Interactions between integrated pest management, pollinator introduction, and landscape context on avocado *Persea americana* productivity

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With 3 figures and 1 table

Abstract: Pest management and insect pollination are important services that support crop production but are most often studied in isolation in cropping systems. Avocado *Persea americana* Mill. is an economically important crop in East Africa, which suffers from pest threats and potential drawbacks of the global pollinator crisis. The integration of pest and pollinator management is a growing research trend as a potential solution for sustainable crop production with minimum adverse effects on the environment and biodiversity. This study assessed potential interactions between landscape context, honeybee *Apis mellifera* L. introduction and integrated pest management (IPM) on avocado pests *Bactrocera dorsalis* (Hendel) and *Thaumatotibia leucotreta* (Meyrick), pollinators, and productivity in Kenya. Results showed an interaction between honeybee introduction and IPM on *A. mellifera*, with the highest mean abundance on the farms with both honeybee colonies and IPM. The abundance and diversity of non-*Apis* flower visitors were not affected by IPM and honeybee introduction across the landscapes. Pollinator introduction and IPM implementation resulted in a 941% fruit set increase and up to 97% fruit abscission within the high vegetation productivity class. Pest abundance significantly decreased on the farms with IPM, resulting in a 6% increase of final fruit weight compared with the farms without IPM. Overall, integration of pest and pollinator management did not synergistically increase the final avocado yield but represented a potential strategy to reduce pest densities while preserving wild visitors and benefiting from secondary products of honeybee colonies.

Keywords: *Apis mellifera*, honeybee, pollination, *K*-means algorithm, smallholder, Tephritidae, Tortricidae

1 Introduction

Research interests in ecological intensification have been growing because of its potential role to maximise crop production while reducing economic and environmental costs (Bommarco et al. 2013). Mechanisms that drive positive impacts of ecological intensification on crop production are not well understood, with inconsistent findings across previous studies (Tamburini et al. 2019). The normalised difference vegetation index (NDVI) is the most used remote-sensed metric of landscape vegetation productivity to assess animal responses and crop productivity to environmental changes (Pettorelli et al. 2011). However, there is limited understanding of interactions between landscape vegetation productivity and agroecosystem services on crop productivity (Pettorelli et al. 2011). Beyond the landscape effect on

crop productivity, ecosystem services interact with each other, influencing crop yield either synergistically, additively or negatively (Tamburini et al. 2019). For instance, the interaction between pest control and pollination on crop production is explained by the compensatory potential of crops, hence the importance of crop type in the evaluation of the interaction between pest control and pollination on crop production (Munguía-Rosas et al. 2015, Gagic et al. 2016).

Avocado *Persea americana* Mill. (Lauraceae) is an important commodity crop that depends mainly on honeybees *Apis mellifera* (L.) (Hymenoptera: Apidae) for pollination (Dymond et al. 2021). In most regions, avocado pollination is also achieved by several non-honeybee insects such as hoverflies (Syrphidae), blowflies (Calliphoridae), stingless bees (Apidae), wild bees (Apidae, Halictidae) and wasps (Vespidae) (Dymond et al. 2021). Due to the global

pollinator decline, avocado pollination may be vulnerable like other insect pollinator dependent crops (Potts et al. 2010).

Besides issues related to pollination, avocado production is jeopardised by the oriental fruit fly *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae) and the false codling moth *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) (Toukem et al. 2020). These polyphagous pests damage fruits through oviposition and larval feeding on the fruit pulp, resulting in reduced marketability. Integrated pest management (IPM) of *B. dorsalis* and *T. leucotreta* in mango *Mangifera indica* L. (Anacardiaceae) and citrus (*Citrus* spp.) (Rutaceae) farms have shown some success in sub-Saharan Africa but has yet to be investigated on avocado farms (Ndlela et al. 2016, Malan et al. 2018).

Despite these challenges related to avocado production, the demand for avocado products in the past decade has increased globally, thus reinforcing the adverse effects of agricultural industrialisation on biodiversity and the environment (FAOSTAT 2019). The combination of pollination services and IPM is likely a potential sustainable practice to achieve high yields and quality of avocado at minimum environmental and economic costs. Here, the effects and interactions between landscape context, honeybee introduction and IPM on avocado pests, pollinators and pollination benefits (fruit set, abscission, and weight) were assessed. The following hypotheses were tested in this study: (1) introduction of honeybee colonies increases the abundance of *A. mellifera* and does not influence other flower visitors, (2) implementation of IPM reduces avocado pest abundance and fruit infestation, (3) landscape vegetation productivity influences effects of honeybee introduction and IPM on the abundances of pests and honeybees, fruit set, fruit abscission, and final fruit weight.

2   Materials and methods

2.1   Study site, experimental layout, and farm selection

The field experiment was conducted in Murang'a county, Kenya, between September 2019 and June 2020. Murang'a is the major avocado-producing area in Kenya, where the crop is mainly grown by smallholder farmers in mixed cropping systems (Toukem et al. 2020).

