Bulletin of Entomological Research

cambridge.org/ber

Influence of crop protection strategies and landscape structure on *Bactrocera dorsalis* infestation in mango orchards in La Réunion Island

Research Paper

Cite this article: Moquet L, Barbier J-M, Chiroleu F, Dieudonné E, Pomares F, Fournier É, Moutoussamy M-L, Delatte H (2025) Influence of crop protection strategies and landscape structure on *Bactrocera dorsalis* infestation in mango orchards in La Réunion Island. *Bulletin of Entomological Research*, 1–11. https://doi.org/10.1017/S0007485325100618

Received: 7 July 2025
Revised: 5 September 2025
Accepted: 12 October 2025

Keywords:
agricultural practices; agroecosystem; landscape use; oriental fruit fly; pest management

Corresponding author: Laura Moquet; Email: laura.moquet@cirad.fr

Laura Moquet[1], Jean-Marc Barbier[2], Frédéric Chiroleu[1], Emma Dieudonné[1], Floriane Pomares[1], Élisa Fournier[1], Marie-Ludders Moutoussamy[1] and Hélène Delatte[1]

[1]UMR PVBMT, CIRAD, La Réunion, France and [2]UMR Innovation, INRAE, Montpellier, France

Abstract

The distribution and abundance of insect pests are influenced by landscape structure and composition, particularly through modifications to biocontrol services and the proportion of suitable habitats within the landscape. In addition, pest populations are affected by agricultural practices at different landscape scales, ranging from field-by-field to area-wide. Our study focuses on one of the world's most invasive and polyphagous pests of fruits and vegetables: the Oriental fruit fly, *Bactrocera dorsalis* (Hendel, 1912) (Diptera: Tephritidae). We analysed how farmer practices, landscape composition, and mango varieties were related to *B. dorsalis* infestation in an insular tropical agroecosystem with disparate farming systems, where crop plots are of modest size and interconnected with various habitat types. Fruit infestations were regularly recorded during 18 months in different plots on all mango varieties of the study area. Agricultural practices were determined through semi-structured interviews and categorised according to the farm structure and practices related to *B. dorsalis* management. Landscape composition was determined from high-resolution satellite imagery and local surveys, and the area of landscape cover was calculated within a 500 m buffer around each sampled orchard plot. We demonstrate that both landscape and local factors influence the infestation indexes of *B. dorsalis* in mango orchards. At a landscape scale, *B. dorsalis* was favoured by habitat diversity, which probably provided complementary larval food resources and enabled populations to maintain throughout the year. On a local scale, individual farmers' practices had a significant influence on infestation indexes. The proportion of infested fruits was lower in plots managed by farmers who practised sanitation.

Introduction

The distribution and abundance of insects are influenced by the structure and composition of the landscape (Fahrig *et al.,* 2011; Hunter, 2002; Tscharntke and Brandl, 2004; Tscharntke *et al.,* 2002). For pests, it is often assumed that diversity of habitat types in a landscape should reduce pest abundance, primarily by enhancing biocontrol services (top-down effects) and by increasing the proportion of unsuitable habitats and dispersal barriers in the landscape (bottom-up effects) (Bhar and Fahrig, 1998; Cohen and Crowder, 2017). Other studies have shown, conversely, that heterogeneous landscapes can also provide more suitable conditions for pest species (Tscharntke *et al.,* 2016), and the impact of landscape diversity is likely dependent on the landscape composition. For example, wild areas can provide natural enemies with food, refuge and alternative hosts/prey (Santoiemma *et al.,* 2018). Consequently, the responses of pests to landscape use remain heterogeneous across studies and difficult to predict (Karp *et al.,* 2018), particularly in agroecosystems where agricultural areas are often close to natural and inhabited environments.

In addition, pest populations are affected by the agricultural practices and the management decisions made by each farmer (Jasrotia *et al.,* 2023; Lichtenberg *et al.,* 2017; Pujari *et al.,* 2013; Rehman *et al.,* 2022). Farmers can adopt some preventive measures by managing plant and soil health, implementing prophylaxis such as orchard sanitation, selecting suitable varieties, and using cultural practices such as sowing under plant cover and minimum tillage (Deguine *et al.,* 2012). Other practices can promote the decrease of pest populations and increase beneficial organisms, such as using traps against pests, mating disruption practices or providing refuge or food areas for natural enemies (Brunner *et al.,* 2002; Deguine *et al.,* 2012).

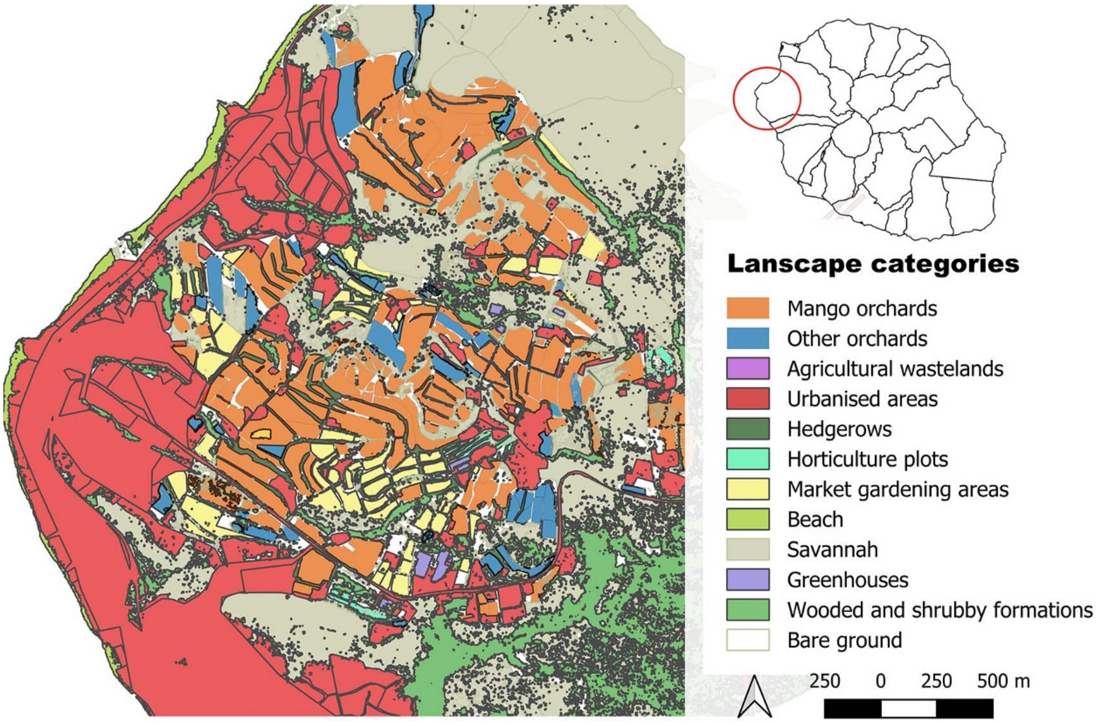

Figure 1. The study location. The study of *B. dorsalis* infestation rates is taking place on La Réunion, a French tropical island in the Indian Ocean. The sampling site is located in the western part of the island (red circle), in 150 ha of mango orchards. In this area, we described the landscape according to 12 categories: agricultural wastelands, urbanised areas, hedgerows, horticulture plots, market gardening areas, savannahs, beaches, greenhouses, orchards (mango orchards), wooded and shrubby formations and bare grounds.

Pest management practices can be applied at various landscape scales. Traditional and integrated pest management (IPM) approaches typically focus on individual fields or farms, despite the mobility of insect pests (Hendrichs *et al.,* 2007; Barzman *et al.,* 2015; Stenberg, 2017). In contrast, area-wide pest management (AWPM) treats larger regions simultaneously, reducing reinfestation from neighbouring areas and enabling the effectiveness of techniques like the sterile insect technique within integrated programs (Elliott *et al.,* 2008). Given the mobility of insect pests, the success of these management strategies is likely influenced by the composition of the surrounding landscape stressing the role of landscape context in pest control.

