Research Article

Stop me if you can: quantification of the effect of interfaces between plots on the dispersal of *Cosmopolites sordidus*

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Abstract

BACKGROUND: *Cosmopolites sordidus* **is one of the most damaging pests of banana worldwide. To date, most studies have addressed the control of this pest at the plot level, without considering the landscape scale, whereas between plots dispersion could be important. The aim of this study was to investigate the ability of** *C. sordidus* **to cross contrasted field interfaces. The 10 following interfaces were investigated: forests, hedgerows, field tracks, grassy areas, finely and coarsely tilled soil zones, ditches with and without water, vegetable gardening zones, and pheromone trap lines. Individually marked weevils were released on one side of the interface and recovered daily on the other side, allowing the estimation of the velocity and the crossing success of** *C. sordidus* **for each interface.**

RESULTS: Highest permeabilities (with a crossing success above 70%) were obtained for vegetable gardening zones, finely tilled soil zones, forests, and coarsely tilled soil zones. Intermediate permeabilities were measured for hedgerows, field tracks, grassy areas, and ditches without water. Only the line of pheromone traps and submerged ditches had a strong barrier effect on *C. sordidus*, **with a crossing success below 12%. Wind strength, percentage of sky, and vegetation height were negatively correlated to the** *C. sordidus* **crossing success.**

CONCLUSION: Overall, our results showed that only ditches with water and lines of pheromone traps were efficient in stopping the dispersal of *C. sordidus*. **The next step will be to conduct research to incorporate the use of these two interfaces at farm and landscape scale into integrated pest management strategies.**
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Keywords: banana weevil; landscape ecology; hedgerows; insect movement; pheromone traps

Pests cause important yield losses on major crops (wheat, rice, maize, potatoes, soybeans and cotton), representing 11% on average worldwide.[1] In the 1960s, there was a dramatic increase in insecticide applications, which quickly became the primary means of controlling insect pests. However, the impact of these products on the environment and human health[2] now required the development respectful and sustainable practices. Recently, Deguine *et al.* (2023) proposed that agroecological crop protection should combine prophylactic practices, conservation of biodiversity to sustain ecological regulations, and soil preservation.[3] Prophylactic practices include the removal of pest individuals, for example, by trapping or removing parts of the crops that host these pests. Physical protection of fields or of crops is a means to limit pest foraging by making it hostile or inaccessible to insect pests. Such an approach was successfully applied to protect plants from flying insects, for example, *Cydia pomonella* on apple orchards[4] and *Lepidoptera* on cabbage and tomato.[5,6] To date, there has been little attention paid to the role of natural interfaces in the limitation of the dispersal of pests. Inversely there have been trends to remove semi-natural habitats to facilitate the use of modern agricultural machinery or to convert them

into new crops.[7] Installing new physical barriers may require significant investment for farmers.[8] For this reason, it is important to optimize existing landscape elements to minimize the dispersal of insect pests. The role of the landscape on the dynamic of insects has been extensively addressed in landscape ecology.[9–12] While the role of connectivity between habitats has often been addressed, for instance Aviron *et al.* (2018) showed that the connectivity of annual crops at a scale of 500 m is positively correlated with the abundance of *Carabidae*

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species, the barrier effect of some elements were more scarcely studied separately.[13] This may be because studies that rely on correlations between landscape metrics and organism abundances are not well-suited for uncovering directional processes. The barrier effect is also suggested to be important in the case of disease dispersal.[14,15]

Cosmopolites sordidus (Germar, 1824) (Coleoptera: Curculionidae) is the main pest of *Musa* and *Ensete*.[16] It can lead to significant yield losses of up to 40% in the 3rd cycle.[17] Females of *C. sordidus* lay their eggs on the corm of the banana plant. After hatching, the larvae create tunnels within the corm, limiting the plant's intake of water and nutrients. In severe cases, the entire banana plant can topple over.[16] *Cosmopolites sordidus* exhibits a K-type strategy, that is a long lifespan of 1 to 4 years with a low reproductive rate (1 to 2 eggs per week).[18] It is a cryptic species living in soil litter and with a diet specific to the *Musa* genus.[16] It has gregarious behavior, with males producing a pheromone that attract both sexes.[19] It exhibits strong positive hygrotropism, negative phototropism,[16] and is active during the night.[20–22]

Cosmopolites sordidus is recognized as a species with a low dispersal ability almost exclusively by crawling. In banana plantation conditions, *C. sordidus* presents a restricted search area.[23] A detailed analysis of its movement, carried out by Vinatier *et al.* (2010) using RFID technology (Radio Frequency Identification), concluded that its average distance of movement is 0.5 m per night (keeping only the period of activity) with a maximum of 9 m per night.[24] Furthermore, when the living environment of *C. sordidus* is disturbed, such as when banana plants are destroyed, a large part of the *C. sordidus* population disperses to neighboring plots seeking new host plants, this population dispersal could be deduced when captures in neighboring banana plots increases.[25] The elements present at the interface between plots could thus act as a limitation to the colonization of plots that were previously sanitized. A modeling study suggested that *C. sordidus* should be less abundant in landscapes with greater fragmentation.[26] Very few data from the field exist on the role of interfaces between plots on the dispersal of this pest. Vinatier *et al.* (2010) found that individuals turned around once they reached the edge of the plots surrounded by deep ditches.[24] Wallace (1938) observed that only a few individuals crossed grass strips that were 4 to 10 m wide.[27] These results suggest that linear elements of the landscape can act as barriers, but to date no experimental data support this hypothesis. Effective barriers would be a crucial element in an integrative management strategy for control of this pest.