A fully crossed design of landscape vegetation productivity (low, medium, and high class), honeybee introduction (absence and presence of managed honeybee colonies), and IPM (absence and presence of IPM) with three replicates was implemented on avocado farms.

A total of 36 avocado farms, ranging between 0.4 and 1 ha, were randomly selected using socio-economic criteria and insect foraging distances (Adan et al. 2021) (Sup. Fig. 1).

2.1.1   Landscape vegetation productivity and introduction of managed colonies of *Apis mellifera*

The landscape was classified into three classes (low, medium, and high) of vegetation productivity as a proxy of the normalised difference vegetation index (NDVI) (Adan et al. 2021, Toukem et al. 2020). Managed honeybee colonies from *icipe*'s apiaries were kept in Langstroth hives and installed on avocado farms at a density of 2 colonies/farm at the onset of bloom (September 2019). Hives were placed at the southern border of the farms and kept throughout the study.

2.1.2   Integrated pest management of *Bactrocera dorsalis* and *Thaumatotibia leucotreta*

Suppression of *B. dorsalis* and *T. leucotreta* populations started at the fruit set and continued until harvesting. The farms received the following IPM package: (1) attract-and-kill fruit fly device (Bactrocera-Block, Kenya Biologics, Kenya) comprised of a wooden block impregnated with methyl eugenol (ME) and malathion, (2) attract-and-kill gel (LastCall FCM, Insect Science, South Africa), which contained the pheromone (E, E, Z)-7,8,8-dodecenyl acetate and permethrin, (3) protein bait (FruitFly Mania, Kenya Biologics, Kenya) made of hydrolysate proteins, and (4) soil drenching with Mazao Campaign 69 (a.i. *Metarhizium anisopliae* ICIPE 69) (RealIPM, Kenya). These products were applied on avocado farms following the procedure described in Sup. Fig. 1.

2.2   Monitoring of flower-visiting insects

A total of 180 trees were monitored during the peak (October 2019) and late flowering (November 2019) periods, between 09:00 AM and 05:00 PM, under sunny weather conditions. Trees were monitored along a 100 m long transect in the middle of the farm, using a sweep net at 2.5 m above the ground. Five avocado trees spaced by 7 m were selected along the transect and monitored each for 8 min. Captured insects were preserved in 70% ethanol for further identification (Sup. Table 1).

2.3   Population monitoring of *Bactrocera dorsalis* and *Thaumatotibia leucotreta*

In all the farms, Lynfield traps baited with methyl eugenol (River Bioscience, South Africa) were used for population monitoring of *B. dorsalis* while Delta traps baited with the sex-pheromone (Crytrack, Kenya Biologics) were used for *T. leucotreta* monitoring. Two traps (one for each target pest) were set on the farm 20 m apart along the same transect used for the surveys of flower-visiting insects. Traps were checked every two weeks and captured fruit flies were preserved in 70% ethanol, while the sticky paper of the Delta trap was wrapped inside a polythene bag. ME blocks and pheromones were replaced with new ones every six and four weeks,

respectively. Insects were counted and identified using keys described by De Meyer (1998), Drew & Romig (2016) (for fruit flies), and Gilligan & Epstein (2014) (for moths).

Pests were also evaluated through fruit incubation. Hanging and fallen fruits were collected and incubated separately following the protocol described in Toukem et al. (2020). Emerging adults were preserved in 70% ethanol for morphological identification using the keys described above.

2.4 Assessment of fruit set, abscission, and yield

Fruit set was assessed on three trees per farm in September 2019 (tree selection as described in 2.2). Initially, four panicles were marked, and the number of fruits was counted four and 12 weeks later to determine fruit set and the proportion of abscised fruits, respectively. Between March and June 2020, fruits of at least 16 cm in diameter were harvested from the same trees and weighed every three or four weeks, depending on fruit growth.

2.5 Data analyses

2.5.1 Response variables

Flower visitors were divided into two groups for analysis: (i) honeybee *A. mellifera* and (ii) wild visitors, which included all flower-visiting insects except *A. mellifera*. The diversity of wild visitors was measured with the Shannon index using species and family level identification. Generalised linear mixed models (GLMM) were performed on the abundance of honeybees and wild visitors, assuming a negative binomial error distribution. The Shannon index of wild visitors was modelled using GLMM assuming a normal error distribution. For honeybee, wild visitors, and Shannon index models, the random effect structure included farm nested within the monitoring round. Daily catches of *B. dorsalis* and *T. leucotreta* per trap were log-transformed to assume a normal error distribution and analysed using generalised least squares models with a Gaussian autoregressive correlation structure to accommodate spatial autocorrelation in the data (Moran I test: $P < 0.05$ for *B. dorsalis* and *T. leucotreta*). The infestation index for ground- and tree-collected fruits were not analysed because of the very low emergence of pests (< 10 individuals).

