperatures. At most, the pheromone emission rate increased by a factor of 13 for temperatures ranging from 28 to 62 °C. For temperatures ranging from 15 to 25 °C, Van der Kraan and Ebbers (1990) demonstrated that the rate of pheromone emission increased by a factor of 2–2.5. Concerning the humidity of the air, when it increases, the emission rate of the pheromone decreases (Howse et al., 1998). The effect of the different climatic variables integrated into the model on the number of *C. sordidus* captures probably comes from the combination of the effect of climatic factors on the release rate of the pheromone from the bait and the biology of the *C. sordidus*. The wind speed affects the concentration of the pheromone in the air and consequently the perception of the *C. sordidus* (Celani et al., 2014; Suckling et al., 1999). Captures were maximal for wind speed ranging between 7 and 10 m.s-1. For the lowest and highest wind speeds, we can hypothesize that *C. sordidus* has more difficulties to perceive and locate the pheromone baits. However, its effect remains minimal compared to other climatic factors. The sensitivity of the bait to climatic conditions thus explains why its renewal has a positive effect on the number of captures of *C. sordidus*. The use of semiochemicals in the capture of pests requires knowledge of their release rate (Byers, 1988; Heuskin et al., 2011). In future studies it would be interesting to better quantify how climatic factors alter the release rate of the pheromones from the bait.

4.3. Conclusion

This study is one of the first to focus on mass trapping of *Cosmopolites sordidus* in fallows. Our results suggest that trapping efficiency is much higher in fallows than in banana fields. This can be explained by the absence of another source of attractiveness in the field (i.e. banana) that could interfere with the attractiveness of the pheromone bait. Of the two trapping methods tested in fallow, internal fallow trapping was the only strategy that make possible the complete sanitizing of the fallow plots in 12 months. Our results provide the first evidences of the effect of climatic factor on the capture of pheromone baits in fallows and is a plea for more specialized research in chemical ecology.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cropro.2023.106501.

References

Akaike, H., 1974. A new look at the statistical model identification. IEEE Trans. Automat. Control 19, 716–723. https://doi.org/10.1109/TAC.1974.1100705.

Akello, J., Dubois, T., Gold, C.S., Coyne, D., Nakavuma, J., Paparu, P., 2007. *Beauveria bassiana* (Balsamo) Vuillemin as an endophyte in tissue culture banana (Musa spp.). J. Invertebr. Pathol. 96, 34–42. https://doi.org/10.1016/j.jip.2007.02.004.

Alpizar, D., Fallas, M., Oehlschlager, A.C., Gonzalez, L.M., 2012. Management of *Cosmopolites sordidus* and *Metamasius hemipterus* in banana by pheromone-based mass trapping. J. Chem. Ecol. 38, 245–252. https://doi.org/10.1007/s10886-012-0091-0.

Arruda, L.S., Rolim, G.G., Barros, E.M., Pereira, F.F., Torres, J.B., 2020. Colonization and spatial distribution of boll weevil in commercial Cotton fields. Neotrop. Entomol. 49, 901–915. https://doi.org/10.1007/s13744-020-00813-7.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Software 67, 1–48. https://doi.org/10.18637/jss.v067.i01.

Beauhaire, J., Ducrot, P.-H., Malosse, C., Rochat, D., Ndiege, I.O., Otieno, D.O., 1995. Identification and synthesis of sordidin, a male pheromone emitted by *Cosmopolites sordidus*. Tetrahedron Lett. 36, 1043–1046. https://doi.org/10.1016/0040-4039(94)02437-G.

Birch, L.C., 1948. The intrinsic rate of natural increase of an insect population. J. Anim. Ecol. 17, 15. https://doi.org/10.2307/1605.

Bolker, B.M., Brooks, M.E., Clark, C.J., Geange, S.W., Poulsen, J.R., Stevens, M.H.H., White, J.-S.S., 2009. Generalized linear mixed models: a practical guide for ecology and evolution. Trends Ecol. Evol. 24, 127–135. https://doi.org/10.1016/j.tree.2008.10.008.