The monitoring of insect dispersal remains challenging. It can be achieved at larger scales using genetic markers, as it was successfully achieved for aerial pathogens.[28] At smaller scales, mark-recapture methods make it possible to differentiate individuals from the rest of the population. Hagler and Jackson (2001) presented different methods: sticking on tags, mutilating the individual, marking with hinges or ink, or even the use of fluorescent powder.[29] More precise methods such as the RFID technology, as used in the study by Vinatier *et al.* (2010), allowed multiple measurements of the position of each individual, thus offering more details on trajectories.[24] However, RFID radiotracking is complex to apply to large populations and is labor intensive. In the situation where individuals can easily be re-captured by trapping (as in the case of *C. sordidus* with pheromone traps), classical mark-recapture methods are particularly suitable to assess the dispersal of an insect between a release point and a trap.

In this study, we used a classical mark-recapture approach to investigate the ability of *C. sordidus* to cross contrasting interfaces. Our experimental design consisted of releasing individually marked *C. sordidus* on one side of a given interface and recovering them daily on the other side using pitfall traps baited with an attractive lure. We tested 10 different interfaces, including the main landscape elements found in Martinique. For each interface, we examined the velocity and crossing success of 60 *C. sordidus* over a 2-week period. We also characterized the interfaces and recorded weather factors to improve our understanding of their effects on the movement of *C. sordidus*.

MATERIALS AND METHODS

Experimental sites
Experiments were carried-out in Martinique (Lesser Antilles) in two locations: the CIRAD research station of Rivière-Lézarde, Saint-Joseph (14°39′45″ N, 60°59′56″ W) and the CIRAD research station and its surroundings in Petit Morne, Lamentin (14°37′4″ N, 60°58′44″ W). The experiment took place between April and June 2022. In the Petit Morne site, the average temperature was 26.8 °C and the monthly rainfall ranged between 49 and 210 mm in April and June, respectively. In the Rivière-Lézarde site, the average temperature was 25.8 °C and the monthly rainfall ranged between 66 and 262 mm in April and June, respectively. The two stations are both located at similar altitudes below 50 m above sea level. These two sites, which are representative of banana production areas of Martinique, were not directly surrounded by banana farms and included the interfaces to be tested. Ten interfaces were tested (with 3 to 13 replicates per interface) including field tracks, hedgerows, grassy areas, finely and coarsely tilled soil zones, ditches with and without water, forests, vegetable gardening zones, and a line of pheromone traps with a trap every meter (Fig. 1).