The proportion of fruit set and abscised fruits per tree were fitted in beta-binomial mixed models, assuming a beta distribution. The random effect structure comprised the cardinal side nested within the tree and the farm. Before fitting the models, values were logit-transformed to fit in the open unit interval (0,1). Furthermore, the direct effects of pollinators on pollination services were evaluated using linear relationships between fruit set and abundance of *A. mellifera*, wild visitors, and the Shannon index at the farm level. The fruit weight for each tree was cumulated over the harvesting rounds and log-transformed before fitting in GLMM, assuming a normal error distribution. The random effect structure comprised nested trees within the farm.

2.5.2 Model fitting procedure

For each response variable described in 2.5.1, effects of landscape vegetation productivity, honeybee introduction, IPM, and interactions were assessed in the models. Models were validated graphically when there was no evidence of dispersion and autocorrelation in the residuals. Effects were tested using the Wald F-test (for *B. dorsalis*, *T. leucotreta*, Shannon index, and weight) or the Wald chi-square test (for fruit set and abscission, *A. mellifera*, and wild visitors). Mean comparison among groups was performed with the Tukey test. All statistical tests were performed at $\alpha = 0.05$ in R (R Core Team 2019).

3 Results

3.1 Flower-visiting insects of avocado

Model summary and accuracy for each response variable are presented in Sup. Table 2 and Fig. 1, respectively. Flower-visiting insects captured during the surveys belonged to 70 species in 29 families (Sup. Table 1). The most abundant families were Apidae, Calliphoridae, Syrphidae, and Rhiniidae. *Apis mellifera* comprised on average 95.6% of Apidae collected during both monitoring periods. Other Apidae included *Braunsapis* sp., *Ceratina* (*Simioceratina*) sp., and Halictidae such as *Nomia* sp., *Lasioglossum* (*Ipomalictus*) sp., *Pseudapis* (*Pseudapis*) sp., *Patellapis* sp., and *Systropha* sp. The Syrphidae community was dominated by *Allograpta calopoides* (Curran) and *Eristalinus quinquelineatus* (Fabricius). Identification of Calliphoridae was limited to two sub-families (Chrysominae and non-Chrysominae), with Chrysominae being the most abundant group throughout the study. Rhiniidae were identified as belonging to six morphospecies among which Rhiniidae sp. 2 was the most abundant (Sup. Table 1). Statistical analyses showed no interactions between landscape vegetation productivity, honeybee introduction, and IPM on the abundances of honeybees and wild visitors, and the Shannon index (Table 1 and Sup. Table 2). However, there was an interaction between honeybee introduction and IPM on the abundance of honeybees, with the highest mean abundance in IPPM farms (Fig. 2a).