Budenberg, W.J., Ndiege, I.O., Karago, F.W., 1993. Evidence for volatile male-produced pheromone in banana weevil *Cosmopolites sordidus*. J. Chem. Ecol. 19, 1905–1916. https://doi.org/10.1007/BF00983795.

Byers, J.A., 1988. Novel diffusion-dilution method for release of semiochemicals: testing pheromone component ratios on western pine beetle. J. Chem. Ecol. 14, 199–212. https://doi.org/10.1007/BF01022542.

Carval, D., Perrin, B., Duyck, P., Tixier, P., 2015. Local and neighboring patch conditions alter sex-specific movement in banana weevils. Ecol. Evol. 5, 5735–5743. https://doi.org/10.1002/ece3.1818.

Celani, A., Villermaux, E., Vergassola, M., 2014. Odor landscapes in turbulent environments. Phys. Rev. X 4, 041015. https://doi.org/10.1103/PhysRevX.4.041015.

Chabrier, C., Tixier, P., Duyck, P.-F., Carles, C., Quénéhervé, P., 2010. Factors influencing the survivorship of the burrowing nematode, *Radopholus similis* (Cobb.) Thorne in two types of soil from banana plantations in Martinique. Appl. Soil Ecol. 44, 116–123. https://doi.org/10.1016/j.apsoil.2009.10.005.

Chown, S., Nicolson, S.W., 2004. Insect Physiological Ecology: Mechanisms and Patterns. Oxford University Press, Oxford ; New York.

Côte, F.X., Abadie, C., Achard, R., Cattan, P., Chabrier, C., Dorel, M., de Lapeyre de Bellaire, L., Risède, J.M., Salmon, F., Tixier, P., 2009. Integrated pest management approaches developed in the French West Indies to reduce pesticide use in banana production systems. Acta Hortic. 375–382. https://doi.org/10.17660/ActaHortic.2009.828.38.

Cuillé, J., 1950. Recherches sur le Charançon du Bananier *Cosmopolites sordidus*, Germar: Monographie de l'insecte et Recherche de ses Chimiotropismes., IFAC Série. In: Société D'éditions Techniques Coloniales. Paris, France.

Duyck, P.-F., Dortel, E., Vinatier, F., Gaujoux, E., Carval, D., Tixier, P., 2012. Effect of environment and fallow period on *Cosmopolites sordidus* population dynamics at the landscape scale. Bull. Entomol. Res. 102, 583–588. https://doi.org/10.1017/S0007485312000089.

Fu, B., Li, Q., Qiu, H., Tang, L., Zhang, X., Liu, K., 2019. Evaluation of different trapping systems for the banana weevils *Cosmopolites sordidus* and *Odoiporus longicollis*. Int. J. Trop. Insect Sci. 39, 35–43. https://doi.org/10.1007/s42690-019-00009-6.

Gold, C.S., Messiaen, S., 2000. Le charançon du bananier *Cosmopolites sordidus*. Parasites et ravageurs de Musa. Infomusa 6, 19–21.

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 Manag. Rev. 6, 79–155. https://doi.org/10.1023/A:1023330900707.

Heuskin, S., Verheggen, F.J., Haubruge, E., Wathelet, J.-P., Lognay, G., 2011. The use of semiochemical slow-release devices in integrated pest management strategies. In: Biotechnology. Agronomy, Society and Environment.

Howse, P.E., Stevens, I.D.R., Jones, O.T., 1998. Insect Pheromones and Their Use in Pest Management. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-011-5344-7.

Leonhardt, B.A., Dickerson, W.A., Ridgway, R.L., Devilbiss, E.D., 1988. Laboratory and field evaluation of controlled release dispensers containing Grandlure, the pheromone of the boll weevil (Coleoptera: Curculionidae). J. Econ. Entomol. 81, 937–943. https://doi.org/10.1093/jee/81.3.937.