The experimental set up
Each of the 49 experiments were carried out in a 6 × 10 m area including the tested interface (Fig. 2). On one side, three pitfall traps (yellow color, 216 mm high, including 100 mm buried and inner diameter of 148 mm, Arysta Lifescience) baited with the sordidin aggregation pheromone (Cosmoplus®, Scyll'Agro, Hastingues, France) were placed 3 m from the edge of the interface to assess and with 2 m between them. To optimize the diffusion of the pheromone, the pheromone traps were placed upwind of the prevailing winds (east to west). On the other side, 60 marked *C. sordidus* individuals were placed (six meters away from the pheromone traps). This distance was chosen to remain in the area of attraction of the pheromone traps.[30] Each individual was marked with a unique queen bee marking dot (color and number using the Thorne queen marking kit®, Thomas apiculture marking kit, France). The dots were glued to the back of *C. sordidus* to not disturb its movements. The marked individuals were released at the end of the afternoon to prevent the risk of desiccation and predation (especially by birds). They were released in a line of 3 m, with a distance of 5 cm between each one. A new pheromone lure was placed in each trap just before *C. sordidus* release. The individuals having reached the traps were monitored daily over a period of 14 days. Before setting up their main experiments on the movement of *C. sordidus*, Vinatier *et al.* (2010) verified
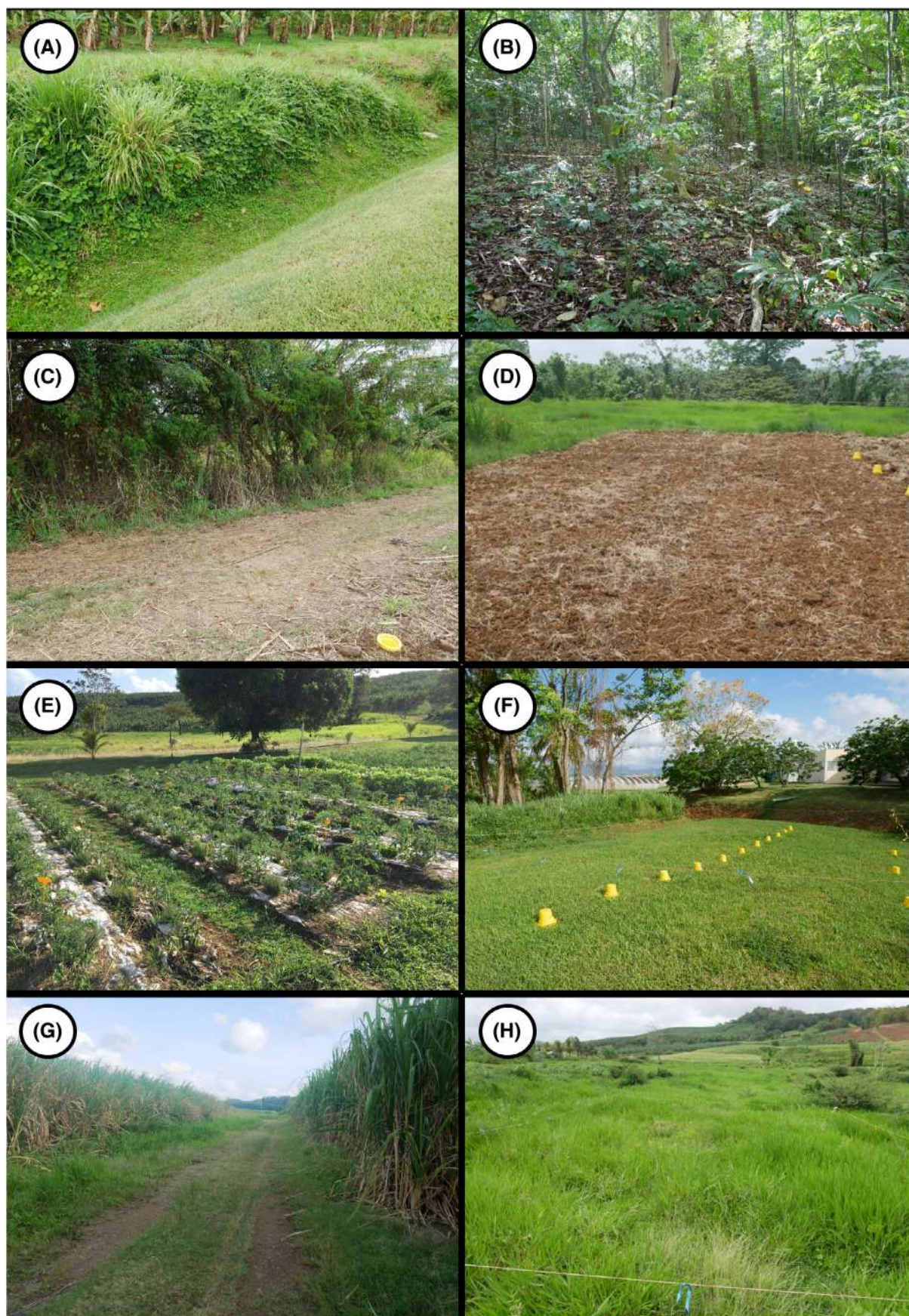
Figure 1. Pictures showing eight tested interfaces: ditch without water (A), forest (B), hedgerow (C), tilled soil zone (D), vegetable gardening zone (E), line of pheromone traps (F), field track (G) and grassy area (H).
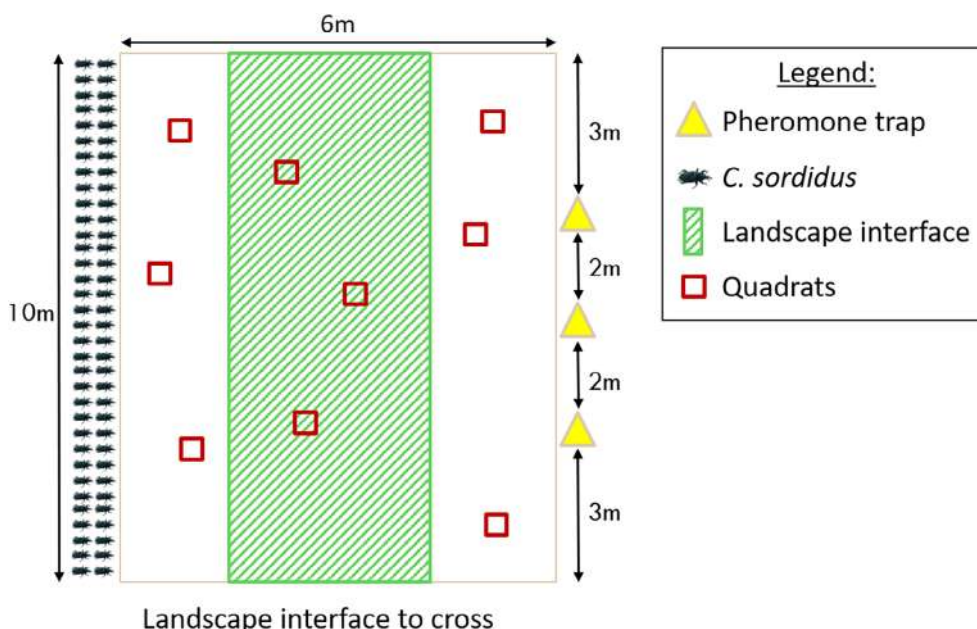
Figure 2. Illustrating of the experimental design used to test the influence of an interface (hatched green) on the dispersal of *Cosmopolites sordidus* (left) towards pheromone traps (yellow triangles on the right). Red squares represent quadrats used to characterize the plant community.

that the weight of RFID chips did not influence their speed of movement.[24] Since our tags are much smaller than RFID tags, we hypothesized that they also had no influence. In total, 2940 *C. sordidus* were marked and released. There were three repetitions for the following treatments: finely tilled soil zones, coarsely tilled soil zones, ditches with and without water, forests, vegetable gardening zones, and the pheromone trap lines. Field tracks were repeated six times, hedgerows nine times and the grassy areas 13 times. This resulted in a total of 49 independent experiments. To limit the interference between the experiments, a minimum distance of 50 m was left between each one.