3.2 Population dynamics of avocado pests

Overall, mean daily catches of *B. dorsalis* in the low (49.4 ± 6.9) and medium (48.3 ± 6.7) vegetation productivity classes were comparable but significantly higher than those in the high class (1.33 ± 0.3) ($F = 4.65$, df = 2, 408, $P = 0.01$). There was a significant interaction between landscape vegetation productivity and honeybee introduction ($F = 3.89$, df = 2, 408, $P = 0.02$), whereby mean daily catches of *B. dorsalis* were lower in the high vegetation productivity class with and
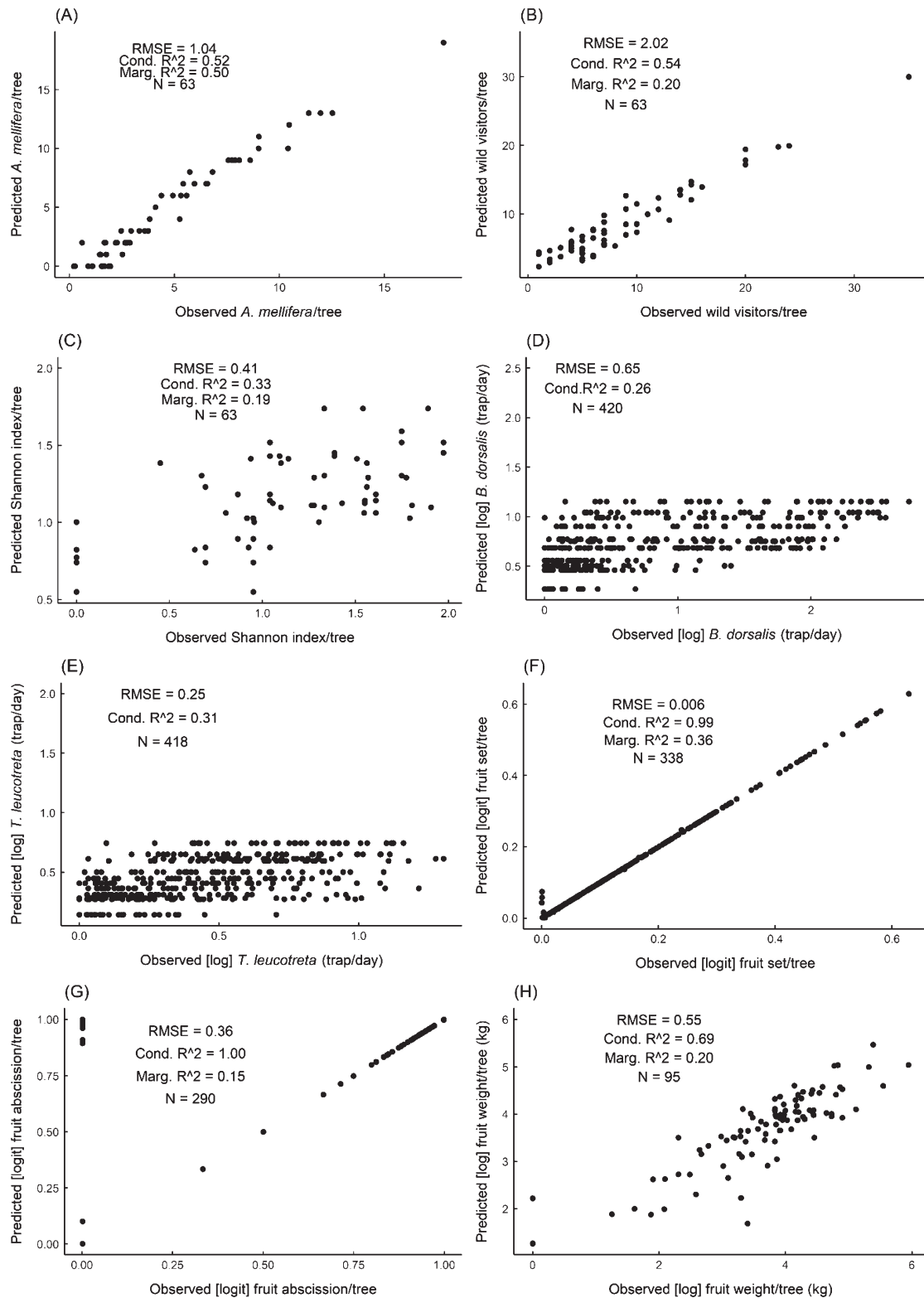
Fig. 1. Plots of predicted values vs. observed values showing the accuracy of the fitted generalised linear mixed models of abundances of honeybee **(A)** and wild visitors **(B)** (both assuming a negative binomial error distribution), Shannon index of wild visitors **(C)** (normal error distribution), fruit set **(F)**, abscission **(G)** (both assuming a beta error distribution), and fruit weight **(H)** (assuming a normal error distribution). Models explaining variations of daily catches of *Bactrocera dorsalis* **(D)** and *Thaumatotibia leucotreta* **(E)** (both assuming normal error distribution) were fitted using the generalised least squares method. The interactions between landscape vegetation productivity, pest control, and introduction of *A. mellifera* colonies were set as explanatory variables in all the models. RMSE = root mean squared error, Cond. R^2 (conditional R^2) and Marg. R^2 (marginal R^2) shows the variance explained by the model and the fixed effects, respectively.

Table 1. Summary of statistical tests of landscape vegetation productivity (low, medium, and high classes), pest control (IPM) (no, yes), the introduction of honeybee *Apis mellifera* colonies (no, yes), and interactions between the factors on pest abundance, Shannon index of wild visitors, final fruit weight (using *F* test), and pollinator abundance, fruit set, and abscission (using chi-square test). Probability values in bold denote a significant effect at the 5% significance level.