In light of the agroecosystem metacommunity dynamics, where local communities are established in disparate farming systems and where distinct habitat patches interact, it is intelligible to assess both the efficacy of individual farmer strategies and the influence of landscape composition in the vicinity of the plot. This is particularly relevant in cases where crop plots are of modest size, situated in close proximity to one another or to other habitat patches potentially favourable to pests. It has been shown that pest density depends not only on the local characteristics of orchards, but also on the characteristics of the surrounding landscape, however, the way in which these parameters influence pest density depends on the organism being studied (Lavigne *et al.,* 2017; Le Provost *et al.,* 2021; Ricci *et al.,* 2009; Rusch *et al.,* 2010).

Our study focuses on the oriental fruit fly, *Bactrocera dorsalis* (Hendel, 1912), (Diptera: Tephritidae), among the most invasive and polyphagous pests of fruits and vegetables (White and Elson-Harris 1992), causing severe annual economic losses (Allwood *et al.,* 1997; Alvarez *et al.,* 2016; Cugala *et al.,* 2020; Papadopoulos *et al.,* 2024; Stonehouse *et al.,* 1998). This species has invaded Africa and Oceania (Zeng *et al.,* 2019), has been repeatedly detected in the USA especially in California and Florida (Carey *et al.,* 2017), and in parts of Europe (Nugnes *et al.,* 2024). Farmers use different strategies to manage this pest. The generally used practices comprise (i) orchard sanitation (removal of infested/fallen fruits); (ii) protein-insecticide bait sprays attracting both sexes; (iii) trapping either with protein bait or with male attractant (Methyleugenol); and (iv) chemical treatments. While IPM is promoted, pesticides are still used. Studies have shown that fruit fly control based on a single technique is unlikely to be successful and that it is preferable to combine different approaches (Billah and Ekesi 2006; Ekesi *et al.,* 2016; Hendrichs *et al.,* 2007; Vargas *et al.,* 2016; Zida *et al.,* 2023).

This study analysed how landscape composition and diversity, together with local farmer practices, were related to the infestation rate of *B. dorsalis*. We hypothesised that landscape richness increases infestation rates by providing alternative resources for this generalist species. In addition, we supposed that farmers can also influence infestation rates locally through their actions and practices. We assumed that orchards where sanitation and trapping were applied would experience lower levels of *B. dorsalis* infestation rates.

These hypotheses were tested within a specific tropical island agroecosystem characterised by relatively small, closely situated crop plots and diverse farming systems in La Réunion. La Réunion is a French Island in the Indian Ocean. Mango orchards occupy approximately 300 ha in this tropical island, mainly distributed in the West and Southwest. The production represents 1960 tons sold yearly on the local market or for export in 2022 (20%, Agreste, 2023). Many mango varieties are cultivated in La Réunion, however, the José and Cogshall varieties currently account for more than 80% of the orchard (Vincenot *et al.,* 2009).

https://doi.org/10.1017/S0007485325100618 Published online by Cambridge University Press

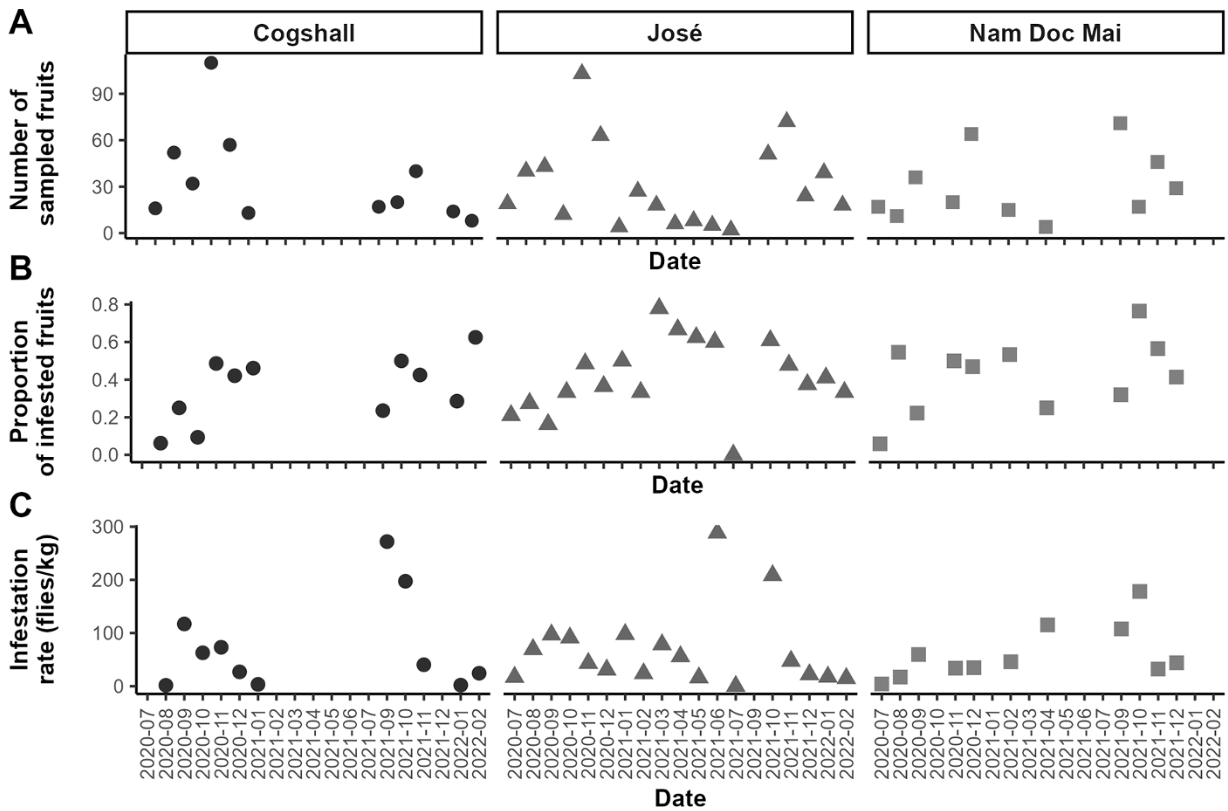

Figure 2. Number of collected fruits (A), proportion of infested fruits (B), and infestation rate (flies/kg; C) according to the month of sampling for the three mango varieties.

Materials and methods

Sampling area

Sample site was located in Saint-Paul (La Réunion, France), the municipality with the largest mango production, in the western part of the island (coordinates: –21.03805, 55.22963), in the area called 'Grand-Fond' where approximately 30% of the total area (150 ha) is mango orchards (Fig. 1).

Infestation rate

We regularly collected mangoes between June 2020 and February 2022 to monitor Tephritidae infestation (Fig. 2). Among 15 farms, 1 to 3 orchards were visited each week to collect mangoes from trees if ripe mangoes on them or from the ground otherwise. The GPS location of the sampled plots was recorded. Fifteen ripe fruits were collected per variety, whenever possible, from orchards and dates. Fruits were randomly collected regardless of the presence or absence of potential holes. We collected a total of 1234 fruits belonging to the three main varieties: José, Cogshall, and Nam Doc Mai.

Fruits were taken to the laboratory and subjected to a standardised protocol (Boinahadji *et al.,* 2019; FAO/IAEA, 2019; Leblanc *et al.,* 2012; N'Dépo *et al.,* 2019). Fruits were individually weighed, placed in plastic boxes with sand as a pupation substrate, and covered with fine mesh cloth. Fruit samples were kept in a climatic room until pupation in favourable conditions (25°C ± 2°C and 70% ± 20% humidity; Duyck *et al.,* 2004). Over a period of three weeks, the sand was sifted regularly to check for Tephritidae pupae. Pupae were then kept in plastic boxes until emergence. They were taxonomically identified at the species level (using a multi-entry identification key to African frugivorous flies, Virgilio *et al.,* 2014). For each fruit, we collected data on (i) the status of the fruit: The sample was considered 'positive' if at least one larva developed into a pupa. It is an indicator of the loss to the farmer, since a single individual in the fruit can make it unmarketable; and (ii) the number of emerging individuals of each fruit fly species. We calculated the infestation rate for positive samples as the number of flies per kilogram of fruit (Dominiak, 2022; Follett *et al.,* 2021).