Characterization of the interfaces

Each landscape interface was characterized with 25 × 25 cm quadrats to quantify the plant community and with pictures to quantify the tree stratum. According to the heterogeneity of the studied area, four to nine quadrats were measured. For each quadrat, a visual estimate, was made to characterize the relative presence of three elements: living vegetation, dead debris (litter) and bare soil, it was then translated into a percentage of cover. These recovery percentages were inspired by the Domin scale,[31] in our case, the sum of the recovery of these elements was equal to 100%. Within the quadrats, the height of the grass was measured three times with a graduated ruler. Moreover, for each experimental zone with a tree stratum (hedgerows and forests), hemispherical pictures of the sky were taken at 56.5 cm above the ground using a Lumix® camera (DC-GX800K model, 12–32 mm, F3.5-5.6) and a KamLan® lens (7.5 mm, F3.2). Three pictures were made for each subzone or zone at the same height. The pictures of the sky taken with the hemispherical lens were then analyzed with the ImageJ program[32] for calculating the percentage of sky on each picture. We estimated the roughness of finely and coarsely tilled soil interfaces by measuring the length between the two tips of a

1.40 m bike chain when disposed on the ground in order to follow the soil surface. The distance between the two tips of the chain was reduced according to the soil profile. Then the ratio between this measure and the full length of the bike chain was calculated (Fig. S1). A ratio close to one indicates a soil with fine structure (with small aggregates and few holes), while a small ratio indicates that the soil was rough (with larger aggregates and more holes). This method was replicated five times for each type of soil and each replicate. All the measures taken to describe the interfaces are summarized in Table S1. The weather factors during the experimental period were collected from the meteorological stations of Météo-France Martinique (ST-JOSEPH LEZARD and LAMENTIN-AERO stations). The daily rainfall, air temperature, wind strength and relative humidity were integrated during the 14 days of each experiment by averaging them, except for the rainfall that was cumulated.

Analysis methods

To analyze the cumulated number of recaptured *C. sordidus* for each type of interface, we used a Verhulst model, with the following formula:

$$\frac{dN}{dt} = N \times a \times \left(1 - \frac{N}{K}\right)$$

with N, the number of individuals captured each day; 'a', the number of *C. sordidus* having crossed the 6-m interface per day, which estimates the velocity of *C. sordidus*; and 'K', the number of individuals having succeeded in crossing the interface in 14 days (maximal value being 60 that was the number of *C. sordidus* released). The Verhulst model was fitted using the function 'ode' from the package 'deSolve'.[33] Parameters 'a' and 'K' were estimated with the 'nls' function provided by the 'stats' package. Therefore, we used linear models to evaluate the relation between the estimated parameters 'a' and 'K' and the measured

environmental factors: rainfall, air temperature, relative humidity, wind strength, the percentage of vegetation covering, the height of the grass, and the percentage of sky. We performed a variance inflation factor (VIF) to check that there was no collinearity between predictors.[34] Relative humidity, air temperature and wind strength were highly correlated factors, so we included them separately in the model. Wind strength turned out to be a more significant predictor to explain the velocity '*a*' and the success of the crossing '*K*'; only this factor was retained in the final model. Subsequently, we standardized all factors in order to make them easily comparable on a same 'scale'. A backward selection was achieved to build a complete model. We graphically checked the normality of the residuals of the model. The linear models were fitted using the 'lm' function in the 'stats' package of R 4.2.0. In all analyses we used an alpha level of 0.05.