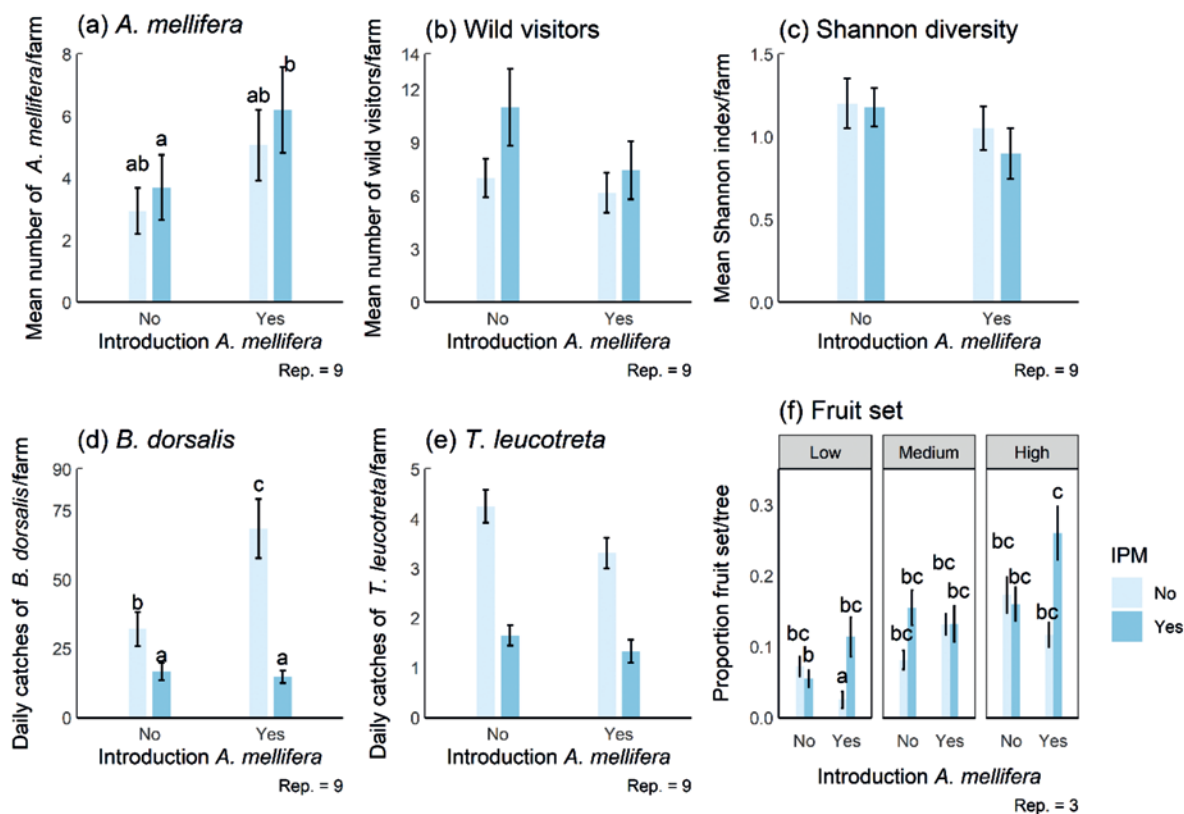|	Pests				Pollinators						Pollination services					
	B. dorsalis		*T. leucotreta*		*A. mellifera*		Wild visitors		Shannon index		Fruit set		Fruit abscission		Fruit weight	
Explanatory variables	$F_{(df)}$	P	$F_{(df)}$	P	$\chi^2_{(df)}$	P	$\chi^2_{(df)}$	P	$F_{(df)}$	P	$\chi^2_{(df)}$	P	$\chi^2_{(df)}$	P	$F_{(df)}$	P
IPM	3.20	0.07	140.3	**<0.0001**	3.93	0.05	0.52	0.46	0.22	0.64	0.02	0.87	4.03	**0.04**	4.99	**0.03**
	(1,408)		(1,406)		(1,48)		(1,48)		(1,20.5)		(1,322)		(1,274)		(1,21.4)	
Honeybee intro.	0.003	0.95	9.46	**0.002**	0.007	0.93	1.00	0.31	0.05	0.82	1.97	0.16	1.42	0.23	1.23	0.27
	(1,408)		(1,406)		(1,48)		(1,48)		(1,27.5)		(1,322)		(1,274)		(1,21.5)	
Landscape	4.65	**0.01**	17.5	**<0.001**	1.44	0.48	3.16	0.20	3.38	0.05	2.56	0.27	15.9	**0.0003**	3.50	**0.04**
	(2,408)		(2,406)		(2,48)		(2,48)		(2,21.1)		(2,322)		(2,274)		(2,21.3)	
IPM × honeybee intro.	6.21	**0.01**	0.02	0.87	4.34	**0.03**	1.87	0.17	0.41	0.52	3.13	0.07	0.54	0.46	1.07	0.31
	(1,408)		(1,406)		(1,48)		(1,48)		(1,24.1)		(1,322)		(1,274)		(1,21.2)	
Landscape × IPM	1.28	0.27	2.29	0.10	5.85	0.05	0.30	0.85	0.52	0.60	5.59	0.06	8.14	**0.01**	1.94	0.16
	(2,408)		(2,406)		(2,48)		(2,48)		(2,20.5)		(2,322)		(2,274)		(2,21.2)	
Landscape × honeybee intro.	3.89	**0.02**	0.48	0.61	0.58	0.74	2.33	0.31	0.41	0.66	73.4	**<0.0001**	69.2	**<0.0001**	1.44	0.25
	(2,408)		(2,406)		(2,48)		(2,48)		(2,22.7)		(2,322)		(2,274)		(2,22.1)	
Landscape × IPM × honeybee intro.	1.25	0.28	1.32	0.26	5.41	0.06	2.19	0.33	0.37	0.69	22.8	**<0.0001**	19.1	**<0.0001**	0.59	0.56
	(2,408)		(2,406)		(2,48)		(2,48)		(2,22.4)		(2,322)		(2,274)		(2,21.7)	

Fig. 2. Interaction between pest control (no, yes) and introduction of *A. mellifera* (no, yes) on pollinators (*Apis mellifera*, wild visitors, and Shannon index), pests (*Bactrocera dorsalis* and *Thaumatotibia leucotreta*) and fruit set. Columns and error bars represent the mean and the standard error, respectively. Mean comparisons among the four groups were performed with the Tukey test at a 5% level of significance. The absence of letters on top of error bars denotes a lack of significant interaction between pest control and the introduction of *A. mellifera*. Rep. denotes the number of replicates for each group.