Table 1. Farm typologies

Farm structure	Surface area with mango trees	Specialisation in mango production	Membership in a cooperative
A	>30 ha	+++	Yes
B	~10 ha	++	Yes/no
C	3–5 ha	+	Yes/no
D	<3 ha	+ /+++	No
Practices for *B. dorsalis* management	**Intensity of trapping**	**Removal of fallen young fruits**	**The use of chemical treatments against *B. dorsalis***
1	Monitoring trap	Yes	According to trap monitoring
2	Trapping	Yes	Yes
3	Trapping	No or a little	Yes
4	Null	No	No

https://doi.org/10.1017/S0007485325100618 Published online by Cambridge University Press

Table 2. Number of collected fruits of each mango variety according to the typology of farms (see Table 1 for the typology of farm structure and practices for *B. dorsalis* management)

Farm structure	Practices for B. dorsalis management	Number of fruits 'Cogshall'	'José'	'Nam Doc Mai'
A	1	0	51	27
A	3	44	84	41
B	2	21	55	21
B	2	30	11	38
B	3	0	21	17
C	1	0	19	37
C	1	54	7	0
C	1	16	4	0
C	2	31	19	71
C	2	53	38	7
C	3	32	82	48
C	3	18	52	0
D	4	17	34	0
D	2	59	25	21
D	3	0	29	0

Landscape composition description

We utilised high-resolution satellite imagery to map the study area's landscape cover. The 'pleiades' satellite images used in this study were acquired on the Kalideos website of the CNES (National Centre for Space Studies). We carried out with the R package RandomForest (Liaw and Wiener, 2002) an automatic processing chain using the Random Forest (RF) automatic classification algorithm through an object-oriented approach on this image to classify the land use. A manual reclassification of identification errors and refinement were then carried out using QGIS software (version 2.18.14) based on our knowledge of the land and the cartography of the agricultural plot.

We obtained 11 landscape categories: agricultural wastelands, urbanised areas, hedgerows, horticulture plots, market gardening areas, savannahs, beaches, greenhouses, orchards (including mango orchards), wooded and shrubby formations and bare grounds. The area of this landscape covers was calculated in a 500 m buffer (Putri *et al.*, 2025; Wen *et al.*, 2023) around each sampled orchard plot. Orchards (84% of which are mango orchards), market gardening areas and horticulture plots were environments with host plants for *B. dorsalis*. Hedgerows varied in composition and could include host plants (e.g. *Pithecellobium dulce, Citrus* spp., *Ziziphus* spp., etc.) or non-host plant species (e.g. *Leucaena leucocephala*). Urban areas were mixed, comprising non-vegetated areas and gardens with potential host plants. Then other categories such as agricultural wastelands, savannahs, beaches, greenhouses and most of the wooded and shrubby formations did not contain host plants.

Landscape diversity

From this landscape description we calculated the richness as the number of landscape categories in the 500 m buffer and the Shannon index expressed as: $H = -\sum pi \ \log_2 pi$ where pi is the proportion of the area occupied by the landscape categories in the 500 m buffer.

Typology of agricultural practices

We carried out a survey on 15 farms in the study area in 2021. The type of interview used in these surveys was semi-structured. First, the farmers spoke freely about the different themes addressed by the investigator, then precisions and quantitative data were asked. The questionnaire of 56 questions was organised around several themes: (1) presentation of the producer and his family, (2) general presentation of the farm and its context, (3) description of the agricultural production system, the mango place and its economic valorisation, (4) other productions and activities, (5) management of the orchard (mango tree), and (6) means of control against mango tree pests with a focus on *B. dorsalis*.

Farms were then categorised according to two modalities (Tables 1 and 2):

Farm structure and mango production were assessed based on total farm size, mango area, mango's share in farm income, and cooperative membership. Within the 150 ha study area, 67 ha were owned by two farmers (Group A). Other farms were classified as medium (~10 ha, Group B), small (3–5 ha, Group C), and very small (<3 ha, Group D). Large, mango-specialised farms were generally part of cooperatives, unlike smaller, more diversified farms, which rarely were members.

Three main strategies were used to manage *B. dorsalis*. (i) Trapping with a male attractant (Methyleugenol), applied at low density (<10 traps/ha, Group 1) for monitoring or high density for control (Group 2 and 3). (ii) The orchard sanitation, mainly through the removal of fallen young fruits (Vargas *et al.*, 2016). We differentiated farmers according to whether they used this strategy (Group 1 and 2) or not (Group 3 and 4). (iii) Chemical treatments, including both conventional and organic-approved products; farmers were grouped based on systematic annual use of chemicals. Group 4, although represented by a single farm, was included as a control with no intervention against *B. dorsalis*.

Statistical analysis

All statistical analyses were performed using R software (R Core Team 2024).

To avoid the collinearity of environmental variables (the 11 landscape categories, richness and Shannon index) in statistical models, an exploratory analysis was carried out using PCA and correlation matrix visualisation (Supplemental data S1). We thus kept three variables with little or no correlation and a strong contribution of those variables to the total variance of the PCA: richness, Shannon index, and quantity of orchards in a 500 m buffer around each sampled orchard plot.

For each mango variety, we carried out a Generalised Linear Model ('glm' function) to test the effect of the main landscape category (orchards), landscape indices (richness and Shannon), farm categories (farm structure and practices for *B. dorsalis* management), and the fruiting season (season 1 from June 2020 to May 2021 and season 2 from June 2021 to February 2022) on fruit fly infestation. The interactions between the fruiting season and all other variables were included in the model. In addition, to test the effect of mango varieties on fruit fly infestation, we selected data for the periods (months) during which we collected fruits of

https://doi.org/10.1017/S0007485325100618 Published online by Cambridge University Press

Table 3. Generalised linear effects (GLM) model tables of the proportion of infested fruits (binomial, link = 'logit') and infestation rate (Gamma, link = log) according to the typology of farms (farm structure, practice for *B. dorsalis*), the landscape structure in a 500 m buffer (mango orchards, Shannon index and richness), the fruiting season (2020–2021 or 2021–2022) and the interaction between factors (only variables selected after stepwise model selection were represented)

		Cogshall				José				Nam Doc Mai			
	Variable		LR Chisq	df	*P* value		LR Chisq	df	*P* value		LR Chisq	df	*P* value
Proportion of infested fruits	Practices for *B. dorsalis*		**19.578**	**3**	**<0.001**		**27.610**	**3**	**<0.001**		**17.184**	**2**	**<0.001**
	Farm structure		0.238	3	0.971		_	_	_		**18.804**	**3**	**<0.001**
	Season		0.080	1	0.777		_	_	_		1.124	1	0.289
	Richness		_	_	_	+	**13.550**	**1**	**<0.001**	+	**7.552**	**1**	**0.006**
	Shannon	+	**14.864**	**1**	**<0.001**	-	**7.010**	**1**	**0.008**	+	0.497	1	0.481
	Mango orchards		_	_	_		_	_	_		_	_	_
	Saison: Practices for *B. dorsalis*		_	_	_		_	_	_		**9.667**	**2**	**0.008**
	Saison: Farm structure	+	**19.544**	**3**	**<0.001**		_	_	_		_	_	_
	Saison: Richness		_	_	_		_	_	_		_	_	_
	Saison: Shannon	+	3.720	1	0.054		_	_	_	-	**12.729**	**1**	**<0.001**
	Saison: Mango orchards		_	_	_		_	_	_		_	_	_
Infestation rate	Practices for *B. dorsalis*		**8.523**	**3**	**0.036**		**22.848**	**3**	**<0.001**		**9.931**	**2**	**0.007**
	Farm structure		**13.440**	**3**	**0.004**		7.790	3	0.051		1.637	3	0.651
	Season		**4.633**	**1**	**0.031**		**11.920**	**1**	**0.001**		0.762	1	0.383
	Richness		_	_	_	+	0.296	1	0.586	-	0.147	1	0.701
	Shannon	+	**4.774**	**1**	**0.029**	-	0.432	1	0.511	+	3.415	1	0.065
	Mango orchards	+	**14.967**	**1**	**<0.001**	-	2.972	1	0.085	+	0.533	1	0.465
	Saison: Practices for *B. dorsalis*		**14.066**	**1**	**<0.001**		**5.992**	**2**	**0.050**		**7.688**	**2**	**0.021**
	Saison: Farm structure		**11.751**	**3**	**0.008**		_	_	_		**14.490**	**3**	**0.002**
	Saison: Richness		_	_	_	+	**13.209**	**1**	**<0.001**	+	**4.909**	**1**	**0.027**
	Saison: Shannon		_	_	_	-	**11.839**	**1**	**0.001**		_	_	_
	Saison: Mango orchards	-	**5.852**	**1**	**0.016**	-	2.669	1	0.102	-	**7.603**	**1**	**0.006**