RESULTS

Movement of weevil across different landscape interfaces

For each experiment, over the 60 weevils release, between 1 and 56 *C. sordidus* were recaptured. Even if the experiments lasted 14 days, most of the captures occurred in the first 4 to 5 days after weevils were released (Fig. 3). There were very contrasting recapture rates between treatments (Fig. 3): the vegetable gardening zones were the interfaces with the highest recapture rate (88%) while the ditches with water and the line of pheromone traps were the interfaces with the lowest recapture rate (11% and 7%, respectively). The majority of the interfaces led to high crossing success for *C. sordidus* (with the '*K*' parameters ranging from 28 ± 4.8 to 49 ± 2.8) with the exception of the ditches with water and the line of pheromone traps (with the '*K*' parameters equal to 7 ± 3.3 and 6 ± 0.69, respectively) (Fig. 4(B)). We distinguished
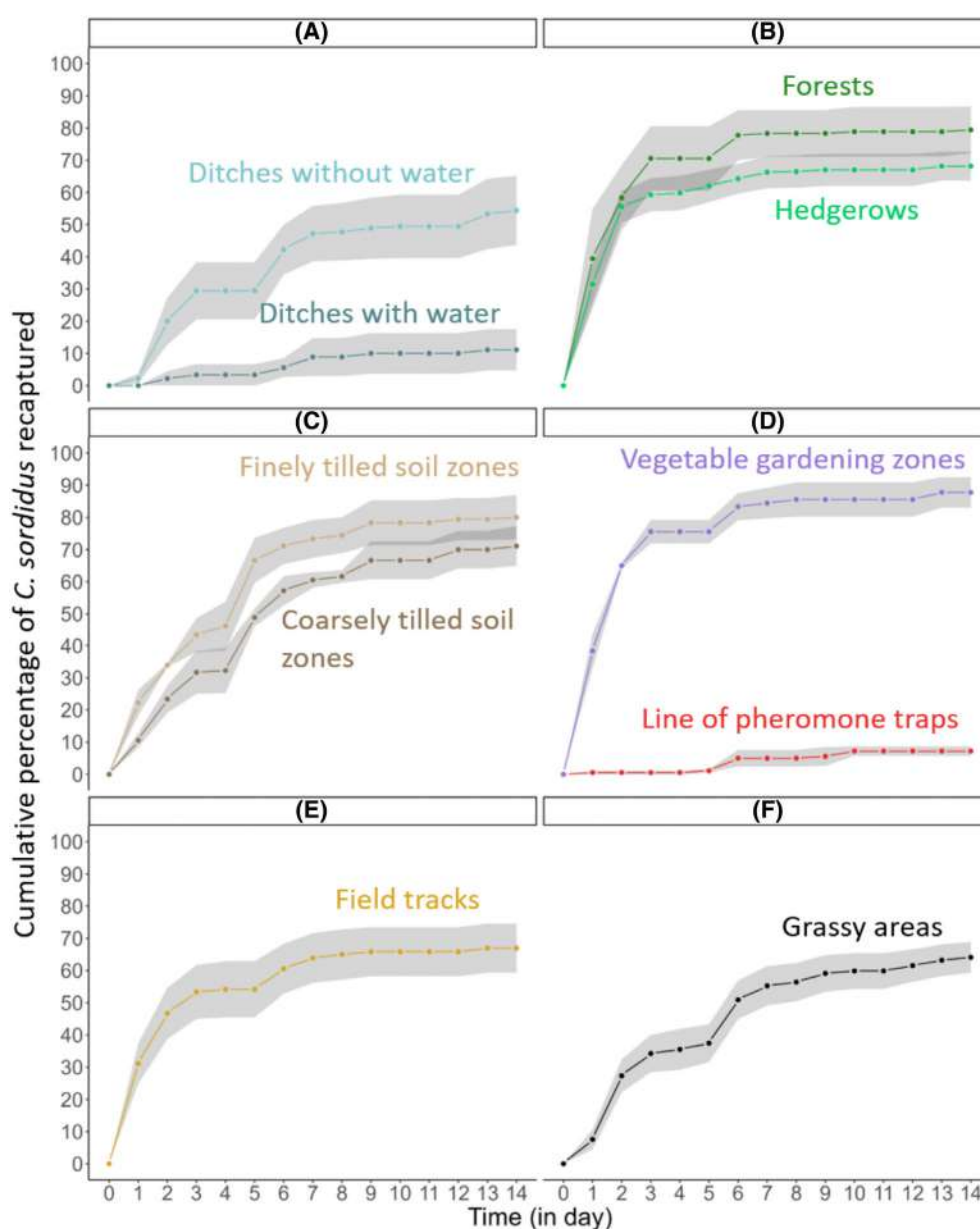

Figure 3. Cumulative percentage (mean ± se) of *Cosmopolites sordidus* caught in pheromone traps, for the 10 tested interfaces over the 14 days following the insect release.
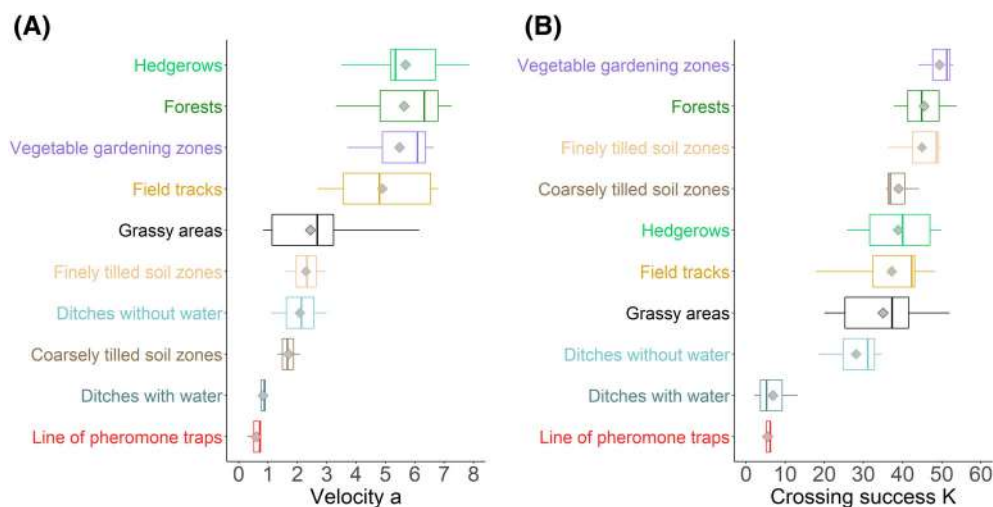
Figure 4. Distribution of the estimates of the parameters of the Verhulst model corresponding to the velocity '*a*' (A) and the crossing success '*K*' (B) according to the tested interfaces. The grey diamonds show the mean value.

three groups of interfaces according to their velocity. First, the hedgerows, forests, vegetable gardening zones and field tracks were the environments that were crossed the fastest (with the '*a*' parameter ranging from 4.89 ± 0.73 to 5.68 ± 0.46). Then, an intermediate group containing the grassy areas, ditches without water, and tillage zones both fine and coarse (with the '*a*' parameter ranging from 1.69 ± 0.22 to 2.44 ± 0.44) (Fig. 4(A)). Finally, ditches with water and the lines of pheromone traps that exhibited the slowest velocity '*a*' were 0.83 ± 0.09 and 0.6 ± 0.15, respectively (Fig. 4(A)).