without honeybee introduction compared with farms in the low and medium classes. Mean daily catches of *B. dorsalis* were two to four times lower on the farms with either IPM only, or both IPM and *A. mellifera* introduction, compared with honeybee introduction only and control farms (F = 6.21, df = 1, 408, P = 0.01) (Fig. 2d). Among the farms without IPM, the mean daily catches of *B. dorsalis* on the farms with honeybee colonies were two times higher compared to the farms without colonies (Fig. 2d). However, interactions between landscape vegetation productivity, honeybee introduction, and IPM on *B. dorsalis* catches were not significant (F = 1.25, df = 2, 408, P = 0.28) (Sup. Table 3).

Statistical results of the effects of landscape vegetation productivity, honeybee introduction, IPM, and interactions on daily catches of *T. leucotreta* are summarised in Table 1. The mean daily catches of *T. leucotreta* on the farms with IPM were 2.5 times lower than those in farms without IPM (F = 104.3, df = 1, 406, P < 0.0001). Results also indicated an independent effect of the landscape vegetation productivity (F = 17.5, df = 2, 406, P < 0.0001), with comparable mean daily catches of *T. leucotreta* in the low (2.95 ± 0.3) and medium (3.14 ± 0.3) vegetation productivity classes, but significantly different from those in the high class (1.75 ± 0.1). Like *B. dorsalis*, there were no significant interactions between landscape vegetation productivity, honeybee introduction, and IPM on *T. leucotreta* catches (F = 1.32, df = 2, 406, P = 0.26) (Sup. Table 3 and Fig. 2e).

3.3   Fruit set, fruit abscission, and yield

Fruit set per tree varied between 0% and 49%, while the proportion of abscised fruits varied between 0% and 100%. Results showed significant interactions between landscape vegetation productivity, honeybee introduction, and IPM on fruit set (χ^2 = 22.8, df = 2, 322, P < 0.0001) (Sup. Table 2 and Table 1). The highest mean fruit set per tree was recorded in the high vegetation productivity class with both IPM and honeybee introduction but was not significantly different from other treatments except in the low class with IPM only and honeybee introduction only (Fig. 2f). There was also an interaction between landscape vegetation productivity and honeybee introduction (χ^2 = 69.2, df = 2, 274, P < 0.0001), whereby the mean fruit set per tree in the low vegetation productivity class with and without honeybee colonies were significantly lower than fruit set in other treatments (Fig. 3a). No independent effects of the landscape vegetation productivity, honeybee introduction or IPM on fruit set were reported (Sup. Table 2 and Table 1).

There was a positive linear relationship between fruit set and the Shannon index (ß = 0.03, t = 2.25, P = 0.03), while there was no linear relationship between fruit set and abundance of honeybees (ß = –0.002, t = –1.06, P = 0.29) or wild visitors (ß = –0.001, t = –1.10, P = 0.27).

Overall, the mean proportion of abscised fruits per tree in the medium and high vegetation productivity classes were higher than in the low class (χ^2 = 15.9, df = 2, 274,

P = 0.0003) (Fig. 3a). There was also an interaction between landscape vegetation productivity and IPM on fruit abscission (χ^2 = 8.14, df = 2, 274, P = 0.01), with an increase of 11% and 16% fruit abscission on the farms with IPM in the low and high vegetation productivity classes compared to the farms without IPM in the same classes. The interaction between landscape vegetation productivity and honeybee introduction (χ^2 = 69.3, df = 2, 274, P < 0.0001) was explained by a significant increase of fruit abscission by 17% and 30%, respectively, on the farms without honeybee colonies in the low and medium vegetation productivity classes compared to the farms in the low class with honeybee colonies (Fig. 3b). There were also interactions between landscape vegetation productivity, honeybee introduction, and IPM on fruit abscission (χ^2 = 19.1, df = 2, 274, P < 0.0001). The lowest mean proportion of abscised fruits per tree was recorded in the low vegetation productivity class with honeybee introduction only, and significantly different from the low class without IPM and honeybee introduction. The mean proportion of abscised fruits in other treatments was not statistically different from each other (Fig. 3b).

The final fruit weight was influenced by the landscape vegetation productivity (F = 3.50, df = 2, 21.3, P = 0.04), with the highest mean fruit weight per tree in the medium vegetation productivity class (77.9 ± 13.0 kg), followed by the high class (60.5 ± 9.3 kg) and significantly different from that in the low class (35.7 ± 4.7 kg). In addition, the mean fruit weight in farms with IPM (61.2 ± 10.3 kg) was higher than in the farms without IPM (57.6 ± 6.1 kg) (F = 4.99, df = 1, 21.4, P = 0.03), irrespective of landscape vegetation productivity and honeybee introduction. However, there were no interactions between landscape vegetation productivity, honeybee introduction, and IPM on the fruit weight (F = 0.59, df = 2, 21.3, P = 0.56) (Fig. 3c).