_: variable removed of the model after stepwise model selection.
- or +: negative or positive estimate for quantitative variables.
Bold: significant parameter (*P* value < 0.05).

https://doi.org/10.1017/S0007485325100618 Published online by Cambridge University Press

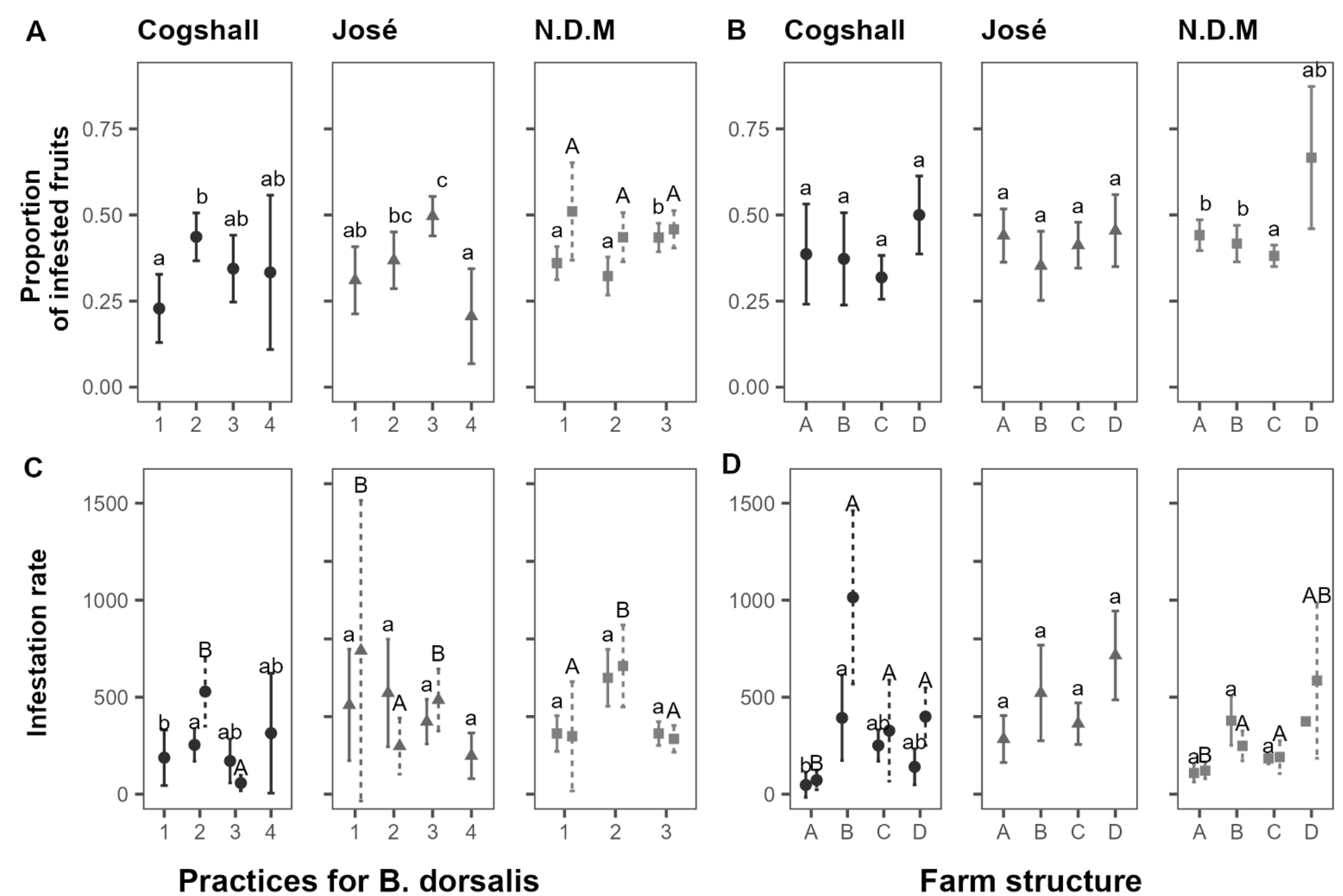

Figure 3. Proportion of infested fruits (A, B) and infestation rate (flies/kg; C, D) for each mango variety according to farm typology: (A and C) practices for *B. dorsalis* management and (B and D) farm structure. Value is mean ± 1.96 standard error. Different letters indicate significant differences among tested conditions for each mango variety and each fruiting season. When there was significant interaction between the factors and the fruiting season, we differentiated the fruit seasons as follows: season 1 (2020–2021, solid lines, lower case letter) and season 2 (2021–2022, dashed lines, upper case letter). N.D.M: Nam Doc Mai variety.

the three varieties (August, September, November, and December 2020, and October and November 2021). Thus, we carried out a GLM analysis with mango varieties, the fruiting season, and their interaction.

Fruit fly infestation was modelled by (i) the proportion of infested fruits with a binomial response variable (infested = 1 vs. non-infested = 0) and a logit link function, and (ii) the infestation rate, calculated as the number of flies per kilogram of fruit in positive samples, with a gamma distribution and a logarithmic link function. We performed stepwise model selection (function stepAIC, Venables and Ripley, 2002) to identify a minimally adequate model based on AIC (Akaike information criterion). We started with a complete model and used a bidirectional mode (backwards and forward) of stepwise search. We visually checked for homoscedasticity, quasi-normality, and independence of residuals, and we tested for the presence of spatial autocorrelation in the residuals using a Moran's I test (function testSpatialAutocorrelation, Hartig, 2018). When factor effects were significant, we performed pairwise post hoc tests on marginal means (using the emmeans or emtrends function, Lenth, 2024) to determine which parameters differed from each other.

Results

A total of 13,684 flies emerged from fruits of the three mango varieties studied (Cogshall, José, and Nam Doc Mai). *Bactrocera dorsalis* represented 99.6% of the emerging flies. Additionally, 32 *Ceratitis capitata* (Wiedemann, 1824) (Diptera: Tephritidae) individuals emerged from the José and Nam Doc Mai varieties.

There was no significant correlation between the proportion of infested fruit and infestation rate (F = 2.23, $P = 0.091$).

Proportion of infested fruits

The proportion of infested fruit was significantly related to the landscape diversity: The Shannon diversity index had a significant and positive effect on the proportion of infested fruits for the Cogshall variety ($\chi^2_2 = 14.864$, $P < 0.001$) and a significant negative effect for José Variety ($\chi^2_1 = 7.01$, $P = 0.008$). The Richness index was positively related to the proportion of infested fruits for the José variety ($\chi^2_1 = 13.55$, $P < 0.001$). The proportion of infested fruits was not significantly related to the quantity of orchards within the 500 m buffer area for all tested varieties (Table 3).

The practices for *B. dorsalis* management had a significant effect on the proportion of infested fruits for Cogshall ($\chi^2_3 = 19.578$, $P < 0.001$), José ($\chi^2_3 = 27.607$, $P < 0.001$) and Nam Doc Mai ($\chi^2_3 = 17.184$, $P < 0.001$) varieties (Table 3, Fig. 3A). The farms of group 1 had a significantly lower proportion of infested fruits than farms of group 2 for Cogshall variety (z ratio = −3.470, $P = 0.003$), and than farms of group 3 for José variety (z ratio = −3.480, $P = 0.003$). For the Nam Doc Mai variety, there was an interaction between the fruiting season and the practices for *B. dorsalis* management ($\chi^2_2 = 9.667$, $P = 0.008$) and the farms of group 1 had a significantly lower proportion of infested fruits than farms of group 3 only for the fruiting season 1 (z ratio = −3.610, $P = 0.001$) (Fig. 3A).