Description of characteristics of interfaces

The grassy areas, the line of pheromone traps, the field tracks and the ditches with and without water were characterized by a strong presence of vegetation with little or no soil litter. Among these four interfaces, the field tracks showed more bare soil and a lower height of vegetation, on average 10 ± 3 cm while it ranged between 26.6 ± 11.8 cm and 34 ± 6.5 cm for the other three ones. Tilled soil zones were characterized by bare soil with more debris found in coarsely tilled soil zones, 50.9% on average *versus* 19.6% for finely tilled soil areas. The market gardening zones were unsurprisingly highly artificial interfaces with no litter and alternatively bare soil, grass regrowth and rows of cultivated plants. Forests and hedgerows were special because they were the only ones to

have shrub and tree strata, exhibiting low percentages of visible sky (respectively 11.5% and 46.2% on average). Forests were characterized by a strong percentage of soil litter (96.3% on average). The hedgerows were the combination of a line of trees and shrubs, with a dense low stratum (38.9 ± 11.6 cm for the herbaceous layer) and with an abundant soil litter (51.3% on average) (Table S1). For the ditches and tilled soil zones interfaces, we tested independently the response of '*K*' and '*a*' to the presence of water and the type of tillage (coarse vs. fine), respectively. Interestingly, the crossing success '*K*' was significantly altered by the presence of water in ditches (*P* value = 0.0224). While velocity '*a*' and crossing success '*K*' were higher in the case of fine tillage interfaces compared to coarse tillage interfaces, these differences were not significant ($P = 0.3377$ and $P = 0.6003$, respectively).

Relationships between movement and characteristics of interfaces

Interface characteristics and meteorological data that showed significant effects on '*a*' and '*K*' and that were kept in the final model are presented in Table 1. The number of *C. sordidus* having crossed the interfaces ('*K*') was significantly and negatively affected by wind strength, vegetation height, and percentage of sky (Fig. 5). The standardized estimate of the percentage of sky was higher than those of the height of vegetation and the strength of the wind. The velocity of *C. sordidus* '*a*' was

Table 1. Estimates of predictors and statistics of the linear models for the velocity (*a*) and the crossing success (*K*)

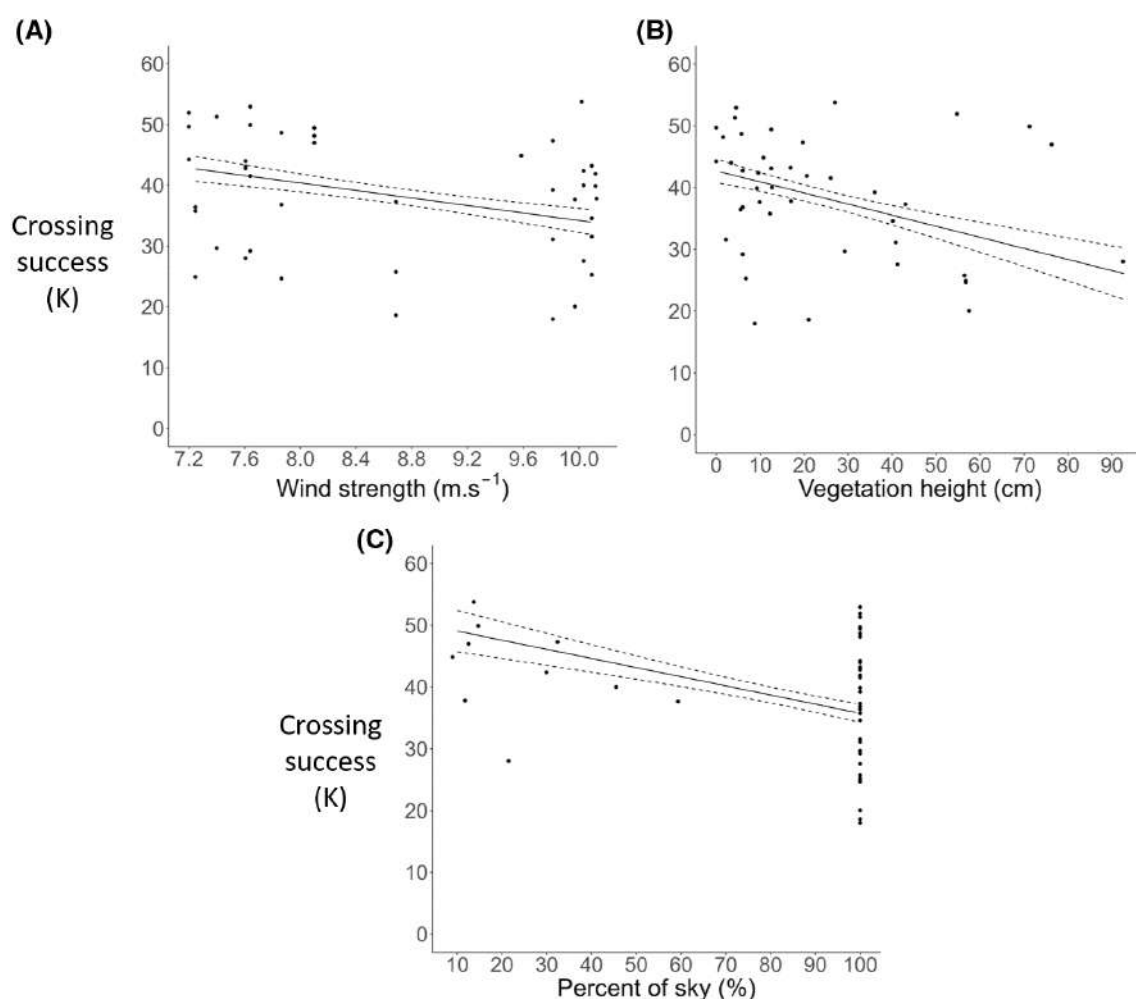| Response variable	Predictors	Estimate	Sum of square	df	*F*-value	*P*-value
Crossing success (*K*)	Intercept	38.33	63 175.46	1	895.06	<0.0001
	Wind strength	−3.64	513.13	1	7.27	0.0103
	Vegetation height	−4.22	672.09	1	9.52	0.0037
	Percent of sky	−4.88	842.25	1	11.93	0.0013
Velocity (*a*)	Intercept	3.81	623.33	1	191.26	<0.0001
	Rainfall	−0.66	18.11	1	5.56	0.0234
	Percent of sky	−0.94	37.10	1	11.38	0.0017