4   Discussion and conclusions

In addition to *A. mellifera*, other Apidae and Halictidae undoubtedly contributed to avocado pollination as their pollinator role in many crops is widely acknowledged (Dymond et al. 2021). Avocado pollination was also supported by numerous non-bee insects, among which were *Eristalinus* species (Syrphidae), whose pollination efficiency on many crops has been reported previously (Campoy et al. 2020). This is in line with previous findings that reported a large diversity of avocado flower visitors in sub-Saharan Africa (Mulwa et al. 2019, Dymond et al. 2021). The abundance and diversity of wild visitors were not affected by IPM implementation, thus providing evidence on the lack of harmful effects of the IPM package. However, the abundance of honeybees was more important on the farms with IPM than in farms without. In contrast to this finding, previous studies reported repellent effects of the spinosad-based protein bait (GF-120) on stingless bees *Trigona fulviventris* (Guérin) and
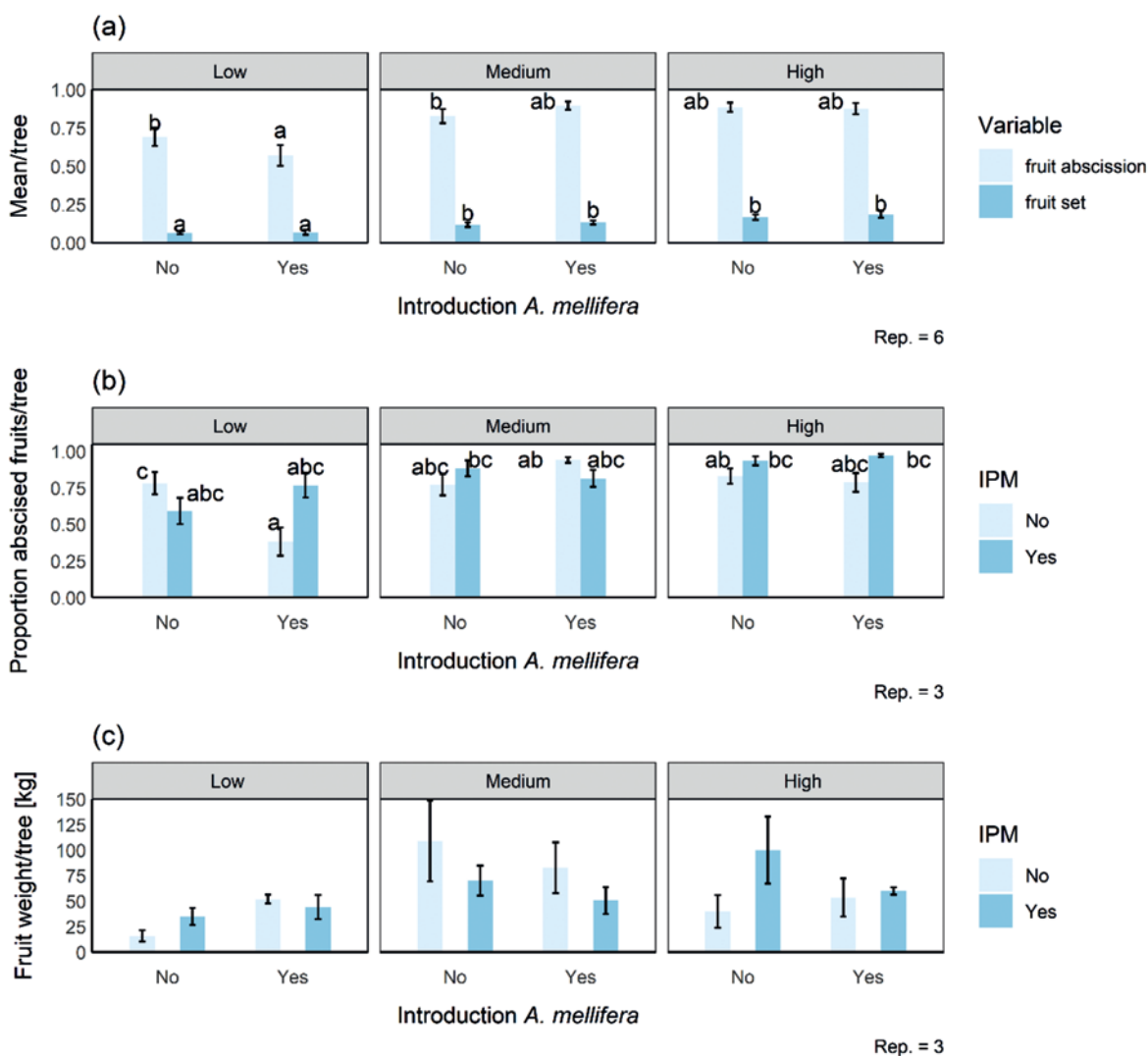
Fig. 3. Interaction between landscape vegetation productivity classes (low, medium, and high) and introduction of *Apis mellifera* colonies (no, yes) on the proportions of fruit set, abscised fruits, and final fruit weight per tree. Columns and error bars represent the mean and the standard error, respectively. For each variable, a pairwise comparison was performed among the six groups using the Tukey test. Groups with different letters on top of errors bars are different at a 5% significance level. Rep. denotes the number of replicates for each group.