The farm structure had a significant effect on the proportion of infested fruits for the Nam Doc Mai varieties ($\chi^2_3 = 18.804$, $P < 0.001$, Table 3, Fig. 3B): Farms of group C had a significantly lower proportion of infested fruits than the farms of group A (z ratio = − 2.668, $P = 0.038$) and B (z ratio = −3.089, $P = 0.011$).

Infestation rate

Landscape context had a significant effect on the infestation rate (number of flies per kg of fruit) only for the Cogshall variety. The Shannon index ($\chi^2_1 = 4.774$, $P = 0.029$) and the quantity of orchards in the 500 m buffer ($\chi^2_1 = 14.967$, $P < 0.001$) had a significant and positive effect on the infestation rate (Table 3). There was an interaction between the fruiting season and the quantity of orchards in the 500 m buffer ($\chi^2_1 = 5.852$, $P = 0.016$). Increasing the quantity of orchards has the effect of increasing the infestation rate in season 1, while slightly decreasing the infestation rate in season 2.

The practices for *B. dorsalis* management had a significant effect on the infestation rate for all mango varieties (Cogshall: $\chi^2_3 = 8.523$, $P = 0.036$; José: $\chi^2_3 = 22.848$, $P < 0.001$; Nam Doc Mai: $\chi^2_3 = 9.931$, $P = 0.007$). There were also significant interactions of the fruiting season with practices for *B. dorsalis* management for Cogshall ($\chi^2_2 = 14.066$, $P < 0.001$), José ($\chi^2_2 = 5.992$, $P = 0.050$) and Nam Doc Mai varieties: ($\chi^2_2 = 7.688$, $P = 0.021$). For Cogshall, the infestation rate was significantly higher in group 2 than in group 1 during the first season (t = 2.660, $P = 0.045$), and group 2 was significantly higher than group 3 during the second fruiting season (t = 3.220, $P = 0.002$). For the José variety, the infestation rate was significantly higher in groups 1 and 3 than in group 2 (t = 3.580, $P = 0.001$; t = 4.600, $P < 0.001$, respectively). For the Nam Doc Mai variety, the infestation rate was significantly higher in group 2 than group 1 (t = 3.580, $P = 0.001$) and group 3 (t = 4.600, $P < 0.001$) only during the second fruiting season. The farm structure had a significant effect on the infestation rate of the Cogshall varieties ($\chi^2_3 = 13.440$, $P = 0.004$) with a significant interaction between the farm structure and the fruiting season ($\chi^2_3 = 11.751$, $P = 0.008$). Infestation rate was significantly lower in group A than group B (t = 2.770, $P = 0.033$) during the first season and was significantly lower in group A than group B (t = 3.750, $P = 0.002$), C (t = 2.900, $P = 0.023$), and D (t = 3.210, $P = 0.009$) during the second fruiting season.

Mango varieties

The proportion of infested fruits and infestation rate were not significantly different among mango varieties ($\chi^2_2 = 2.26$, $P = 0.323$ and $\chi^2_2 = 1.08$, $P = 0.583$, respectively; Table 4).

Discussion

This study demonstrates that the infestation of mangoes by *B. dorsalis* is influenced by the landscape structure and farmers' practices within this specific tropical island agroecosystem characterised by relatively small, closely situated crop plots and diverse farming systems. Due to constraints in field availability under similar bioclimatic conditions, our dataset was unbalanced, limiting our ability to test all interactions between farm structure, control practices, landscape use, and mango varieties, factors known to interact and influence pest dynamics in complex ways, as shown in previous studies (Rusch *et al.,* 2010).

Effect of landscape diversity on B. dorsalis infestation

As hypothesised, a correlation was observed between landscape diversity and *B. dorsalis* infestation. The landscape diversity, approximated by the Shannon and Richness indexes, was correlated with the proportion of infested fruits. For example, we observed that the Shannon diversity index was positively correlated with the proportion of infested fruits for the Cogshall variety, and the Richness index was positively correlated with the proportion of infested fruits for the José and Nam Doc Mai varieties. However, an inconsistent result was obtained, with the proportion of infested fruits exhibiting a negative correlation with the Shannon index for the José mango variety. This suggests that the interaction between diversity, infestation rate and mango varieties is complex and may be subject to variation due to numerous factors. The impact of landscape diversity on natural enemies of pest species has already been investigated across a range of cropping systems and study regions (Bianchi *et al.,* 2006; Chaplin-Kramer *et al.,* 2011; Priyadarshana *et al.,* 2024). A literature review demonstrated that pest pressure was lower in more heterogeneous landscapes in 45% of the studied publications and higher in 15% (Bianchi *et al.,* 2006). However, other studies suggest that increased landscape heterogeneity benefits different taxa, including pest species, by providing favourable resources (reviewed in Priyadarshana *et al.,* 2024). For instance, Santoiemma *et al.,* (2018) demonstrated that the density of the generalist species *Drosophila suzukii* is higher in heterogeneous landscapes. In addition, it was already shown that heterogeneity of landscape was positively correlated with the abundance of *B. dorsalis* (Putri *et al.,* 2025; Wen *et al.,* 2023). In the present study, the heterogeneity of the landscape may increase the probability of habitats with host plants around the plots studied, thereby facilitating the maintenance of larger fruit fly populations throughout the year. In particular, the Shannon index was found to be negatively correlated with the proportion of savannah (see Supplemental data S1), which is an unfavourable environment for fruit flies without host fruits for larvae in the area surrounding the study plots.

Effect of the mango orchards prevalence on B. dorsalis infestation

The results of our study did not reveal a specific relation between infestation and the quantity of orchards at landscape scale. The farm structure typology was mainly constructed around the level of crop diversity and the area under mango; thus, it can be considered as an index of mango orchard density on a more local scale. Despite observing a significant effect of the typology on the infestation indexes, the effects varied among different mango varieties, with no discernible trend. In addition, at the landscape scale, the proportion of infested fruits was not significantly related to the quantity of orchards (mainly mango orchards) in the 500-buffer area for all the tested varieties. Thus, the diversity of the landscape was not systematically impacted by an increase in the quantity of orchards in the landscape. It is generally accepted that, because crops provide habitats for pests, a positive relationship is expected between the abundance of pests in the field and the area of cultivated land at a landscape scale (Fahrig, 2003). *Bactrocera dorsalis,* a generalist species, has been observed to be particularly prevalent in mango orchards (Grechi *et al.,* 2022). Our results may be due to the high diversity in the agroecological model system. The study area is notable for the absence of strict monocultures, and other host plants may be present in and around the mango orchards, including lychee trees, pomegranate trees, soursop trees, or jujube trees. The quantity of mango orchards in the 500-buffer was correlated with the quantity of hedgerow and was not negatively correlated to the Shannon or richness index (Supplemental data S1). In addition, responses to landscape structure and composition are scale-dependent (Chaplin-Kramer *et al.,* 2011; Priyadarshana *et al.,* 2024). It is possible that the scale at which we conducted our measurements was not the most predictive for this insect species. However, in our study, the chosen scale of study reflects the smaller size of production areas (in this case, mango production) in insular environments compared to continental environments. Furthermore, it has been shown for *B. dorsalis* that the direction and strength of the relationships between landscape variables and its abundance did not change with spatial distance (from 0.5 to 1.5 km, Wen *et al.,* 2023).