Figure 5. Crossing success '*K*' of tested interfaces by *Cosmopolites sordidus*, as estimated for each experiment with the Verhulst model, according to the average wind speed measured during each experiment (A), the vegetation height (grass strata) measured for each experiment (B), and the percentage of sky measure with hemispheric pictures (C). Solid lines show the fit of the linear models and dashed lines show their standard errors (see Table 1 for details of statistical models).

significantly and negatively affected by rainfall and the percentage of sky (Table 1, Fig. 6). The standardized estimate was higher for the percentage of sky than for the rainfall. Finally, it turned out that relative humidity and percentage of vegetation did not significantly alter the velocity '*a*' and the crossing success '*K*'.

DISCUSSION

The interfaces exhibited very contrasting effects on the crossing capacity of *C. sordidus*. Hedgerows, forests, vegetable gardening zones, and field tracks were easily crossed, with a high crossing success rate and a high velocity. Grassy areas, ditches without water, as well as fine and coarse tillage zones, tended to reduce the velocity of *C. sordidus* but did not reduce the crossing success rate. The ditches with water and the line of traps were the two interfaces that efficiently reduced the crossing success and acted as barriers. Our results suggest that these two interfaces could be integrated in management strategies of *C. sordidus*. The hypothesis that ditches can block *C. sordidus*, already suggested by Vinatier *et al.* (2010), was confirmed here but only in the case of ditches with water.[24] In this case, the water appears to be the key element that blocked *C. sordidus*. If some individuals crossed the interface in a single night, we can assume that

the other uncaptured individuals were either dead or remained motionless, for example with a burrowing behavior.[16] It would be interesting to extend the duration of the tests in order to recapture the less mobile individuals as well as be able to refine the crossing time of *C. sordidus*, which would make it possible to better estimate the impact of the least permeable interfaces on its dispersal.

Our study quantified the effect of interfaces at a small scale (6 m). In the case of tilled soil zones or forests, we can hypothesize that the 'barrier effects' could increase with the area of the forest or tilled soil interfaces/patches. The effect of the size of the interface was suggested by the modeling work of Marsula and Wissel (1994) in the case of *Cochliomyia hominivorax*.[35] Indeed, if the field tracks or hedgerows were not intended to be larger, tilled soil and forests actually have dimensions greater than that of our experimental area. For example, Labrie *et al.* (2016) demonstrated that the abundance of soybean aphids decreased significantly when the width of the obstacle to be crossed increased from 18 to 36 m (in their case grass strips or plastic strips).[36]

In controlled conditions at the laboratory, we observed a mortality rate between 1 and 2 *C. sordidus* per week per 60 individuals. If we assume that the mortality rate excluding predation was the same in the field, only 56 *C. sordidus* on average should be alive
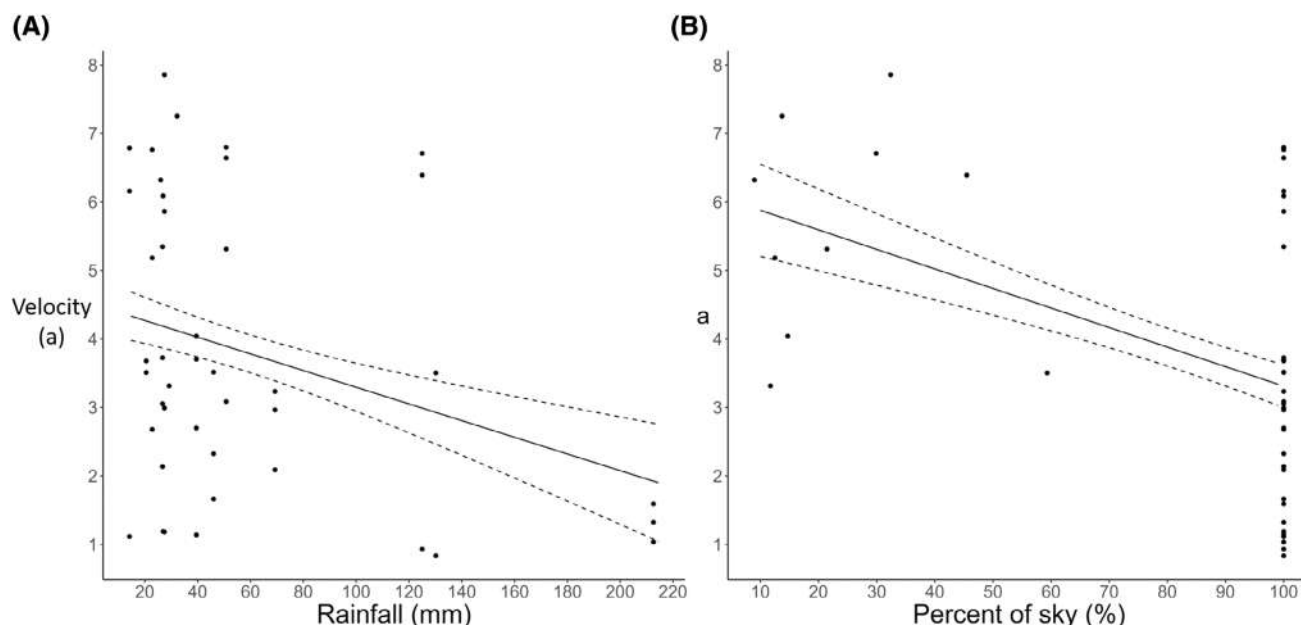
Figure 6. Velocity '*a*' of *Cosmopolites sordidus* to cross interfaces, as estimated for each experiment with the Verhulst model, according to the cumulated rainfall measured during each experiment (A) and the percentage of sky measure with hemispheric pictures (B). Solid lines show the fit of the linear models and dashed lines show their standard errors (see Table 1 for details of statistical models).