Lopes, R.B., Laumann, R.A., Moore, D., Oliveira, M.W.M., Faria, M., 2014. Combination of the fungus *Beauveria bassiana* and pheromone in an attract-and-kill strategy against the banana weevil, *Cosmopolites sordidus*. Entomol. Exp. Appl. 151, 75–85. https://doi.org/10.1111/eea.12171.

Lopes, R.B., Michereff-Filho, M., Tigano, M.S., 2011. Virulence and horizontal transmission of selected Brazilian strains of *Beauveria bassiana* against *Cosmopolites sordidus* under laboratory conditions. Bull. Insectol. 64, 201–208.

Lozano-Soria, A., Picciotti, U., Lopez-Moya, F., Lopez-Cepero, J., Porcelli, F., Lopez-Llorca, L.V., 2020. Volatile organic compounds from entomopathogenic and nematophagous fungi, repel banana black weevil (*Cosmopolites sordidus*). Insects 11. https://doi.org/10.3390/insects11080509.

Mellanby, K., 1939. Low temperature and insect activity. Proc. R. Soc. Lond. B 127, 473–487. https://doi.org/10.1098/rspb.1939.0035.

Montgomery, D., Peck, E., 1992. Introduction to Linear Regression Analysis. Wiley, New York, USA.

Negrete González, D., Ávalos Chávez, M.A., Lezama Gutiérrez, R., Chan Cupul, W., Molina Ochoa, J., Galindo Velasco, E., 2018. Suitability of *Cordyceps bassiana* and *Metarhizium anisopliae* for biological control of *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) in an organic Mexican banana plantation: laboratory and field trials. J. Plant Dis. Prot. 125, 73–81. https://doi.org/10.1007/s41348-017-0126-4.

Poeydebat, C., Tixier, P., De Lapeyre De Bellaire, L., Carval, D., 2017. Plant richness enhances banana weevil regulation in a tropical agroecosystem by affecting a multitrophic food web. Biol. Control 114, 125–132. https://doi.org/10.1016/j.biocontrol.2017.08.009.

R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Rannestad, O.T., Saethre, M.-G., Maerere, A.P., 2011. Migration potential of the banana weevil *Cosmopolites sordidus*. Agric. For. Entomol. 13, 405–412. https://doi.org/10.1111/j.1461-9563.2011.00535.x.

Rhino, B., Dorel, M., Tixier, P., Risède, J.-M., 2010. Effect of fallows on population dynamics of *Cosmopolites sordidus* : toward integrated management of banana fields with pheromone mass trapping. Agric. For. Entomol. 12, 195–202. https://doi.org/10.1111/j.1461-9563.2009.00468.x.

Risède, J.-M., Achard, R., Brat, P., Chabrier, C., Damour, G., Guillermet, C., De Lapeyre de Bellaire, L., Lǿeillet, D., Lakhia, S., Meynard, C., 2019. The agroecological

transition of Cavendish banana cropping systems in the French West Indies, 2019. In: Côte, F.-X., Poirier-Magona, E., Perret, S., Rapidel, B., Roudier, P., Thirion, M.-C. (Eds.), The Agroecological Transition of Agricultural Systems in the Global South, Agricultures et Défis Du Monde Collection, AFD, CIRAD, Éditions Quæ, Versailles, p. 360. Quae.

Roth, L.M., Willis, E.R., 1963. The humidity behavior of *Cosmopolites sordidus* (Coleoptera: Curculionidae). Ann. Entomol. Soc. Am. 56, 41–52. https://doi.org/10.1093/aesa/56.1.41.

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 Protect. 17, 581–589. https://doi.org/10.1016/S0261-2194(98)00056-8.

Rull, J., Prokopy, R.J., 2003. Trap position and fruit presence affect visual responses of apple maggot flies (Dipt., Tephritidae) to different trap types. J. Appl. Entomol. 127, 85–90. https://doi.org/10.1046/j.1439-0418.2003.00700.x.