Effect of agricultural practices on B. dorsalis infestation

The findings of this study demonstrate a correlation between the practices of individual farmers and the proportion of infested fruits. Crop protection strategies can impact pest populations directly or indirectly by modifying natural enemy communities (Marliac *et al.,* 2015). We observed a significant effect of the practices against *B. dorsalis* on the proportion of infested fruits and the infestation rate. It is particularly noteworthy to note that individual practices influenced infestation rates despite the landscape context, the proximity and different practices between farms. However, the limited number of replicates in each category does not allow us to identify precisely which practices should be favoured. However, among practice, sanitation is now recognised as the basis of all effective integrated pest management (IPM) to control fruit fly (Ekesi *et al.,* 2016; Vargas *et al.,* 2016; Verghese *et al.,* 2006). The collection and removal of all discarded fruits from the trees and the ground has been shown to have a significant impact on the population dynamics of fruit flies, through the disruption of their lifecycle (Liquido, 1993). In our study, the farms of groups 1 and 2, which prioritise orchard sanitation over mass trapping and chemical treatments, exhibited a lower proportion of infested fruits compared to farms in group 3 for José and Nam Doc Mai varieties. We have focused our work on the sanitation of young fruit that has fallen to the ground. This fruit is susceptible to infestation by fruit flies (Amin, 2017), yet is less frequently removed by farmers. Farmers who initiate fruit removal at the abscission stage tend to engage in this orchard sanitation throughout the fruiting season.

Mango varieties

We observed no significant difference in infestation between the three mango varieties when comparing fruits collected during the same period. However, the landscape diversity and composition, and farm typology had different effects on the level of fruit fly infestation according to mango variety. These results could be attributed to the fruiting period of the studied varieties. Cogshall is an early variety, Nam Doc Mai is more of a seasonal variety, and José has an irregular fruiting period (Jessu *et al.,* 2017). Due to their differing phenology, varieties may be subject to different climatic conditions and biological phenomena. The mango fruiting period provides abundant food resources for fruit flies, which, when combined with favourable weather conditions, leads to an outbreak of fruit fly populations (Bota *et al.,* 2018; Motswagole *et al.,* 2019). At the onset of the fruiting season, the detection and subsequent colonisation of orchards within the agroecosystem is determinant and is probably influenced by the landscape structure (Singh and Satyanarayana, 2009). During peak outbreaks, insect dispersal is shorter, and the high reproduction rate, facilitated by the availability of resources, leads to increased populations (Singh and Satyanarayana, 2009).

Table 4. Generalised linear effects (GLM) model tables of the proportion of infested fruits (binomial, link = 'logit') and infestation rate (Gamma, link = log) according to the mango varieties and fruiting for August, September, November, December 2020, and October, November 2021 (periods where data were available for the three varieties)

	Variables	LR Chisq	df	*P* value
Proportion of infested fruits	Mango variety	2.26	2	0.323
	Season	**14.69**	**1**	**<0.001**
	Mango variety: Season	2.12	2	0.346
Infestation rate	Mango variety	1.08	2	0.583
	Season	**4.44**	**1**	**0.035**
	Mango variety: Season	0.00	2	0.998

Conclusion

Despite the constrained dataset, we were able to demonstrate that the infestation rates of *B. dorsalis* in mango orchards were influenced by both landscape and crop management factors in the case of a specific tropical island agroecosystem with small orchards in a diversified landscape. On a landscape scale, *B. dorsalis* was favoured by habitat diversity, which probably provided complementary larval food resources and enabled populations to be maintained throughout the year. On a local scale, despite disparate farming systems and the interaction of distinct habitat patches, individual farmers' practices influenced infestation indexes. The proportion of infested fruits was lower in plots managed by farmers who prioritise monitoring and sanitation. It would be interesting to see, in an AW-IPM context, whether the application of these practices by a group of neighbouring farmers could increase the effectiveness of *B. dorsalis* control at a larger scale.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0007485325100618.

Acknowledgements. The authors would like to thank the Chamber of Agriculture of La Réunion for facilitating contact with the farmers and farmers who participated in the surveys and consented to the collection of samples on their plots.

Financial support. This study was co-financed by CIRAD, the 'Conseil Régional de La Réunion', European Union, the French State, and the Réunion Region. Europe is committed to Réunion through the EAFRD (the European Agricultural Fund for Rural Development, REU77071-1-000011) and ERDF (the European Regional Development Fund, 2024-1248-005756). This study is part of GEMDOTIS projects (ODEADOM, ECOPHYTO 2).

Competing interests. The authors have no conflict of interest to declare.

Data availability statement. Data will be available on Cirad dataverse: https://dataverse.cirad.fr/

Ethics approval statement. The data were collected, analysed, and published with the agreement of the farmers concerned.

References

Agreste (2023) *Essentiel La Réunion: La Filière Fruits*. La Réunion, France: Direction de l'Alimentation, de l'Agriculture Et de la Forêt Service de l'Information Statistique Et Economique **8**.

Allwood AJ, Leblanc L, Allwood AJ and Drew RAI (1997) Losses caused by fruit flies (Diptera: Tephritidae) in seven Pacific Island countries. In Aciar Proceedings, 208–211. Australian Centre for International Agricultural Research.

Alvarez S, Evans EA and Hodges AW (2016) *Estimated Costs and Regional Economic Impacts of the Oriental Fruit Fly (Bactrocera Dorsalis) Outbreak in Miami-Dade County,* Florida, USA: University of Florida Institute of Food and Agricultural Sciences Extension. **EF988**, 259–266.

Amin AA (2017) Field and laboratory studies on infestation of immature mango fruits by the peach fruit fly, *Bactrocera zonata* (Saunders). *Egyptian Journal of Agricultural Research* **95**, 89–106.

Barzman M, Bàrberi P, Birch ANE, Boonekamp P, Dachbrodt-Saaydeh S, Graf B, Jensen JE, Kiss J, Kudsk P, Lamichhane JR, Messéan A, Moonen A-C, Ratnadass A, Ricci P, Sarah J-L and Sattin M (2015) Eight principles of integrated pest management. *Agronomy for Sustainable Development* **35**, 1199–1215.

Bhar R and Fahrig L (1998) Local vs. landscape effects of woody field borders as barriers to crop pest movement. *Conservation Ecology* **2**, 1–19.

Bianchi FJJA, Booij CJH and Tscharntke T (2006) Sustainable pest regulation in agricultural landscapes: A review on landscape composition, biodiversity and natural pest control. *Proceedings of the Royal Society B: Biological Sciences* **273**, 1715–1727.

Billah MK and Ekesi S (2006) *A Field Guide to the Management of Economically Important Tephritid Fruit Flies in Africa*. ICIPE Science Press: Nairobi, Kenya.

Boinahadji AK, Coly EV, Dieng EO, Diome T and Sembene PM (2019) Interactions between the oriental fruit fly *Bactrocera dorsalis* (Diptera, Tephritidae) and its host plants range in the Niayes area in Senegal. *Journal of Entomology and Zoology Studies* **7**, 855–864.

Bota LD, Fabião BG, Virgilio M, Mwatawala M, Canhanga L, Cugala DR and De Meyer M (2018) Seasonal abundance of fruit flies (Diptera: Tephritidae) on mango orchard and its relation with biotic and abiotic factors in Manica Province, Mozambique. *Fruits* **73**, 218–227.

Brunner J, Welter S, Calkins C, Hilton R, Beers E, Dunley J, Unruh T, Knight A, Van Steenwyk R and Van Buskirk P (2002) Mating disruption of codling moth: A perspective from the Western United States. *IOBC Wprs Bulletin* **25**, 11–20.

Carey JR, Papadopoulos N and Plant R (2017) The 30-year debate on a multi-billion-dollar threat: Tephritid fruit fly establishment in California. *American Entomologist* **63**, 100–113.

Chaplin-Kramer R, O'Rourke ME, Blitzer EJ and Kremen C (2011) A meta-analysis of crop pest and natural enemy response to landscape complexity. *Ecology Letters* **14**, 922–932.

Cohen AL and Crowder DW (2017) The impacts of spatial and temporal complexity across landscapes on biological control: A review. *Current Opinion in Insect Science* **20**, 13–18.

Cugala D, Massimiliano V, Maulid M, De Meyer M and Canhanga L (2020) Economic injury level of the Oriental fruit fly, *Bactrocera dorsalis* (Diptera: Tephritidae), on commercial mango farms in Manica Province, Mozambique. *African Entomology* **28**, 278–289.

Deguine J-P, Rousse P and Atiama-Nurbel T (2012) Agroecological crop protection: Concepts and a case study from Reunion. In Larramendy Marcelo L and Sonia S (eds.), *Integrated Pest Management and Pest Control-current and Future Tactics*. San Antonio: Intech Publisher, 63–76. Croatia: InTech.