Scaptotrigona mexicana (Guérin-Meneville) (all Apidae), and *A. mellifera* (Mangan et al. 2009, Gómez-Escobar et al. 2014). Another interesting finding is the lack of effects of honeybee introduction on wild visitors, likely indicating that the introduced honeybees did not represent any risks for wild insect flower visitors through foraging competition, and pest and disease transmission (Henry & Rodet 2018).

The highest fruit set was detected in the high vegetation productivity class with both IPM and *A. mellifera* introduction, supporting the role of the landscape and IPM in shaping pollination benefits. This interaction can be explained by the potential of the high vegetation productivity class in encouraging a large diversity of wild visitors, which likely facilitated

avocado pollination. This is further supported by the positive linear relationship between the fruit set and the Shannon index detected in this study. The most abundant wild visitors (Calliphoridae, Rhiniidae, and Syrphidae) reported here have been documented in recent studies as occasional pollinators of many horticultural crops including avocado (Cook et al. 2020, Dymond et al. 2021). Studies pointed out that the thermal tolerance of calliphorids and the synchronisation of their foraging behaviour with avocado floral receptivity make them more effective than honeybees (Cook et al. 2020). This result provides additional insights on the importance of encouraging diverse communities of wild visitors in avocado farms rather than introducing honeybee colonies only.

The significant decrease of *B. dorsalis* catches on the farms with IPM and without honeybee introduction likely confirms the effectiveness of the implemented IPM package. In the same way, *T. leucotreta* catches were lower in farms with IPM than in farms without, irrespective of the landscape vegetation productivity class or the presence of honeybee colonies. The combination of IPM components used in this study targeted several stages of the pests and reduced their population densities to a level comparable with that seen in previous studies. For instance, in Kenya, deployment of ME-baited devices in mango orchards reduced *B. dorsalis* populations by 99.5% compared with controls (Ndlela et al. 2016). To the best of our knowledge, this is the first study combining a fungal biopesticide with mass trapping in suppressing *T. leucotreta* in avocado plantations in Africa. Our results on the management of *T. leucotreta* are consistent with those of Mkiga et al. (2021) who reported the effectiveness of pheromone-based mass trapping and fungal-based soil drenches to reduce *T. leucotreta* populations and fruit infestations in citrus orchards. Other studies conducted in South Africa used either entomopathogenic nematodes, entomopathogenic fungi, or mass release of irradiated adults (sterile insect technique) in citrus orchards (Malan et al. 2018, Hofmeyr et al. 2019). On the other hand, the increase in *B. dorsalis* catches on the farms without IPM was more important in the presence of honeybee colonies. This could be explained by the smell of honey sugar or fermentation that attracted fruit flies (Lee et al. 2015). The landscape vegetation productivity also influenced pest populations independently from the pest management approach. These results are in line with our earlier observations of higher abundance of avocado pests in the low and medium vegetation productivity classes than in the low class (Toukem et al. 2020).

The lack of effects of honeybee introduction and interactions with landscape vegetation productivity and IPM on fruit weight should be interpreted with caution as fruit development is influenced by other physiological and abiotic factors, which were not controlled in our study. In this study, the level of fruit abscission was seemingly proportional to the initial fruit set, as farms with a low initial fruit set tended to have low fruit abscission. This fruit abscission may be explained as a response to resource limitation and, or inadequate pollination (Alcaraz et al. 2019). Alternate and irregular fruit bearing of avocado may have induced a high variability among the farms, and hidden interactions between landscape vegetation productivity, honeybee introduction, and IPM on the fruit weight. Nevertheless, the introduction of managed honeybee colonies and IPM might be a valuable approach to increase fruit production and quality on avocado farms and benefit from socioeconomic gains through proceeds from bee-hive products such as honey and bee wax (Jeil et al. 2020). On the one hand, the increase of fruit weight in the medium and high vegetation productivity classes potentially indicates more favourable environmental conditions in these classes than in the low class where resources are limited. On the other hand, the increase of fruit weight in farms with IPM reinforced evidence on the benefits of IPM in suppressing pests and increasing avocado production.

In light of our findings, it can be concluded that avocado pollination depends both on *A. mellifera* and wild visitors. The introduction of honeybee colonies only did not increase the fruit set but interacted with the landscape vegetation productivity and IPM. The implementation of IPM significantly reduced *B. dorsalis* and *T. leucotreta* catches. However, there were no interactions between landscape vegetation productivity, honeybee introduction, and IPM on the fruit weight.

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The pdf version (Adobe JavaScript must be enabled) of this paper includes an electronic supplement: Sup. Table 1–3 and Sup. Fig. 1