Rusch, A., Valantin-Morison, M., Sarthou, J.-P., Roger-Estrade, J., 2010. Biological control of insect pests in agroecosystems. In: Advances in Agronomy. Elsevier, pp. 219–259. https://doi.org/10.1016/B978-0-12-385040-9.00006-2.

Sakamoto, Y., Ishiguro, M., Kitagawa, G., 1986. Akaike Information Criterion Statistics, vol. 81. D. Reidel, Dordrecht, The Netherlands.

Schmitt, A.T., 1993. Biological Control of the Banana Weevil (*Cosmopolites sordidus* (Germar)) with Entomopatogenic Nematodes. (PhD Thesis). University of Reading.

Schumm, Z.R., Alston, D.G., Spears, L.R., 2021. Behavior of the Brown Marmorated Stink Bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), in the Utah agricultural landscape based on trap captures and visual sampling studies. Proc. Entomol. Soc. Wash. 123 https://doi.org/10.4289/0013-8797.123.1.206.

Suckling, D.M., Green, S.R., Gibb, A.R., Karg, G., 1999. Predicting atmospheric concentration of pheromone in treated apple orchards. J. Chem. Ecol. 25, 117–139. https://doi.org/10.1023/A:1020893201446.

Tinzaara, W., Gold, Clifford S., Dicke, M., Van Huis, A., Nankinga, C.M., Kagezi, G.H., Ragama, P.E., 2007. The use of aggregation pheromone to enhance dissemination of *Beauveria bassiana* for the control of the banana weevil in Uganda. Biocontrol Sci. Technol. 17, 111–124. https://doi.org/10.1080/09583150600937089.

Tinzaara, W., Gold, C.S., Dicke, M., Van Huis, A., Ragama, P.E., 2005. Factors influencing pheromone trap effectiveness in attracting the banana weevil, *Cosmopolites sordidus*. Int. J. Pest Manag. 51, 281–288. https://doi.org/10.1080/09670870500337759.

Tixier, P., Malezieux, E., Dorel, M., 2004. SIMBA-POP: a cohort population model for long-term simulation of banana crop harvest. Ecol. Model. 180, 407–417. https://doi.org/10.1016/j.ecolmodel.2004.04.028.

Traore, L., Gold, C., Pilon, J., Boivin, G., 1993. Effects of temperature on embryonic development of banana weevil *Cosmopolites sordidus* (Germar). Afr. Crop Sci. J. 1 https://doi.org/10.4314/acsj.v1i2.69898.

Traore, L., Gold, C.S., Boivin, G., Pilon, J., others, 1996. Développement postembryonnaire du charançon du bananier, *Cosmopolites sordidus*. Fruits 51, 105–113.

Tresson, P., Tixier, P., Puech, W., Carval, D., 2021. The challenge of biological control of *Cosmopolites sordidus* Germar (Col. Curculionidae): a review. J. Appl. Entomol. 145, 171–181. https://doi.org/10.1111/jen.12868.

Uzakah, R., 1995. The Reproductive Biology, Behaviour and Pheromones of the Banana Weevil, *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae) (PhD Thesis). Ph. D. Dissertation. University of Ibadan, Nigeria.

Van der Kraan, C., Ebbers, A., 1990. Release rates of tetradecen-1-ol acetates from polymeric formulations in relation to temperature and air velocity. J. Chem. Ecol. 16, 1041–1058. https://doi.org/10.1007/BF01021009.

Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S, Fourth. Springer, New York.

Vinatier, F., Chailleux, A., Duyck, P.-F., Salmon, F., Lescourret, F., Tixier, P., 2010. Radiotelemetry unravels movements of a walking insect species in heterogeneous environments. Anim. Behav. 80, 221–229. https://doi.org/10.1016/j.anbehav.2010.04.022.