Dominiak BC (2022) The use of host reproduction number and host suitability index to rank hosts of fruit flies in Africa. *International Journal of Tropical Insect Science* **42**, 2717–2729.

Duyck P-F, Sterlin JF and Quilici S (2004) Survival and development of different life stages of *Bactrocera zonata* (Diptera: Tephritidae) reared at five constant temperatures compared to other fruit fly species. *Bulletin of Entomological Research* **94**, 89–93.

Ekesi S, Mohamed SA and De Meyer M Eds. (2016) *Fruit Fly Research and Development in Africa - Towards a Sustainable Management Strategy to Improve Horticulture*. Switzerland: Springer.

Elliott NC, Onstad DW and Brewer MJ (2008) History and ecological basis for areawide pest management. *Publications from USDA-ARS/UNL Faculty* **646**, 15–33.

Fahrig L (2003) Effects of habitat fragmentation on biodiversity. *Annual Review of Ecology, Evolution, and Systematics* **34**, 487–515.

Fahrig L, Baudry J, Brotons L, Burel FG, Crist TO, Fuller RJ, Sirami C, Siriwardena GM and Martin J-L (2011) Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. *Ecology Letters* **14**, 101–112.

FAO/IAEA (2019) *Fruit Sampling Guidelines for Area-Wide Fruit Fly Programmes*. In Enkerlin WR, Reyes J and Ortiz G (eds.), Vienna, Austria: FAO, 46.

Follett PA, Haynes FEM and Dominiak BC (2021) Host suitability index for polyphagous tephritid fruit flies. *Journal of Economic Entomology* **114**, 1021–1034.

Grechi I, Preterre A-L, Lardenois M and Ratnadass A (2022) *Bactrocera dorsalis* invasion increased fruit fly incidence on mango production in Reunion Island. *Crop Protection* **161**, 106056.

Hartig F (2018) DHARMa: Residual diagnostics for hierarchical (multi-level/mixed) regression models. R Packag version 020.

Hendrichs J, Kenmore P, Robinson AS and Vreysen MJB (2007) Area-Wide Integrated Pest Management (AW-IPM): Principles, Practice and Prospects. In Vreysen MJB, Robinson AS and Hendrichs J (eds.), *Area-wide Control of Insect Pests*. Dordrecht: Springer Netherlands, 3–33.

Hunter MD (2002) Landscape structure, habitat fragmentation, and the ecology of insects. *Agricultural and Forest Entomology* **4**, 159–166.

Jasrotia P, Kumari P, Malik K, Kashyap PL, Kumar S, Bhardwaj AK and Singh GP (2023) Conservation agriculture based crop management practices impact diversity and population dynamics of the insect-pests and their natural enemies in agroecosystems. *Frontiers in Sustainable Food Systems* **7**, 1173048.

Jessu D, Sinatamby M and Normand F (2017) *Production Et Qualité de Variétés de Mangues À la Réunion*. POSTER, La Réunion: France.

Karp DS, Chaplin-Kramer R, Meehan TD, Martin EA, DeClerck F, Grab H, Gratton C, Hunt L, Larsen AE, Martínez-Salinas A, O'Rourke ME, Rusch A, Poveda K, Jonsson M, Rosenheim JA, Schellhorn NA, Tscharntke T, Wratten SD, Zhang W, Iverson AL, Adler LS, Albrecht M, Alignier A, Angelella GM, Zubair Anjum M, Avelino J, Batáry P, Baveco JM, Bianchi FJJA, Birkhofer K, Bohnenblust EW, Bommarco R, Brewer MJ, Caballero-López B, Carrière Y, Carvalheiro LG, Cayuela L, Centrella M, Ćetković A, Henri DC, Chabert A, Costamagna AC, De la Mora A, de Kraker J, Desneux N, Diehl E, Diekötter T, Dormann CF, Eckberg JO, Entling MH, Fiedler D, Franck P, Frank van Veen FJ, Frank T, Gagic V, Garratt MPD, Getachew A, Gonthier DJ, Goodell PB, Graziosi I, Groves RL, Gurr GM, Hajian-Forooshani Z, Heimpel GE, Herrmann JD, Huseth AS, Inclán DJ, Ingrao AJ, Iv P, Jacot K, Johnson GA, Jones L, Kaiser M, Kaser JM, Keasar T, Kim TN, Kishinevsky M, Landis DA, Lavandero B, Lavigne C, Le Ralec A, Lemessa D, Letourneau DK, Liere H, Lu Y, Lubin Y, Luttermoser T, Maas B, Mace K, Madeira F, Mader V, Cortesero AM, Marini L, Martinez E, Martinson HM, Menozzi P, Mitchell MGE, Miyashita T, Molina GAR, Molina-Montenegro MA, O'Neal ME, Opatovsky I, Ortiz-Martinez S, Nash M, Östman Ö, Ouin A, Pak D, Paredes D, Parsa S, Parry H, Perez-Alvarez R, Perović DJ, Peterson JA, Petit S, Philpott SM, Plantegenest M, Plećaš M, Pluess T, Pons X, Potts SG, Pywell RF, Ragsdale DW, Rand TA, Raymond L, Ricci B, Sargent C, Sarthou J-P, Saulais J, Schäckermann J, Schmidt NP, Schneider G, Schüepp C, Sivakoff FS, Smith HG, Stack Whitney K, Stutz S, Szendrei Z, Takada MB, Taki H, Tamburini G, Thomson LJ, Tricault Y, Tsafack N, Tschumi M, Valantin-Morison M, Van Trinh M, van der Werf W, Vierling KT, Werling BP, Wickens JB, Wickens VJ,

Woodcock BA, Wyckhuys K, Xiao H, Yasuda M, Yoshioka A and Zou Y (2018) Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. *Proceedings of the National Academy of Sciences* **115**, E7863–E7870.

Lavigne C, Maalouly M, Monteiro L, Ricci B, Toubon J-F, Bouvier J-C, Olivares J, Maugin S, Thomas C and Franck P (2017) Landscape scale and local crop protection intensity affect the abundance of the codling moth and its predation and parasitism in apple orchards. In Begg G, Bianchi F, Birch N, Gerowitt B, Holland J, Lupi D, Moonen C, Ramsden M and van Rijn P (eds.), *IOBC/WPRS Bulletin*. Scotland, UK: International Organization for Biological and Integrated Control of Noxious Animals and Plants (OIBC/OILB), West Palaearctic Regional Section (WPRS/SROP), Vol. **122**, 29–32.

Le Provost G, Thiele J, Westphal C, Penone C, Allan E, Neyret M, Van Der Plas F, Ayasse M, Bardgett RD, Birkhofer K, Boch S, Bonkowski M, Buscot F, Feldhaar H, Gaulton R, Goldmann K, Gossner MM, Klaus VH, Kleinebecker T, Krauss J, Renner S, Scherreiks P, Sikorski J, Baulechner D, Blüthgen N, Bolliger R, Börschig C, Busch V, Chisté M, Fiore-Donno AM, Fischer M, Arndt H, Hoelzel N, John K, Jung K, Lange M, Marzini C, Overmann J, Paŝalić E, Perović DJ, Prati D, Schäfer D, Schöning I, Schrumpf M, Sonnemann I, Steffan-Dewenter I, Tschapka M, Türke M, Vogt J, Wehner K, Weiner C, Weisser W, Wells K, Werner M, Wolters V, Wubet T, Wurst S, Zaitsev AS and Manning P (2021) Contrasting responses of above- and belowground diversity to multiple components of land-use intensity. *Nature Communications* **12**, 3918.

Leblanc L, Vueti ET, Drew RA and Allwood AJ (2012) Host plant records for fruit flies (Diptera: Tephritidae: Dacini) in the Pacific Islands. *Proceedings of the Hawaiian Entomological Society* **44**, 11–53.

Liaw A and Wiener M (2002) Classification and regression by randomForest. *R News* **2**(3), 18–22.