after the 14 days of the experiment. It means that we probably slightly underestimated the percentage of crossing successes.

Vegetation height was only significantly correlated negatively to the crossing success 'K'. We can hypothesize that *C. sordidus* moved less in taller grass because this habitat provides favorable conditions (with good protection against radiation and with preservation of soil moisture), which does not encourage them not to escape to another more favorable habitat.[16] The percentage of sky, which is a proxy for radiation, had a negative effect on the velocity '*a*' and the crossing success 'K' of *C. sordidus*. Due to its sensitivity to desiccation,[20] exposure to strong radiation may have increased the mortality of individuals or increased the occurrence of burrowing behavior.

Rainfall negatively impacted the velocity '*a*' of *C. sordidus*. This result is surprising because *C. sordidus* is clearly hygrophilous[16] and we cannot suspect a higher mortality during rainy periods. Gold *et al.* (2002) demonstrated that the catches of *C. sordidus* were greater during the dry season in Uganda[37] and Duyck *et al.* (2012) highlighted the negative relationship of rainfall with the number of captures in Martinique.[38] We can then assume that it is the movement of *C. sordidus* that is negatively affected by rainfall. One hypothesis could be that the pheromone from baits used in pitfall traps had a reduced diffusion or was not well detected by *C. sordidus* during rainy periods. Wind strength also decreased the crossing success 'K' of *C. sordidus*. We cannot exclude that the wind plays a role on the ability of *C. sordidus* to detect the pheromone lure, however this effect is probably not the most relevant explanatory factor in our case. Indeed, forests and the ploughed interfaces showed very contrasting exposure to the wind, while the crossing successes of these interfaces were similar. The reason for this negative relation may come from the dehydrating effect of the wind that can reduce the survival or the movement of *C. sordidus*.[20]

At the farm scale, the ditches with water and the line of pheromone traps could be used as effective barriers to better control

the spread of *C. sordidus*. Ditches with water should be recommended with care because its efficiency depends on the presence of water. It could be interesting to use ditches with water at key moments of the management of *C. sordidus*, for example during mass trapping in fallows. A belt of ditches with water around fallow plots would be a good complement to the traps located inside it. When ditches with water are not possible, the pheromone trap line appears to be the most effective practice to limit dispersal between plots. In the tested trap lines, traps were separated by 1 m, this is probably too much for being economically viable. In future experiments, it would be interesting to test trap lines with larger distances between traps in order to optimize this practice.

Although, vegetation cover or trees were not found to significantly limit the dispersal of *C. sordidus*, these habitats were previously shown to increase *C. sordidus* predation. For instance, it was demonstrated that insect predators, especially ants,[39,40] can be involved in the regulation of *C. sordidus* and that more complex plant communities tend to increase their abundance and their regulation rates.[41] Recently, Tresson *et al.* (2022) showed that vertebrates such as shrew, lizards and toads can be efficient predators of adults of *C. sordidus*.[42] We can hypothesize that predation also play a role inside interfaces, especially in the case of larger interfaces. We can also imagine that combining interfaces would be an interesting option, for instance by putting together a ditch with water to stop dispersion and a hedgerow to enhance predation.

CONCLUSION

Our investigation addressed a relatively poorly studied process which, however, could be an important lever in farm scale pest management strategies. Indeed, limiting the dispersal of pests between plots is essential to slow down their population dynamics. By implementing barriers that limit the dispersal of *C. sordidus*,

the contamination of banana production plots from neighboring plots undergoing sanitation through fallowing could be minimized. Overall, our results showed that few interfaces were able to slow down the movement of *C sordidus*. Only ditches with water and lines of pheromone traps were efficient in stopping the dispersal of *C. sordidus*. The next step will be to conduct research to optimize the use of these two promising interfaces and incorporate them into integrated pest management strategies.

ACKNOWLEDGEMENTS

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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