Lichtenberg EM, Kennedy CM, Kremen C, Batáry P, Berendse F, Bommarco R, Bosque-Pérez NA, Carvalheiro LG, Snyder WE, Williams NM, Winfree R, Klatt BK, Åström S, Benjamin F, Brittain C, Chaplin-Kramer R, Clough Y, Danforth B, Diekötter T, Eigenbrode SD, Ekroos J, Elle E, Freitas BM, Fukuda Y, Gaines-Day HR, Grab H, Gratton C, Holzschuh A, Isaacs R, Isaia M, Jha S, Jonason D, Jones VP, Klein A-M, Krauss J, Letourneau DK, Macfadyen S, Mallinger RE, Martin EA, Martinez E, Memmott J, Morandin L, Neame L, Otieno M, Park MG, Pfiffner L, Pocock MJO, Ponce C, Potts SG, Poveda K, Ramos M, Rosenheim JA, Rundlöf M, Sardiñas H, Saunders ME, Schon NL, Sciligo AR, Sidhu CS, Steffan-Dewenter I, Tscharntke T, Veselý M, Weisser WW, Wilson JK and Crowder DW (2017) A global synthesis of the effects of diversified farming systems on arthropod diversity within fields and across agricultural landscapes. *Global Change Biology* **23**, 4946–4957.

Liquido NJ (1993) Reduction of oriental fruit fly (Diptera: Tephritidae) populations in papaya orchards by field sanitation. *Journal of Agricultural Entomology* **10**, 163–170.

Marliac G, Penvern S, Barbier J-M, Lescourret F and Capowiez Y (2015) Impact of crop protection strategies on natural enemies in organic apple production. *Agronomy for Sustainable Development* **35**, 803–813.

Motswagole R, Gotcha N and Nyamukondiwa C (2019) Thermal biology and seasonal population abundance of *Bactrocera dorsalis* Hendel (Diptera: Tephritidae): Implications on pest management. *International Journal of Insect Science* **11**, 117954331986341.

N'Dépo OR, My M and Nl Y (2019) Host plants associated with Tephritidae in Côte d'Ivoire and discovery of a new fruit fly species: *Dasus longistylus*. *Journal of Entomology and Zoology Studies* **7**, 1301–1308.

Nugnes F, Carbone C, Ascolese R, Miele F, Pica F, Palmieri A, Griffo RV and Bernardo U (2024) The enemy is already inside! *Bactrocera dorsalis* is a serious threat to European orchards and crops. *Entomologia Generalis* **44**, 1243–1251.

Papadopoulos NT, De Meyer M, Terblanche JS and Kriticos DJ (2024) Fruit flies: Challenges and opportunities to stem the tide of global invasions. *Annual Review of Entomology* **69**, 355–373.

Priyadarshana TS, Martin EA, Sirami C, Woodcock BA, Goodale E, Martínez-Núñez C, Lee M-B, Pagani-Núñez E, Raderschall CA, Brotons L, Rege A, Ouin A, Tscharntke T and Slade EM (2024) Crop and landscape heterogeneity increase biodiversity in agricultural landscapes: A global review and meta-analysis. *Ecology Letters* **27**, e14412.

Pujari D, Badal Bhattacharyya BB and Mrinmoy Das MD (2013) Insect pest management in organic agriculture. *International Journal of Plant Protection* **6**, 467–472.

Putri SOR, Rizali A and Ikawati S (2025) Different effects of local and landscape factors on the population density of two fruit fly species in Indonesian apple orchards. *Biodiversitas Journal of Biological Diversity* **26**, 2079–2087.

R Core Team (2024) R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Rehman A, Farooq M, Lee D-J and Siddique KHM (2022) Sustainable agricultural practices for food security and ecosystem services. *Environmental Science and Pollution Research* **29**, 84076–84095.

Ricci B, Franck P, Toubon J-F, Bouvier J-C, Sauphanor B and Lavigne C (2009) The influence of landscape on insect pest dynamics: A case study in southeastern France. *Landscape Ecology* **24**, 337–349.

Rusch A, Valantin-Morison M, Sarthou J-P and Roger-Estrade J (2010) Biological control of insect pests in agroecosystems: Effects of crop management, farming systems, and seminatural habitats at the landscape scale: A review. *Advances in Agronomy* **109**, 219–259.

Santoiemma G, Mori N, Tonina L and Marini L (2018) Semi-natural habitats boost *Drosophila suzukii* populations and crop damage in sweet cherry. *Agriculture, Ecosystems & Environment* **257**, 152–158.

Singh TVK and Satyanarayana J (2009) Insect outbreaks and their management. In Rajinder P and Dhawan Ashok K (eds.), *Integrated Pest Management: Innovation-Development Process*. Dordrecht: Springer Netherlands, 331–350.

Stenberg JA (2017) A conceptual framework for integrated pest management. *Trends in Plant Science* **22**, 759–769.

Stonehouse JM, Mumford JD and Mustafa G (1998) Economic losses to tephritid fruit flies (Diptera: Tephritidae) in Pakistan. *Crop Protection* **17**, 159–164.

Tscharntke T and Brandl R (2004) Plant-insect interactions in fragmented landscapes. *Annual Review of Entomology* **49**, 405–430.

Tscharntke T, Karp DS, Chaplin-Kramer R, Batáry P, DeClerck F, Gratton C, Hunt L, Ives A, Jonsson M, Larsen A, Martin EA, Martínez-Salinas A, Meehan TD, O'Rourke M, Poveda K, Rosenheim JA, Rusch A, Schellhorn N, Wanger TC, Wratten S and Zhang W (2016) When natural habitat fails to enhance biological pest control – Five hypotheses. *Biological Conservation* **204**, 449–458.

Tscharntke T, Steffan-Dewenter I, Kruess A and Thies C (2002) Characteristics of insect populations on habitat fragments: A mini review. *Ecological Research* **17**, 229–239.

Vargas RI, Piñero JC, Leblanc L, Manoukis NC and Mau RFL (2016) Area-Wide Management of Fruit Flies (Diptera: Tephritidae) in Hawaii. In Sunday E, Mohamed Samira A and Marc DM (eds.), *Fruit Fly Research and Development in Africa - Towards a Sustainable Management Strategy to Improve Horticulture*. Cham: Springer International Publishing, 673–693.

Venables WN and Ripley BD (2002) *Modern Applied Statistics with S*, Fourth edn. New York: Springer.

Verghese A, Sreedevi K and Nagaraju DK (2006) Pre and post harvest IPM for the mango fruit fly, *Bactrocera dorsalis* (Hendel). In Proceedings of the 7th International Symposium on Fruit Flies of Economic Importance, 179–182. Salvador, Brazil.

Vincenot D, Normand F, Amouroux P, Hoarau I, Joas J and Léchaudel M (2009) Guide de production intégrée de mangue à La Réunion. Chambre d'Agriculture de La Réunion and CIRAD, **126**.

Virgilio M, White I and De Meyer M (2014) A set of multi-entry identification keys to African frugivorous flies (Diptera, Tephritidae). *ZooKeys* **428**, 97–108.

Wen Z, Yang Q, Huang B, Zhang L, Zheng H, Shen Y, Yang Y, Ouyang Z and Li R (2023) Landscape composition and configuration relatively affect invasive pest and its associator across multiple spatial scales. *Frontiers in Sustainable Food Systems* **7**, 1114508.

White IM and Elson-Harris MM (1992) *Fruit Flies of Economic Significance: Their Identification and Bionomics*. CAB International: Wallingford, UK.
Zeng Y, Reddy GVP, Li Z, Qin Y, Wang Y, Pan X, Jiang F, Gao F and Zhao Z-H (2019) Global distribution and invasion pattern of oriental fruit fly, *Bactrocera dorsalis*. Diptera: Tephritidae *Journal of Applied Entomology* **143**, 165–176. https://doi.org/10.1111/jen.12582.
Zida I, Nébié K, Sawadogo A, Tassembédo B, Kiénou T, Dabiré RA and Nacro S (2023) Effectiveness of four integrated pest management approaches in the control of fruit flies (Diptera: Tephritidae) in mango agro-ecosystems in the South-Sudanian zone of Burkina Faso. *Advances in Entomology* **11**, 124–142.